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WIND PROPULSION TECHNOLOGIES REVIEW

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With the collaboration and technical expertise of Avel Vor Technologies,
"Bureau d'étude pour les économies d'énergie dans le domaine maritime"

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Abstract

This paper, elaborated within the SAIL project in collaboration with members of WP3 and WP4, presents a quick review of six main wind propulsion technologies existing nowadays and a -non-exhaustive- list of technological enablers that might make Wind Assisted Propulsion (WASP) ships become competitive again under today's sector standards. The objective of this paper is to launch a collective debate about Hybrid Freight Sailing (HFS) among the partners of the SAIL project by creating a common database on wind propulsion.

A short preamble stating the present need for mitigation measures in the maritime freight sector with regard to its unchallenged domination on global freight transportation opens the document. The technological review is then introduced through an historical perspective describing the main issues that finally made sailing ships non-profitable in spite of their long resistance to steam engines. This opening gives the first hints for a deeper thought around an economic model for HFS in Europe and also aptly introduces a first list of the enabling technologies that might make WASP ships competitive with regards to the standards of waterborne freight.

Six briefing notes are then presented (one for each concept): traditional sails, wing-sails, Dynarig, Flettner rotors, Towing kites and Cousteau turbo voile. They have been constructed following the same structure for more readability: first, an explanation of the physic principle and material configuration of the device with schematics, second, a presentation of the available technological choices, third, a list of the most obvious benefits and constraints of the device, followed by projects known for having explored this technology.

The conclusion of the document emphasizes some of the differences that exist at conception stage for WASP ships in comparison with conventional engine powered vessels and it aims at replacing wind propulsion in the wider context of « ships greening » techniques through retrofitting and hybridization. With this context set, we can briefly discuss the financial and technical advantages or drawbacks of the various ways to implement WASP concepts on actual ships.

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Preamble

Nowadays, maritime freight shipping is, by far, the primary means of global trade. According to the figures of the UNCTAD, there were 104 305 registered commercial ships in January 2012, which amounts to a tonnage capacity of 1534 million dwt and also proves that the global fleet follows an almost 10% annual growth[1]. In 2009, ships transported around eight billion tons of seaborne trade; which amounted to almost 90 percent of the global trade for this year[2] . The rising progression of the tonnage shipped by maritime vessels since the 1950's is impressive: 550 million tons were transported in 1950, 1 billion in 1960 and 8 billion today. Already having the lion share of global good transportation (80 to 90 % of all the goods shared globally are transported by boats) waterborne transportation is expected to grow even more in years to come as a result of the modal transfers towards rail and maritime transportation (i.e. low carbon transportation means) that are going to occur in Europe in response to the mitigation policies that are being implemented.

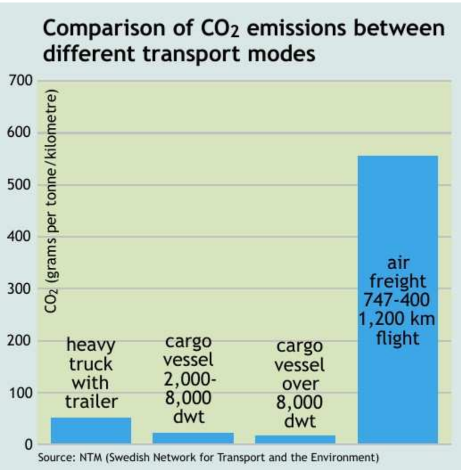

Figure 1 : Comparison of CO2 emissions between different transport modes. Source: Swedish Network for transport and environment

The prominent role of maritime transportation in global trade unveiled by these figures is a direct consequence of the very low cost of waterborne transportation: the constant increase in capacity of large container and bulk ships (which allows enormous scale economies), coupled with the strong resistance to inflation showed by the maritime shipping business[3] and the very high energy efficiency of ships have indeed made maritime shipping the cheapest mean to carry goods around the globe. But even though this position of cheapest global carrier remains unchallenged, the sector's high dependency on oil remains troublesome considering the constant rise of oil prices since the 1970's and the green-house gases mitigation policies being implemented around the globe and more especially in the EU.

According to the European Commission, waterborne transportation is annually responsible for the emission of 100 billion tons of CO2[4] this figure amounts to almost 4,5% of global emissions. But the sector is also responsible for 92% of global SO^2 emissions and 20% of global Nox emissions. Indeed, the fuel commonly used for the propulsion of commercial ships is particularly harmful as its combustion emits more black carbon aerosols than most other fossil propellants. Still, maritime shipping is one of the less carbon-intensive transportation means (again, thanks to the fact that it is the most energy-efficient mean of moving goods) (figure 1) which is why the policies that call for a reduction of the ecological footprint of global trade might further increase the volume of maritime shipping: many large corporations are already committed to increasing their relative use of rail and barge services for environmental and economic reasons[5].

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1 UNCTAD, Review of marine transport 2012 (UNCTAD/RMT/2012). New York, N.Y.: United Nations. Retrieved from http://unctad.org/en/PublicationsLibrary/rmt2012_en.pdf

2 Idem

3 *« For example, bulk shipping costs have increased only about seventy-percent in the last 50 years while U.S. retail prices have risen approximately seven-hundred percent over the same period »* (Maritime International Secretariat Services Ltd, *International shipping – carrier of world trade*, 2006)

4 E C Environment. Emissions from maritime transport. European Commission Transport and Environment, 2011. Retrieved from: http://ec.europa.eu/environment/air/transport/ships.htm.

5 Wright J., B. Bentz, R. Gosier, and D. Jones (2010). Beyond the Tipping Point: Preparing to Thrive in an Oil□ challenged World. Accenture. 24 pp. Retrieved from:

Wind propulsion, as obvious a solution it may appear in the context of maritime transportation, is only one among many options to mitigate the GHG emissions of the sector. Fuel substitutions (from natural gas to hydrogen), speed reduction, waste heat reduction, weather routing or waterflow optimization are among the list of other ways to reduce the ships' GHG emissions. But for obvious historical reasons, wind propulsion is a technique that has been particularly documented and made great progress in the past decades (mainly thanks to sport-oriented innovations). Physical reasons should also be mentioned here: indeed, the wind power is directly delivered to the hull, without losses from the propeller (usually about 50%) that make the wind propulsion system twice as powerful as a thermic propulsion.

The idea of Hybrid Freight Shipping (HFS)[6] is not new and the investigation of sails for commercial shipping really started in the 1980's and especially with the INDOSAIL project in 1984[7]. Since that year, the development of commercial merchant sailing technologies has remained relatively low but continuous. Comparing the fluctuations of oil prices with the number of events related to merchant sailing opportunities shows that, despite its energy-efficiency, conventional maritime shipping is threatened by its entire dependency on oil (figure 2): the interest for wind propulsion clearly follows the rising of oil prices.

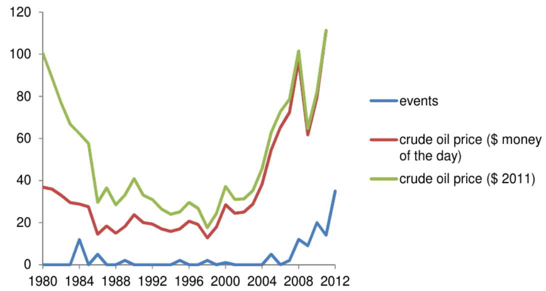

Figure 2 : comparison of oil prices and of worldwide events related to HFS.
Source : Isabelle Rojon's master thesis and BP

As can be read on this graph, large research efforts were made in the 1980's when the oil prices went very high. Comparable efforts to hybridize the propulsion of sailing ships can only be found in the 1920's when Flettner rotors were tested for the first time. However, the fuel prices dropped again in the 90's and the conservative, short-term-benefit oriented shipping industry kept on ruling trade exchanges.

This document aims at describing the various wind propulsion technologies that may be used to hybridize maritime transportation. As an introduction, it seems relevant to relate briefly how sails disappeared from freight shipping in order to understand what drawbacks of sailing vessels made wind propulsion obsolete, which would allow to weigh the usefulness of new technologies to make sailing economically viable again. Then, six types of wind propulsion devices will be presented, following the same description structure for each (physic principle and material configuration, technological choices, main benefits and confines, list of projects exploring this technology).

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http://www.accenture.com/SiteCollectionDocuments/PDF/Accenture_Beyond_the_Tipping_Point.pdf

6 Hybrid Freight Sailing can be defined as a means to mitigate the emissions from maritime ships : wind energy is transformed into propulsive energy by sailing rigs and used to hybridize a traditional thermic propulsion.

7 Schenzle, P., G. Weselmann, et F. Weiss. « The "INDOSAIL" project ». *Journal of Wind Engineering and Industrial Aerodynamics* 19, nº 1-3 (juillet 1985): 19-43. doi:10.1016/0167-6105(85)90055-8.

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Introduction - a quick historical review of the disappearance of sails from freight shipping

Wind propulsion has obviously dominated the history of shipping, in comparison, mechanical propulsion really is quite a new development. From approximately 5400 BC to the end of the XVIIIth century sailing boats have been the fastest waterborne transportation means there was. And contrary to popular belief, sail shipping was far from obsolete at the beginning of the XXth century. It only completely disappeared from global trade at the beginning of World War II, in 1940, at a time when steamships were already made obsolete by the increasing domination of motor ships (figure 3). In fact, the various improvements in sailing ships which occurred all along the XIXth century are a good example of the general pattern that established technology improves when it is challenged by a new technology[8]. The case of sailing ships and steamships is such a perfect embodiment of this pattern that it is often referred to as the *sailing ship effect*.

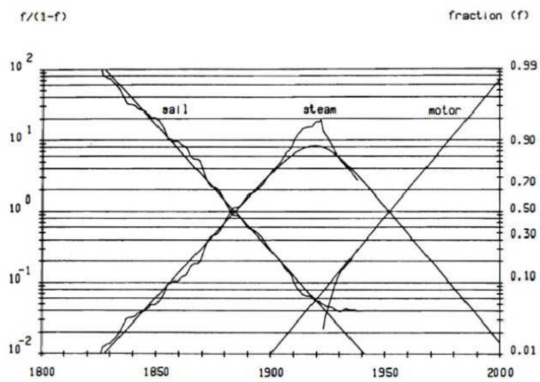

Figure 3 : Substitution of sailing, steam and motor ship, UK.

Source :Grübler, A. and N. Nakićenović, 'Long waves, technology diffusion, and substitution', 1991

And so it appears that what is commonly held as the reason for the disappearance of sailing ships (the application of steam propulsion's principles to sea transportation at the beginning of the XIXth century) is not a sufficient element to explain why sailing ships became history. How and why did they manage to stay on the market for almost a century after the introduction of steam ships?

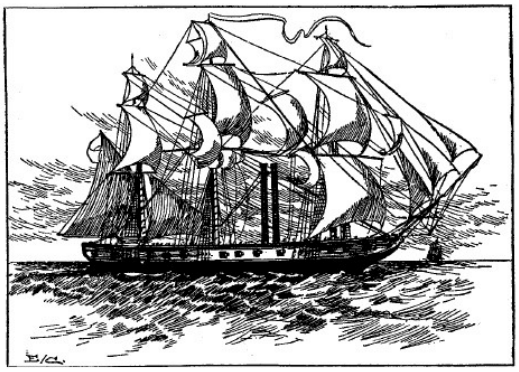

Figure 4 : The Rising Star 1819.

Source : Geels, F.W., 2002, 'Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study', Research Policy, 31(8/9), 1257-1274

The first answer to that question is that sailing boats shifted their focus from transporting passengers and high-value goods to goods where speed was not such an important criterion[9]. Wind powered ships also used the competitive advantage they had as they were relying on well-known technology and adapted infrastructures. But apart from these obvious reasons, the story behind the disappearance of sailing vessels from global trade is much more complicated and interesting.

During the first decades following their apparition, steam engines were mainly considered as a mean to improve existing sailing ships. The first steam engine equipped boat to cross the Atlantic in 1819, *The Rising Star* was mostly a sailing vessel equipped with an auxiliary steam propulsion device (figure 4). And indeed, if steam propulsion rapidly became the norm for inland waterways, it was deemed impossible to sail the ocean with a steamship until 1835[10]. So at first, steam

8 Geels, F.W., 2002, 'Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study', *Research Policy*, 31(8/9), 1257-1274

9 Grübler, A., 1990, 'The rise and fall of infrastructures: dynamics of evolution and technological change in transport', Heidelberg, Physical-Verlag.

10 Dirkzwager, J.M., 1993, 'Scheepsbouw', in: Lintsen, H.W. et al. (eds.), Geschiedenis van de techniek in Nederland:

propulsion was mainly used to raise the security on-board – by making ships more maneuverable in case of storm – ensure more precise estimated times of arrival (ETA), raise the ships' average speed and ease ports maneuvers. But apart from these exotic hybrid ships, sailing ships builders improved ships impressively: in the 1850's in Great Britain, iron started to replace wood as the main construction element allowing the building of larger ships. American ship builders remained faithful to wood but were the first to design the fastest merchant sailing vessels of the XIX^th^ century: the famous clippers[11].

Figure 5 : Clipper Sovereign of the Seas set the record for World's Fastest Sailing Ship in 1854.
Source :http://upload.wikimedia.org/wikipedia/commons/9/99/Sovereignoftheseasdockedphoto.jpg

These fine hulled, and generally three masted, boats were 60 to 70 m long on average and built for speed rather than cargo capacity, associating a large sail surface to a small hull (figure 5). These ships benefited from the best technology of the time and became a new standard for freight shipping between 1840's and 1870's. And when ocean steam boats were finally technologically ready to conquer international trade, from the 1870's, clippers opposed a strong competition. Their speed, security and reliance were truly holding the comparison against steamships' new standards. And the pressure put on the market by the invasion of steamships triggered further improvements of clippers. The multiplication of masts and sails became common-place as the hulls were elongated to the maximum, thanks to metallic structures, to extend cargo capacity.

Early steamships (the golden age of steam shipping having last from the 1880's to the 1930's) still needed important crews to be safely operated and could rapidly become dangerous in case of bad weather. This explains why windjammer were eventually developed from the 1870's as a complement to clippers. These steel or iron made sailing boats, reaching more than 140 m in length, were the last card of sailing ships builders. They were adequately completing the clippers' speed with high cargo capacity and they occupied a niche in the transport of low-value bulk cargoes of little interest to steamship companies, e.g., lumber, coal, guano or grain from the 1870's until the beginning of the 1920's. When clippers finally became obsolete, by the end of the XIX^th^ century, these slow ships were made faster by the multiplication of sails and masts, as *The Thomas Lawson* testifies with the 7 masts (figure 6).

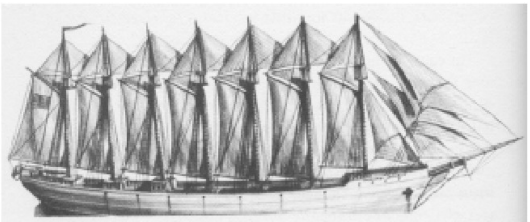

Figure 6 : The Thomas Lawson was the only 7 masts windjammer in history.

Source : Geels, F.W., 2002, 'Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study', Research Policy, 31(8/9), 1257-1274

The last large windjammers, in spite of their incredibly large sail surface were especially designed to spare the crew labor (mainly thanks to steam winches and basic electric devices). Indeed, crew costs had become the main disadvantage of sailing ships in comparison to steamships. For those very reasons, even larger windjammers with auxiliary engines for propulsion were developed during the first decades of the XX^th^ century (the French *France II* (1911) and German *R. C. Rickmers* (1906), both five-masted barques, are the most famous of those times). The huge investments and technological innovations that these ships

De wording van een moderne samenleving, 1800-1890, deel IV, Stichting Historie der Techniek, Walburg Pers, Zutphen, pp. 66-102

11 The first boats that were referred to as « clippers » were designed in Virginia but soon became the « Baltimore Clippers » around 1815. These small (30 meters) ships became famous because of their speed, as they reached 9 knots of average speed

necessitated testify that lots of trade professionals still firmly believed in the economic viability of sails at the beginning of the XX[th] century.

Finally, several drawbacks of sailing ships could not be solved through the optimization process that maintained wind propulsion at a competitive level all along the era of steamships. They can be listed as follows : low speed, imprecise ETA, need for large crews of skilled sailors (high costs), excessive heel angles, limited mechanical power on board and high servicing costs (big sailing ships needed constant maintenance services).

Putting these competitiveness troubles in perspective with the miniaturization of mechanical processes and the emergence of IT technologies that occurred since sailing ships disappeared from the face of global trade changes the game. Indeed, most of these competitive disadvantages could be fixed through resorting to various available technologies. Such as sail automation to drastically reduce crew needs, better weather routing (with the use of a dynamic router constantly adapting the ship's itinerary to weather conditions) and better understanding of sailing systems (thanks to sport motivated prototypes and engineering innovations), small auxiliary electric engines to ensure a reasonable ETA and grant maneuverability while maintaining zero-emission transportation, etc. These technologies are the needed enablers that might make wind propulsion a serious economic option in the XXI[st] century. Before giving a brief description of the various wind propulsion concepts available nowadays, it seems relevant to explore concisely these enabling technologies through a non-exhaustive list.

1 Enabling technologies

A new paradigm to build for hybridization, necessitating computing, and mathematics.
When hybridizing a ship, two concepts have to be kept in mind:

- **The two energy sources have to be combined, and not just putted one upon the other**
- **In most cases, wind is only an auxiliary energy and not the principal one**

These two considerations lead to the necessary development of specific optimization algorithms that are capable of both enhancing wind energy to reduce fuel consumption and combining the two energies to better control arrival time. This is a difficult task due to the fact that wind that is used by the sails is directly linked to the speed and orientation of the ship (the more rapidly the ship is going, the more oriented toward the ship direction the wind will be, making sails less efficient). Due to the antinomy of these objectives (using wind energy only will minimize fuel consumption but expand travel time whereas shipping using fuel only will allow to control travel time but will expand pollution and fuel consumption), an optimum is to find to determine the instant power of the motor that is needed for each wind conditions and for a specific arrival time.

Apart from this optimization, the new weapon for hybridization, many other enabling technologies have been developed to enable modern sailing ships enter into the market. They have been separated in five categories. The first four of these categories gathers the main competitive disadvantages that finally led to the desertion of sailing ships from global trade. The last category gathers the technologies that would enable modern sailing ships to comply with modern trade and security standards. The main inputs of the 21st century, are probably the development of captors that allow to determine the real air flow arriving on the sail or the exact position of the sail, combined with the automation of the sails. The list that is given below is not exhaustive and would need to be completed.

1.1 ETA

- Sailing ships routing software (there is an obvious need for a software that would take into account the specific shapes of the sails of the boat (i.e. the various possible positions of the ship to the wind) and weather conditions to propose the safest and most efficient routes to reach a reasonable ETA.)
- On-board IT solutions (first to calculate in real time the best routing based on constantly updated weather reports and second to manage the sails at their maximum energy output by constantly adapting their shape to immediate wind conditions according to the information given by on-board weather instruments (anemometer, weather vane, barometer, etc.) and Lidars)
- On-board Lidars (to allow the display of wind movements happening some hundreds of meters ahead of the ship in order to anticipate gusts and shifting winds. This may not have an important impact on energy output but could really make sails last longer and would also increase on-board security.)
- Small auxiliary mechanical propulsion device (to guarantee a minimal unpredictability of ETA)

…

1.2 Crew size and skills

- Sails mechanization (i.e. motorized winches, sheets, halyards, furlers and all other ropes used to adjust the sails (vang, Cunningham, mainsheet rail, reefs, etc.). These motorized adjustments have to be manageable from a single dashboard placed in the cockpit to drastically reduce the need for crewmen.)

- Sails automation (i.e. motorized winches, sheets, halyards, furlers and all other ropes used to adjust the sails (vang, Cunningham, mainsheet rail, reefs, etc.) These motorized adjustments can be managed directly by on-board IT solutions to allow the pilot to manage the ship without having to take sails into account.)

…

1.3 Mechanical power on-board

- Auxiliary engines to maintain the propulsion in extreme cases (wind propulsion must not lead to underestimating of the power needed)
- On-board electricity generator for specific needs (related to living and working on-board, sails adjusting motors and on-board IT solutions). Solar panels could be used for low needs (due to the area needed to cover requirements). Wind turbines are also a possible CO2 free solution but with a high productivity loss (when functioning on hybrid ships, they mostly furnish electricity with speed wind due to both diesel and sails propulsion).

…

1.4 Servicing costs

- Resort to innovative building materials (carbon masts or Mylar sails are expensive but would last much longer than traditional materials.
- On-board Lidars (to allow the display of wind movements happening some hundreds of meters ahead of the ship in order to anticipate gusts and shifting winds. This may not have an important impact on energy output but could really make sails last longer and would also increase on-board security.)

...

1.5 Compliance with the modern standards of global trade

- Relevant logistics (on-board and on dock) (there is a need for efficient loading and unloading despite the potential constraints that would raise the presence of a sailing rig on the deck of the ship – shape of the hull, height, wind surface area, etc.)
- Complying with insurances and actual security standards. These are the two questions we need to answer: What are the standards for commercial shipping? And what technologies (apart from the ones listed above) could be useful to maintain these standards on-board of commercial sailing ships?

…

Limits

As it is the case for each innovation, it will take time for them to be tested, developed and commercialized, if they even succeed in passing through all these steps. Many barriers have then to be removed whether they are technical or economical, before they become integrated on most ships.

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2 Wind Propulsion Technology

2.1 General theory

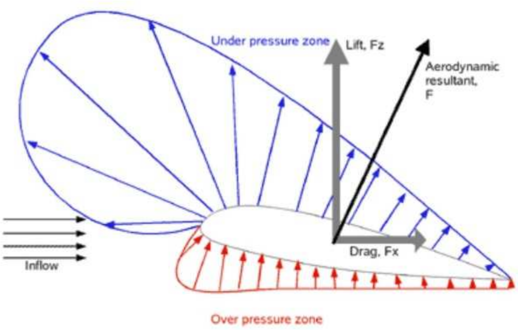


Figure 7 : Standard profile shape of sails and wings.

Source : http://www.cfse.ch/img/site/topic/Wings-Explanations.gif

Wind propulsion is generated by the difference of pressure between both sides of a sail. This difference is due to the asymmetric velocity of the wind around the two sides of a boat sail (or of an airplane wing) – the intrados and the extrados (figure 7 and 8).

For the wind to go around the sail, one way is shorter than the other. Most of the wind will follow this « easiest way » (on the intrados side) and will therefore be slowed down. The remaining wind will follow the longest way around the sail (the extrados side) and will therefore be accelerated, which will make the pressure drop.

This difference of pressure between the intrados and the extrados will generate a force, proportional to the difference of pressure and approximately oriented perpendicularly to the profile.

One of the main specificity of aerodynamic sailing principles is that if the wind (or the direction of the ship) switches, sails' profiles need to be able to evolve to adapt to the new conditions and maintain propulsion. The intrados side of the sail needs to be able to become the extrados side in order to generate a propulsive force whatever the position of the ship to the wind.

Apart from the traditional soft sails made of canvas, many others technologies were developed for wind propulsion (figure 9) and all of them use more or less the aerodynamic principles explain above.

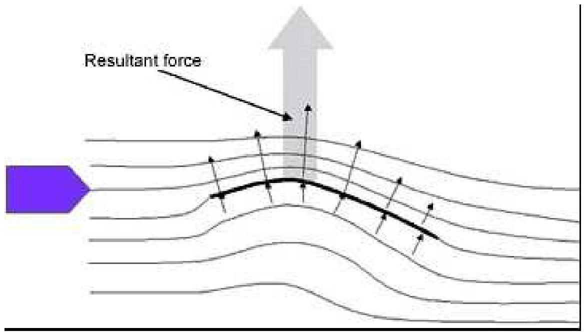


Figure 8 : Exemple on a traditional sail.

Source : http://www.planetseed.com/fr/scienc earticle/la-voile-un-jeu-denfant

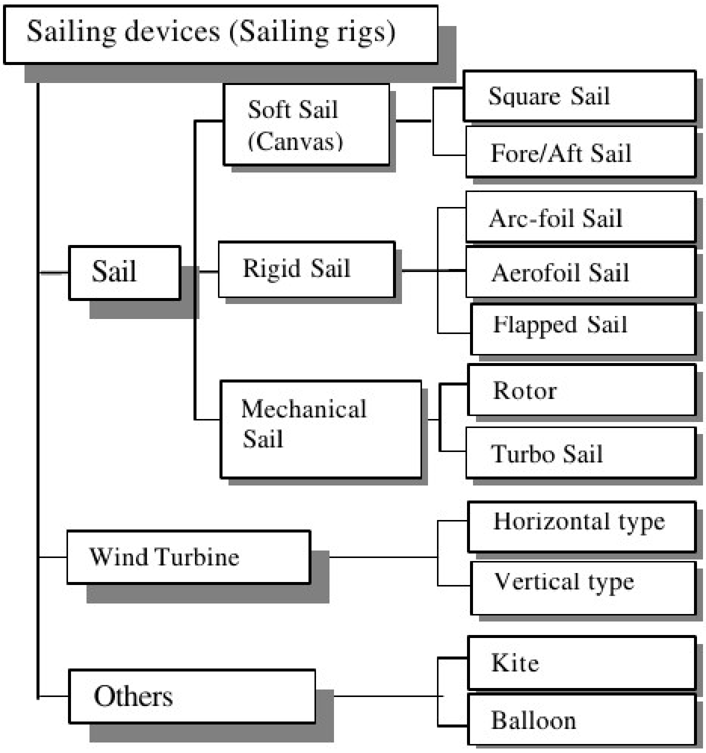


Figure 9 : An organogram of the various wind propulsion technologies.

Source: Yoshimura, Yasuo, 2002, « A Prospect of Sail-Assisted Fishing Boats », Fisheries Science, 68(Supplement 2): 1815-1818

2.2 Traditional sails (Cat rig, traditional Gaffel rig, Bermuda sail, traditional square rig)

Figure 10 : Source: http://www.avel- vor.fr/images/VAA/GL_cote_petit.JPG

2.2.1 Physic principle and material configuration:

Figure 11 : Marconi rig.

Source : http://fr.wikipedia.org/wiki/Gr%C3%A9ement_bermudien

The Marconi rig (consisting in the combination of a bermuda main sail and a head sail affixed to a guyed mast) is very dominant nowadays (see Figure 10). This rig is constituted by a main sail which leading edge, the side of the sail oriented toward the front side of the boat, is affixed to a vertical mast. Its inferior side is maintained stiff thanks to the boom (bermuda main sail). The head sail is placed in front of the mast, its leading edge affixed to the stay which links the head of the mast to the bow.

These two sails are generally attached to a central guyed mast – the shrouds, stay and backstay substantially diminish the weight of the mast. But the same rig can be obtained with an A shaped mast. These two sails are soft sails, made of canva. Battens can stiff this canva in order to enhance the energy output. The softness and shapes of the sails allow the generation of a propulsive energy adaptable to the direction of the wind.

Many adjustments, at conception stage and in use, may influence the propulsive energy output of the sails. The main adjustments are:

- Elongation: the ratio between the size of the mast and the size of the boom. The narrower the sail is, the more it is efficient up-wind. On the contrary, the larger a sail is, the more it is efficient down-wind.
- The curvature of sails profiles, that are made possible thanks to their suppleness, is what allows them to produce a good propulsive energy without switching off (phenomenon that occurs when the wind stops circulating along the profile of the sail but bypass it instead, which returns an absence of propulsive energy)

The sail profile depth is defined by the position of the hollow (value *m*) and its size (value *f*), (figure 11). This data is defined at conception stage. When modifying the size of the hollow, one can obtain a flat sail profile which will be more efficient up-wind, or a deeper sail profile which will be more efficient down-wind.

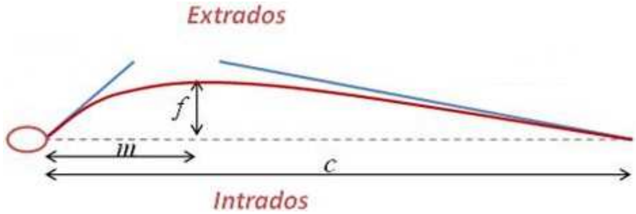


Figure 12 : hollow shape adjustments of the sail.

Source : http://www.finot.com/ecrits/Damien%20Lafforgue/article_voiles.html

The various adjustments of the tension of sails-related ropes (stay, low forestay, backstay, runner, sheet, vang, cunningham) allow to influence the energy output of the sails but requires a lot of skillful workforce.

This type of rig has been successfully enhanced through decades of progress. These progress allowed the simplification of sails' adjustment and the standardization of sailing ships building techniques, making sailing less expensive and enjoyable for a larger number of people. But these progress also enhanced the energy output of this rig by complicating the possible adjustments and using new materials which also made it elitist and expensive in some cases.

2.2.2 Technological choices

The self-sustained mast is generally made of aluminum (except for racing rigs, for which masts are often made of carbon and lightly shrouded so that they can rotate their studied profiles with the main-sail to create a better sail profile), placed at the center of the hull and heavily shrouded to reduce its weight and size. These mast may hold as much as 4 spreaders, a stay and low forestays, and backstays or runners. All these cables are cluttering the deck of those ships, they also communicate the forces they receive to the hull that has to be designed and reinforced for that purpose.

Few years ago, bi-pod masts have emerged has an alternative to the traditional self-sustained mast. These A shaped masts allow to get rid of most cables and shrouders and limit the pressure applied to the hull, but they are still quite rare.

The sails are generally made of « average » canvass that are easily affected by the heavy pressures of the wind and ropes, which ends up modifying the sails' performance.

The head sail is often installed on a furler to ease its deployment and allow an easy reduction of the surface of the sail in case of strong winds. But this simple process is not optimum since it substantially diminishes the performance of the sail. Indeed, in a strong wind, the ship has to diminish the energy output of its sails by reducing their surface and flatten them to the maximum. But since the sail are not designed flat, a half furled foresail will tend to have a deeper curvature than the same sail fully deployed. A phenomenon that is increased by the softness of sails' canvass and by their years of service, returning a less energy efficient sail.

The main sail is most often battened and set with a boom to reinforce its stiffness in order to maintain the required sail profile depth.

Most bermuda main sails are also lowerable: they are raised and lowered along the mast. Lowerable sails give more energy output as their profiles remain unaltered by reefing (reducing wind surface by suppressing the first second or third levels of the sail, by fastening the corresponding batten to the boom).

Main sails mast or boom furlers are also available, requiring less management of the sails and adjusting ropes, but their energy output is substantially lower since their use lead to the suppression of sail battens.

Many different foresails are used, each corresponding to precise weather conditions and wind directions; which means that in order to maximize the energy output of the rig, the sails need to be switched every time the conditions change. This system substantially raises the performances of traditional sails, but requires a lot of skilled workforce.

There is most frequently only one main-sail, but made out of very stiff canvass (such as Mylar) and reinforced with large carbon battens in order to get a squared shaped sail (that maximizes higher sail surface to get the stronger altitude winds). This type of main-sail can be reduced with the use of reefs and adapted to wind conditions by many adjustments (tension and position of the mainsheet, tension of the runners, tension of the Cunningham... All these adjustments require time and skills.

A few technical improvements have recently been made:

- Remote control of the sails weather manual (with a joystick) or automatic (software)
- Adaptation of the sail position to the wind conditions in anticipation and in retrospect
  - These to adaptations may be used in parallel on a hybridized system

2.2.3 Benefits

- Traditional sails, especially mounted on Marconi rigs, are very widespread, which makes knowledge on their usage, energy outputs, ease of automation and technological choices proportionally widespread.
- These technologies are already on the market and can easily be transposed to professional maritime activities.

2.2.4 Confines

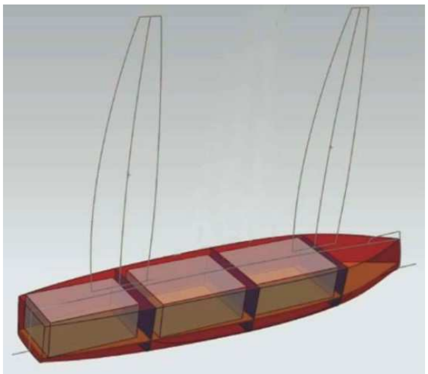
- The rigs that have the best energy outputs are also the ones that require the most workforces and skills.
- The mast and sails require lots of shrouds and adjusting ropes, which makes automation difficult and clutters the deck.
- As for all types of sails (except kytes) the addition of sails on a ship will generate instability. Specific studies will need to be conducted
- Automation implies technological choices: it will be easier to put a selftacking Genoa than an overlapping Genoa for example.

2.2.5 Non-exhaustive list of the projects exploring this technology

- Avel-Vor-Technologies : http://www.avel-vor.fr : currently working on various activities within the SAIL project to develop hybridization with traditional sails
- Green heart Project: http://www.greenheartproject.org/en/

…

2.3 Wing-sails



Source: http://www.propelwind.com/media/propelwind-presentation-en

2.3.1 Physic principle and material configuration

Wing-sails (also referred to as thick-sails) are exploiting their thick profiles to generate greater propulsion. The extrados and the intrados being farer from one another, the depression and overpressure generated by the profile are much more important than on a traditional hollowed sail.

These wing sails are affixed to slightly shrouded or self-sustained masts. Wing-sails are shaped like an airplane wing which raises the problem of adapting its profile to the wind shifts. An airplane wing's intrados and extrados never switch sides, contrary to sails that constantly need to do so. Wing-sails must therefore be able to rotate around the mast to follow the wind.

Current research about this wind propulsion technology is focused on the look for better aerodynamic profiles, ones that would be able to reach the best energy output for a wing in slow winds – indeed, modern wings shape is the result of centuries of aerodynamic experiments on much stronger wind pressure than the one witnessed on sailing vessels.

2.3.2 Technological choices:

Source: http://www.buildboats.info/graphic/wingsail1.jpg

The two main technological choices available for wing-sails depend on the design of the profile: it can be continuous or separated and articulated (see table below).

Another more recent option relies in the availability of lowerable wing-sails. Indeed, these wing-sails first made their appearance with completely lowerable stiff profiles: they were made of two symmetric elements and were impossible to lower. If the wind is unfavorable, the two elements remain in line and the sail is left to freely rotate. If the wind is favorable, the two elements are positioned so as to create an unsymmetrical profile and the rotative mast is used to put the sail in the wind.

Now that lowerable wing-sails have been tested, the problems raising from having a permanent wind surface can be set. These lowerable wing-sails are generally built around a self-sustained mast, and made of thick battens (to shape the sail profile) and strong canvas (along which the wind is accelerated and slowed down around the wingsail).

The benefits of lowerable wing-sails are obvious, they give better energy output than traditional sails but are easily manageable. : The sails are lowerable in the same way they on traditional Marconi rigs without furlers.

Separated and articulated wing-sail profile

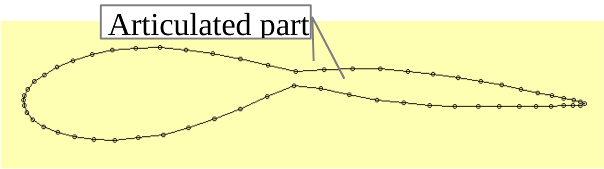


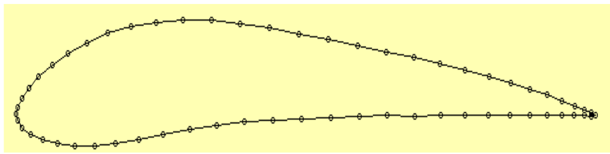
Figure 13 : separated and articulated wing-sail profile.

Principle :
For separated and articulated profiles, 2 (or more) symmetric profiles are put in line with each other and then articulated in order to generate an asymmetrical wind inflow around it (figure 12). This asymmetrical profile can be more or less accentuated at any time to react to immediate wind conditions.

Benefits :
As for traditional sails, the profile depth of the sail can be adjust to immediate wind conditions. Adjustments such as web geometry variations to update its characteristics and sail's ratio are the two main features that can be adjusted with a separated and articulated wing profile.

Confines :
Adjustments are more numerous and harder to automatize.

Continuous wing-sail profile



Principle :
For continuous profiles, the structure must be able to adopt the hollow shaped profile of efficient sails and must be able to revert this profile in order to adapt to the ship's changing position to the wind.(figure 13)

Benefits :
Adjustments are minimal which would make automation or motorization much easier than on a Marconi rig.

Confines :
The non-adaptability of continuous profiles to the sail from conception stage.

2.3.3 Benefits

- The self-sustained or lightly shrouded guyed mast and the few number of adjustments of the sail allow for an open-deck.
- Wing-sails profiles are returning a very high energy output, generating a strong lift effect: the profile's thickness raises the lift while diminishing the needed angle between the profile and the wind to generate this lift. This feature returns a stronger propulsive force and decreases the induced drag that slows down the ship movements.
- The application is eased since there are only a few distinct adjustments: setting up the sail/ adjusting sail profile/ orienting the rig according to winds direction to generate the lift.
- If the appropriate technological choices are made, the mast may be enabled to make a full spin

around its axis; guaranteeing gentle and safe maneuvers.

- Wing-sails are very efficient when the ship moves up-wind.
-

2.3.4 Confines

- For stiff, non-lowerable sails the danger lies in the fact that the wind surface cannot be diminished, even in the eventuality of strong winds which endangers the ship and its crew.
- Self-sustained masts and articulated battens are hard to design and are still extremely costly.
- Wing-sails have a low energy output when the ship moves down-wind.

2.3.5 Non-exhaustive list of the projects exploring this technology :

- Propelwind: http://www.propelwind.com/

Appart from propelwind, no active projects to adapt wing-sails to commercial ships have been found (non-lowerable stiffed wing-sails do not seem attractive for trade needs and lowerable wing-sails just emerged).

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2.4 Dynarig sails

Source :http://www.gdnp.nl/currentprojects

Source: http://www.b9energy.com/Portals/B9/HYD_B9%20commercial%20sailing%20ship%20WIP_May2011.jpg

2.4.1 Physic principle and material configuration

The dynarig sail system consists in a self-sustained rotational mast and many horizontals appendages affixed to the mast . The sails are consist of a large number of canvas panels that can be adjusted individually and that, altogether, constitute a sail.

Sail profile's symmetry is what makes it so peculiar. The intrados and extrados are always on the same sides of the sail: wind will come from one side and then another without having to change the sail geometry. (figure 14).

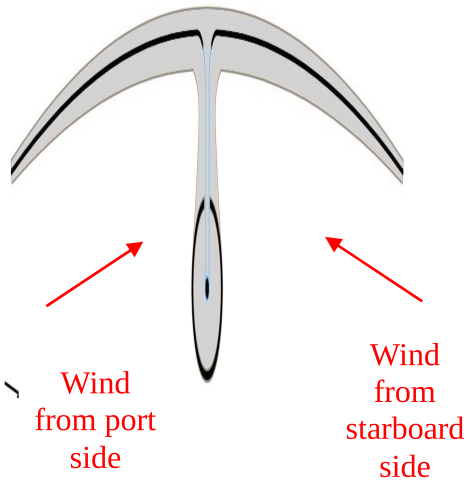

Figure 15 : Dyna-rig sails' symetric profile

2.4.2 Technological choices

There are 4 main technological choices available for Dyna-rig sails

Sail profile	***Furlable pannels***	***360° rotational mast***	***Sails stiffness***
Principle : Since the profile of the sail is not adjustable (the only way to adjust a Dynarig sail to the wind is to rotate the mast) it must be defined once and for all at conception stage.	**Principle :** To set the sails on a Dynarig system, there are two options : the panels can be folded on the horizontal appendages to be hoisted vertically, or the sail panels can be unfurled horizontally. In which case a furler is	**Principle :** A rotative mast is always needed on a Dynarig propulsion system (as it is the only way to put the sails to the wind) but optionally, this mast can be enabled to do a complete revolution (a 360° self-rotation) but the the	**Principle :** The peculiar profile of Dynarig sails can also be designed with stiff materials since their intrados and extrados sides do not need to be switchable.

	installed in the mast to furl each sail panel from the middle.	deck needs to be open.	
Benefits : Depending on the chosen profile, the maximum energy output of the sails can be find down-wind or up-wind : a flat profile for up-wind efficiency and a hollowed profile for down-wind and cross-wind efficiency.	**Benefits :** Furlable sail panels make it easier to automate the adjustment of sail surface to wind conditions. The energy output is not deteriorated by the furler since the sail panels are never partially unfurled : it is either totally set or not at all. Furthermore, each pannel being held on each of its four corners, the sails last longer.	**Benefits :** Maneuvers are made easier : a fully rotational mast increases on-board security since most maneuvers are made soft and secured.	**Benefits :** A stiffer sail allows to reach a better energy output.
Confines: No adjustment of the sails shape of the sails is possible on a Dyna-rig propulsion system. Once the design has been set, the only way to change it is to replace the masts.	**Confines:** The use of folded panels requires more workforce, but furlers are costly and forbid the use of a half furled panel.	**Confines:** A 360° rotating mast is costly and installing it implies that over technological choices do not stand in the way : furlable panels may be hindrance and the deck must be open.	**Confines:** Stiff sails cannot be lowered : this forbids the adjustment of the sail surface to wind conditions, which can be a major problem in case of strong winds.

2.4.3 Benefits

- The self-sustained, lightly guyed mast and the few settings needed allow little congestion of the deck
- The sails being almost still on the yards, their wearing is significantly reduced.
- The use is very easy: little operating is needed, the mast is set in the desired direction and power follows.
- The maneuvers are safe and secured by the ability of the mast to make a spin on itself
- A dynarig sail returns a very good efficiency output when the ships is moving down-wind
- Reefing is made easy : in case of strong winds, each canva pannel can be lowered independently.
- Dynarig sails keeps better energy output in the long run. Indeed, each panel being hold simultaneously by its for corners, distortion of sail profile is much less likely to occur and sails last longer.

2.4.4 Confines

- The sails won't be efficient to go upwind
- The mast, yards and many commands to operate the sails make it expensive
- In the case of rigid sail, it can become counterproductive, or even dangerous in case of strong wind.

2.4.5 Non-exhaustive list of projects exploring this technology

- Fair transport : http://www.fairtransport.eu/
- B9shipping : http://www.b9energy.com/B9Shipping/tabid/4036/language/en-US/Default.aspx
- ...

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2.5 Kites

Source: http://www.skysails.info/uploads/pics/Keyvisual_BBC_blau_20.png


Source: http://www.maritimejournal.com/__data/assets/image/0019/703603/varieties/carousel.jpg

2.5.1 Physic principle and material configuration

The kites, shaped like traditional sails, are usually attached to the bow with a cable, generating tensile power. The generated force is directly used, no parasite efforts on the vessels structures are needed.

These sails of several hundred meters square are delicate to use; the hoisting and hauling down are difficult to manage and require specific structures and procedures.

2.5.2 Technological choices

Two sail types can be distinguished: dynamic and static.

Dynamic kites	***Static kites***
Principle: *Dynamic* kites will produce a much greater power, but must be moving following an ∞-movement. These movements will increase the speed of the wind received in the wing, considerably enhancing its traction power; however these wings must be operated smoothly to follow the right course and be prevented from falling. These wings allow upwing sailing, but demand perfect operation.	**Principle:** *Static* kites are set to fly and stay motionless; their power is limited but their handling is much easier: no additional settings or moving devices are needed. The link to the deck is made with a horizontal tiller, and set on a swivel. These wings only operate when running downwind.
Benefits: Dynamic kites have an important energy output though they do not solicit much the ship's structure.	**Benefits:** The use of static kites is really easy since no adjustments are required once the kite is set up in the air.
Constraints: Dynamic kites must be operated to produce power. Either one cable only ties it to the boat, in which case a piloting device is installed up the cable, just before the wing: containing sensors and operators, it will direct it so it describes the expected ∞. This machine is very expansive and	**Constraints:** The technology for static sails is limited, for it is the geometry of the wing which sets its capacity. The generated force is transmitted onto the ship through two cables linked to a swiveling rail, allowing the kite to remain stable. These kites only operate when running downwind.

fragile.
It is also possible to operate the wing from the deck, through several cables, lengthened or shortened following the operating needs. This however demands unwavering skills and a very advanced, reliable and expensive technology.

Furthermore, these kites raise the problem of their insensitivity to the ship direction: the wing can only follow the wind. And finally as it demands several minutes to be set on or off, this technique requires the heading to be steady, at the risk of finding the wing pulling the ship back.

2.5.3 Benefits

- Kites guarantee a completely open-deck.
- The forces exerted on the ship is directly used for propulsion. This technology gets rid of most of the parasite efforts that are usually transfered to the hull or the rig for most wind propulsion devices.

2.5.4 Confines

- The sails are difficult to hoister as they are extremely large and delicate to deploy. It requires a dedicated structure, and a specific procedure
- Sails may become a brake if not hauled down when the wind becomes unfavorable.

2.5.5 Non-exhaustive list of projects exploring this technology

- Skysails : http://www.skysails.info/english/

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2.6 Flettner rotors

Source wikipedia commons

2.6.1 Physic principle and material configuration

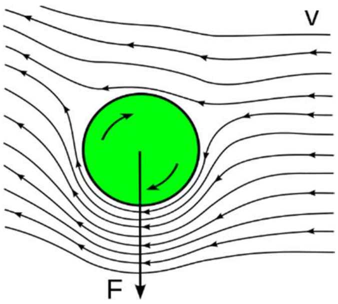

Figure 16 : The Magnus effect exploited by Flettner rotors.

Source : http://fr.wikipedia.org/wiki/Effet_Magnus

Flettner rotors use the Magnus Effect to produce power from air flows. German physicist Anton Flettner showed that any rotating physical body placed down a wind stream accelerated its speed on one side and decelerated it on the other. This produces the same force as a classic sail: the speed differential on opposite sides generated a difference in pressure, itself creating a force, perpendicular to the flow (figure 15).

Be the wind unfavorable, the rotor is held still, creating only a force following the wind's direction.

There is only one possible adjustment of the sailing system: the rotative speed of the rotors.

2.6.2 Technological choices :

During the manufacturing process, diameter and height must be determined as well as the coating or material used for the tube. When operated, only the rotating speed needs setting, so little attention is needed, with no complexity. The tube must endure important mechanical efforts, both flexion and torsion, which may cause a distortion deteriorating its performance. The building must be made to prevent or reduce these distortions. Little information and experiences exist on this system, but theoretical studies show promising potentialities.

2.6.3 Benefits

- No setting and handling is needed apart from the rotating speed.
- Little congestion of the deck.
- Theoretical studies indicate the generated force may be important.

2.6.4 Confines

- The important wind load may cause the system to be a disadvantage, if not a danger when winds are unfavorable.
- Few feedback exists from the few equipped ships.

2.6.5 Non-exhaustive list of projects exploring this technology

E-ship 1 owned by Enercon (third larger wind turbine manufacturer in the world): http://www.enercon.com

(During a press release (29/07/2013), Enercon, gave average figures of the fuel savings allowed by Flettner rotors on the E-ship 1 along its first 3 years of existence: http://www.enercon.de/p/downloads/PM_E-Ship1_Ergebnisse_DBU_en.pdf)

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2.7 Turbo sail

Source: http://www.flickr.com/photos/davehams ter/6286906624/

2.7.1 Physic principle and material configuration :

The turbo sails, developed by Cousteau and Bertin, is a very thick, oval-shaped sail, equipped with a paned on its back part, oriented along the wind. Following its position, an extrados or intrados as with a classic sail, whilst remaining able to work in any direction.

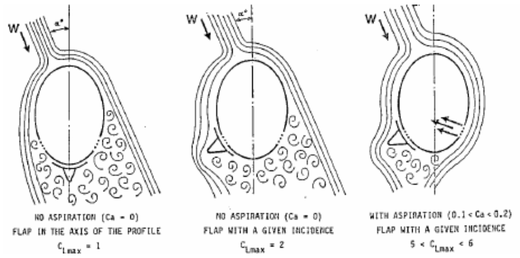

Figure 17 : The mechanism of a turbo-sail.

Source: Yoshimura, Yasuo, 2002, « A Prospect of Sail-Assisted Fishing Boats », Fisheries Science, 68(Supplement 2): 1815-1818

The hollow mast is put under depression by a fan; hatches come to fill the perforations done all along the mast, on one or the other side of the mast, depending on the wind. The combined effect of the depression on the perforations will hold the air flow against the sail, thus considerably enhancing the generated force.

Depending on the incidence of the flap with the wind and on the aspiration force created by the fan (Figure 16), the traditional aerodynamic sailing effect (the generation of overpressure and under-pressure zones around the sail) may be more or less efficient.

The Figure 18 depicts a more complete graphic explanation of the physic principle that makes turbo-sails generate a propulsive energy output.

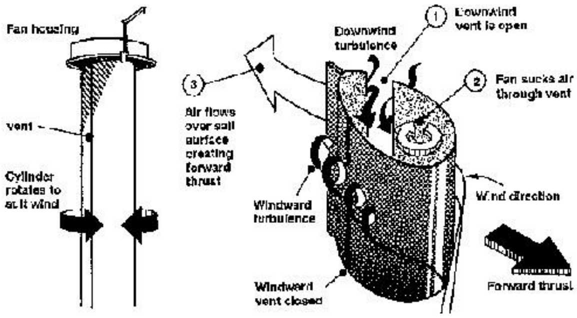

Figure 18 : a more complete description of the mechanisms of a turbo-sail.

Source: http://www.paperblog.fr/3992219/principe/

2.7.2 Technological choices

Still undetermined.

2.7.3 Benefits

- The generated power is relatively high, compared to the congestion of the deck
- The operating is simple, few settings need to be done.

2.7.4 Confines

Source: http://www.cousteau.org/img/static/turbosail.jpg

- The wind load is important and could be dangerous in case of unfavorable wind
- The system incorporates many large moving devices, their adjustment must be precise, making it expensive
- The number of moving devices makes the maintenance expensive

2.7.5 Non-exhaustive list of projects exploring this technology

The *Alcyone,* built by Mauric (a design office) in 1985 and promoted by Cousteau's team, is the only known ship that ever used turbo-sails. Still, precise evaluation of this rig performances and fuel savings it might allow is still lacking.

Conclusion: a few words about the implementation of WASP concepts

As a conclusion, it must be stated that there are two ways to implement on board of commercial ships the wind-propulsion technologies reviewed along this document.

One, of course, is the building of a new ship from scratch (i.e. designing and building a prototype that might demonstrate the efficiency of a particular wind-propulsion technology) such as the *Alcyone* or the *E-ship 1*. This option is certainly the one that would use the potential of such or such technology to its maximum – as the shape of the hull, the repartition of the freight on-board and the loading and unloading infrastructures will be adapted to the specific rig chosen by the designers. But it is also a very costly and highly time-consuming solution. Designing and building a wind assisted ship from scratch costs much more money and expertise than a traditionally engined one. Indeed, have to take into account at design stage: the hull form and main particulars to reduce induced resistance and/or provide additional stability, the wheel house location to comply with regulations on sight lines, rudders shape and/or traditional appendages (dagger boards, skegs) to reduce induced resistance, the installation of the engine to provide maximum efficiency even when the ship is lightly loaded (which would typically require electric drives with generator sets that are not needed on traditional engine installation) make costs rise significantly in comparison with the design of a fuel engine propulsion ship.

The other option to implement the wind-propulsion technologies lies in the retrofitting of existing ships. This implies to choose a wind technology in accordance with the characteristics of the ship that will be retrofitted.

However, green retrofitting of existing ships is a subject in its own and does not stop at wind-propulsion devices. Cleaner technology retrofit is a wide concept that may cover incremental improvements to existing ships (such as the inclusion of air pollution prevention equipment (e.g. scrubbers, selective catalytic reduction), the use of alternative fuels (e.g. Liquefied Natural Gas (LNG), Methanol, etc...) or even improvements in the ship hull and propellers[12]. As green retrofitting covers so many different operations, its cost can vary considerably[13]. But one thing is for certain: it is the fastest mean to hybridize the commercial seaborne fleet. The high longevity of commercial ships completely forbids the idea of a renewed greener fleet before several decades. But some wind propulsion technologies are more adapted to retrofit than others; kite is the only technology that can be used on almost any existing ship whatever its shape, size and purpose. This gives towing kites a very significant advantage over other technologies as a mean to hybridize as fast as possible maritime freight transportation.

Green retrofitting of ships is a dense, complex subject that cannot be addressed in any exhaustive way here. The Transport Research and Innovation Portal (TRIP) a FP7 funded organization hosts a project labeled: REFRESH “Green retrofitting of existing ships” that will end in 2015[14]. If you are looking for more information on the matter, you can visit their website or contact them.

Finally it must also be stated that wind propulsion is only one among many options to hybridize maritime transportation: fuel substitution (with hydrogen, LNG or bio-gases) or reliance on a solar or wind-powered

12 Köhler, J., 2011. Case study and contrasting scenarios of international transport fulfilling objectives of sustainable development

13 Frouws J. et al., 2012, Retrofit Costs Considerations of New Green Technologies for Ships, ATENA Conferences System, NAV 17th International Conference on Ships and Shipping Research

14 http://www.transport-research.info/web/projects/project_details.cfm?Id=45102 + another European project on retrofitting, to end by 2014, is RETROFIT (also financed by the FP7) : http://www.retrofit-project.eu/

engine are also means to hybridize maritime freight shipping. But these solutions are not mutually exclusive: an LNG fueled engine, for example, can then be coupled to a wind propulsion device to create a zero emission Wind Assisted Propulsion ship. Furthermore, an even better energy efficiency could be reached with such a boat through more minor changes on-board: propeller polishing, water flow optimization, hull coating and cleaning, waste heat reduction, reliance on the auto-pilot and weather routing.

NOTE:

This document is a discussion paper that is not meant to be scientifically accurate nor exhaustive. It was built as a launcher of the debate among the partners of the project SAIL, a mean for everyone to gather around the same vision: a review of existing technologies and of their technical characteristics was really lacking – which nipped in the bud all attempts to build a collective thinking on the matter of HFS.

Still, this purely technical approach of WASP ships needs to be completed by an economic analysis of HFS (sketched with the historical perspective of the introduction and the implementation cost considerations of the conclusion). Indeed, one could arguably say that the monopole of a purely technical approach of WASP ships since the 1950s has favored a competition between engineers, each defending their specific design. The eagerness of the technical debate over various concepts forbade a deeper analysis over an economic model for WASP ships. Thus, this document only is a starting point that will need to be cross-checked with the economic prospective documents that are soon to be published by E&E and other members of the WP4.

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International glossary

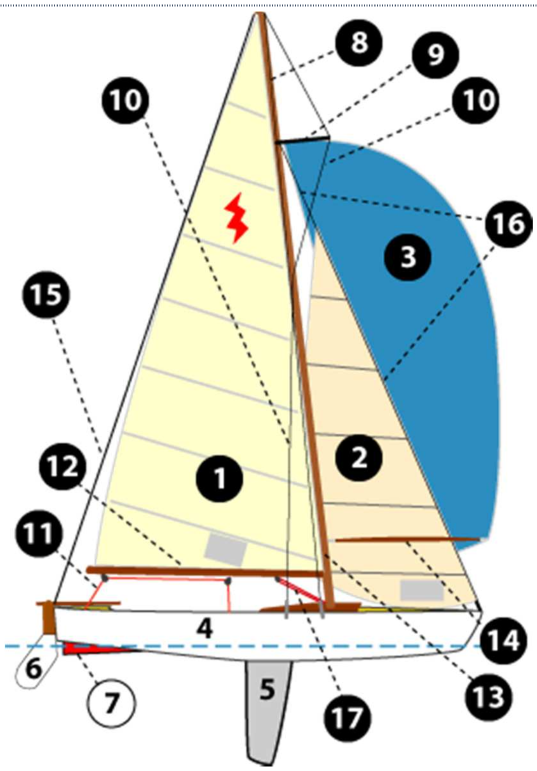

Figure 19 : Source: http://en.wikipedia.org/wiki/File: Sailingboat-lightning -num.png

	en	fr	de	nl
1	**main sail**	grand-voile	Großsegel	Grootzeil
2	**jib**	foc	Fock	Fok
3	**spinnaker**	spinnaker	Spinnaker	Spinnaker
4	**hull**	coque	Rumpf	Romp
5	**keel/centre board**	quille	Schwert	(Kiel)zwaard
6	**rudder**	safran	Ruderblatt	Roer
7	**skeg**	dérive	Skeg	Scheg
8	**mast**	mât	Mast	Mast
9	**spreader**	barre de flèche	Saling	Zaling
10a	**shroud**	hauban	Want	Want
10b			Jumpstag	
11	**main sheet**	écoute de grand-voile	Großschot	Grootschoot
12	**boom**	bôme	Baum	Giek
13	**mast**	mât	Mast	Mast
14	**spinnaker pole**	tangon	Spinnakerbaum	Spinnakerboom
15	**backstay**	pataras	Achterstag	Achterstag
16	**stay**	étai	Vorstag	Voorstag
17	**vang**	hale-bas	Baumniederholer	Halstalie