“Mircea cel Batran” Naval Academy Scientific Bulletin, Volume XV – 2012 – Issue 2
Published by “Mircea cel Batran” Naval Academy Press, Constanta, Romania

SOME CONSIDERATIONS REGARDING THE STUDY OF SAILING PROPULSION COMBINED WITH A CONVENTIONAL SYSTEM

Ionela – Rodinela TICU[1]
Radu-Alexandru POPA[2]
[1] Constanta Maritime University
[2] "Ovidius" University of Constanta

Abstract: *In this research, we study the way of using a sail as a propellant with other classical propulsion systems. Firstly, we include a state of the art of the existing technologies. After the consideration of the apparent wiind concept, we present the range of usage of this complementary propulsion system. We also include the calculation methodology, the numerical simulations and the wind inputs from a specific route.*

Introduction.

In the present, 90% of the global trade is using the sea as means of transportation and the shipping industry highly depends on fuel. Because of the fact that the amount of fuel is limited, the costs are increasing continuously and this matter is not expected to change in the near or distant future. The problem is not only the fuel cost, but also the environmental concern. Everyday, the governmental regulations regarding air and water quality become more sevear.

This facts forces the shipping industry to build vessels in a much more cleaner way and more economical by optimizing their engines and hulls. The objective is to reduce the fuel consumption, or emissions, which is normally simultaneous. But, the potential to engage the existing propulsion systems is almost exhausted. As we advance in time, new technologies are needed, especially economical technologies. The Flettner rotor and the wing are set at the bow of the ship where profitable wind redirection and speed increasing happen. For these kinds of systems, a global drag reducing effect due to delayed separation is to be expected. The kite consists in an expensive installation and has poor payback on the investment. According to this model, and to the opinions of the experts, the performance of the kite predicts up to 5.0% fuel saving on a worldwide route. However, the wind turbines are not considered profitable.

1. SYSTEM SPECIFIC THEORY

The systems which are analysed are selected from what is feasible to retrofit onboard the fleet and what is assumed to be generating the power which is profitable. In this chapter, we will talk about the power generated from different systems in detail. Almost all of the power presentations in the figures below are presented in equivalent engine power in which the ship propulsion efficiency η_{ship} is set to 0.75 . The system power in ship direction P_S is:

$$P_S = \frac{F_{xAS} \cdot V_S}{\eta_{ship}} \qquad (1)$$

The wing system and the rotor posses one part which is set on the port area and the other one set on the starboard area. If we want to calculate the system power, only one side of the system is expected to be active. It is also expected that no heeling from the system will occur because it can be compensated with the onboard heeling tanks.

1.1. **Flettner rotor**. The Flettner rotor represents a classical technique that has revived with new ship designs and buildings as a result. Earlier trials have had mediocre results, but it is important to investigate how profitable it would be on a ship like the M/V Fedora. The system is expected to create a profitable force in the vessel’s direction and reduce the vessel’s total drag due to late or no separation. Table 3 shows us the data used where the height has a limitation to the bow height and the aspect ratio is set to optimal according to earlier trials from the companies indship and Windfree. If we are to follow the theoriy of a spinning cylinder hit by a free stream, a lift and a drag appears because of to the presence of the Magnus effect, as shown in Figure 1. The forces depend on the rotor size, angular velocity and free stream velocity.

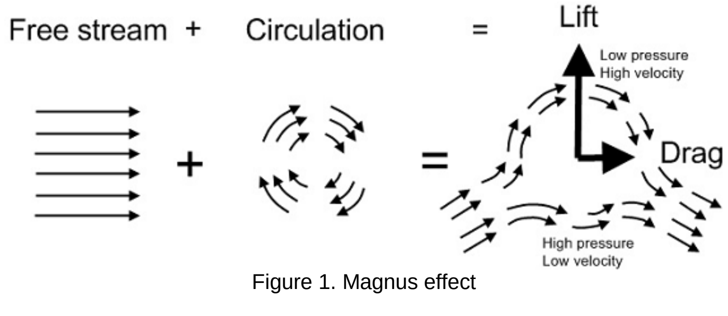

Figure 1. Magnus effect

During the time when the air mass is present at one side of the rotor, it is slowed down. However, the air on the other side is accelerated. Following the equation of Bernoulli, this phenomena provides a lower pressure at the top and higher at the bottom which makes possible the creation of the lifting force. The relation between lift per length of rotor $L_{1/l}$ and circulation Γ can be demonstrated by the Kutta-Joukowski law:

$$L_{\frac{1}{l}} = \rho_A V_A \Gamma \qquad (2)$$

Whereas $\Gamma = 2\pi\omega r^2$; ω is the angular velocity and r is the radius of the rotor.

The rotor can produce a high lift coefficient which depends on its speed of rotation. However, it has its disadvantage; when higher lift is being produced, the lift/drag ratio decreases, resulting the drag to increase. The performance of the rotor at 15 and 20 knots ship speed can be seen as presented in Figure 2 with the percentage of the equivalent engine power needed, induced resistances because of the wind. Also, the waves are included. The mounting position ζ is 20 degrees.

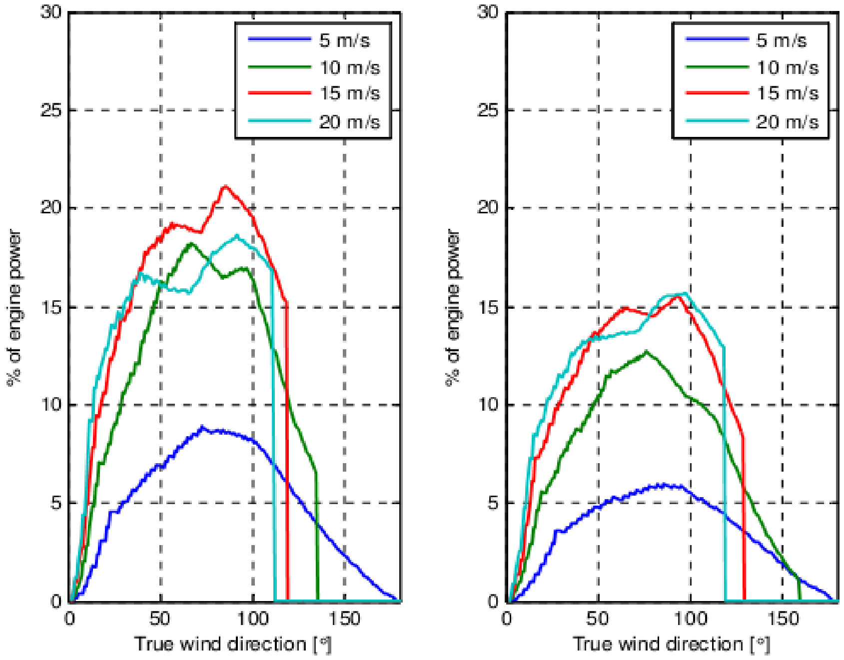

Fig. 2 Rotor power illustrated as percentage of equivalent engine power at 15 and 20 knots ship speed and different true wind angles and wind speeds.

The rotor posseses an efficient performance and it is potent for the wind assisted propulsion. It consists in a cheap and easy installation, although it will require maintenance. There was comparison made in 1986 by T.F. Hanson which states that the cost of the installation of a rotor is only 1/3 of a wing sail, because of the fact that it is assumed to be easier to build. The rotor also has in its possesion a lift coefficient that is more than 6 times stronger than a wing sail according to a standard NACA 2412. However, this ratio is lower when considering a high lift wing. The rotor does not have to make any changes on the attack angle depending on the apparent wind direction because the lift is always orthogonal to the flow. This represents a simpler installation in comparison to a system that must be self adjusting depending on the direction of the wind. There is a main issue: the mounting; because of the bow shape of the vessels in the Wallenius fleet, it is considered to be conceivable to set the propulsion system at the bow.

1.2 The wing . The wing is expected to generate power in ship direction due to lift, and diminish the total ship drag due to late or no separation. In this research, we analyze how the lift and drag forces make an impact on the ship, disregarding any separation improvement. In Figure 3, we analyze a suitable wing profile in the tool JavaFoil. The wing profile design considers adequate Reynolds valorification, with the usage of the wing chord as characteristic length L. The Eppler stall design is considered when deciding C_l for the wing profile. The required characteristics are high C_l and not necessarily a high lift/drag ratio for the same motive as for the rotor.

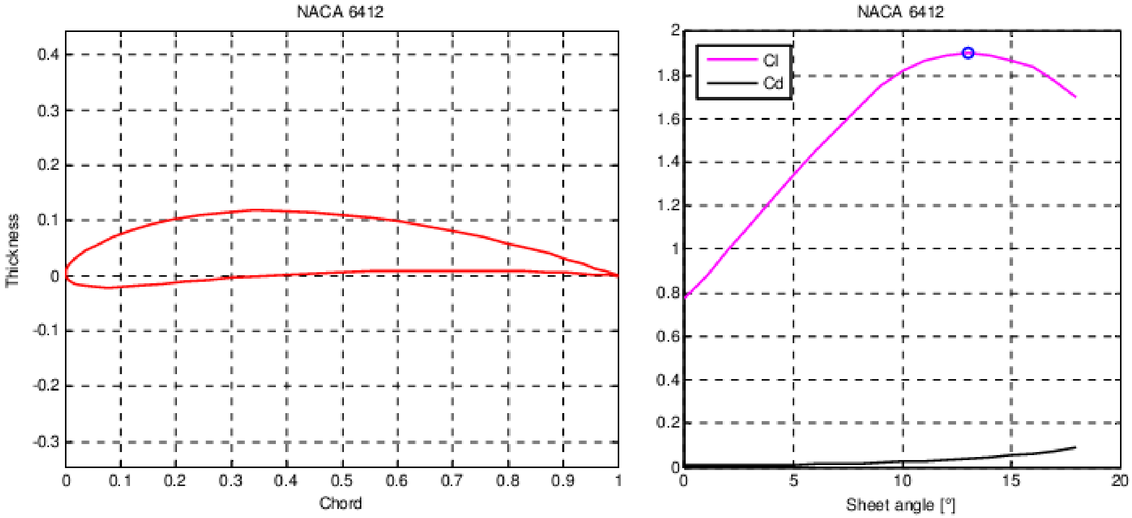

Fig 3 Characteristics of selected wing profile NACA 6412.

The wing performance at 15 and 20 knots ship speed is shown in Figure 4 as percentage of the equivalent engine power needed, induced resistances due to wind and waves are included. Mounting position ζ is 20 degrees.

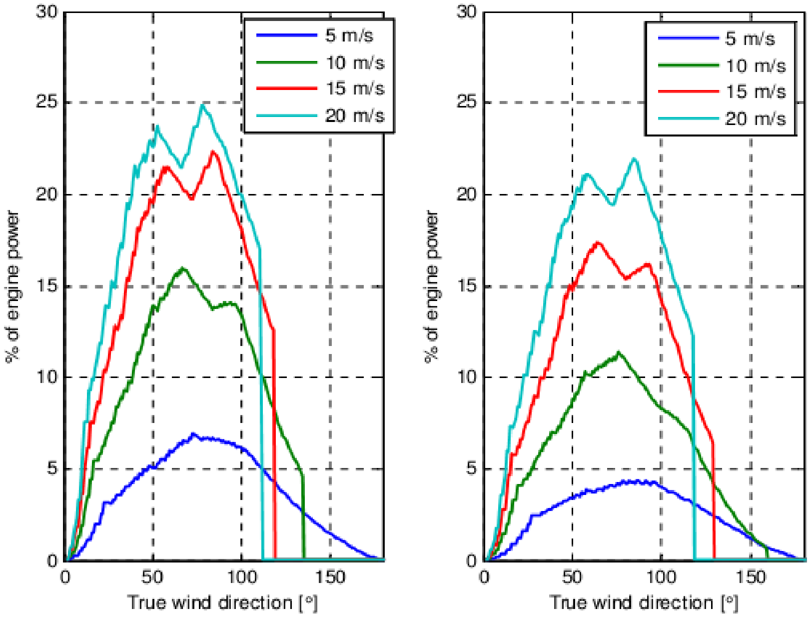

Fig. 4 Wing power illustrated as percentage of equivalent engine power at 15 and 20 knots ship speed and different true wind angles and wind speeds.

The wing has a good performancce and power which not only are profitable but also measurable. The simplest installation consists in the wing fixed in both sheet angle and position on the bow. The analysis demonstrates the fact that the difference between having a totally adjustable and fixed wing is not a big one. Thus the best setting position on the bow is iterated to be ζ=20° degrees. The persuaded effect on separation is also taken into consideration when choosing a mounting position. A fixed setting will be preferable due to its simple and most economical maintenance and installation.

1.3 The kite. The kite generates different forces but in a more complicated way than the wing due to the local heel of kite θ. There are different abilities when the direction is upwind and downwind, dynamical flight mode and variable towing angles τ. The kite has an operating wind between 4 and 19 m/s (Beaufort 3-8) apparent wind speed. The calculation method is presented in the following paragraphs.

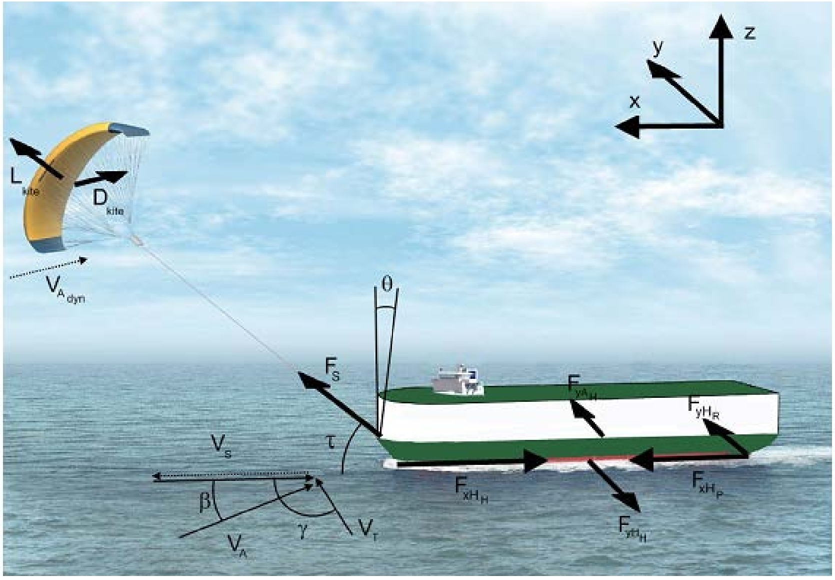

Fig. 5 The kite affects the ship in different ways and directions.

If we calculate the main data on a foil kite we performe with equation (1) to (7), regardless if the airfoil form can't be considered to posses the same C_l and C_d as the wing. Equation (5) and (4) are changed in order to consider the towing angle of the kite. As for the determination of the three dimensional lift coefficient, the free wing-tips must be considered where turbulences may appear. This matter is dependent on the aspect ratio AR and span efficiency factor e.

$$C_L = \frac{C_l}{1+\frac{2}{eAR}} \qquad (3)$$

where C_l represents the two dimensional lift coefficient for the current profile, e represents the span efficiency factor, set to 0.95 AR represents the aspect ratio, as shown in equation (5).

$$C_D = \frac{C_L^2}{\pi \cdot eAR} + C_d + C_{D0} \qquad (4)$$

Where: C_d represents the two dimensional drag coefficient for current profile

C_{D0} consists in the drag from other extremities and in this case the extremities are the lines

An approximate ratio of C_L/C_D is set to. This is used for the determination of C_{D0}, where C_l is set to 1 and C_d+C_{D0} is decided in order for the equation $C_L/C_D = 5$ to be fulfilled.

$$AR = \frac{b^2}{A} \qquad (5)$$

Where b represents the surface span and A consists in the area

A strong point of the kite consists in its flight height that is si higher than the other systems. Here, there is an average set altitude of 200 meters. Together with the dynamic flight that increases the apparent wind velocity for the system, it is a system that can take advantage of strong and stable, high altitude winds. The area may also be considered bigger than for any other system used. The main weak point is that the kite will not always be airborne creating lift in the ship's moving direction. This fact depends not only on the towing angle τ but also on the kite's true flying direction. The towing angle is expected all the time to be 35 degrees to the water level because it is unsafe if the kite is situated nearer to the water.

The apparent wind speed

V_A is used for the calculation of the forces acting on the ship but the wind velocity also must to be corrected V_A due to for heeling angles θ that are assumed to be balancing between -10 to 10 degrees if the kite flies in dynamic mode:

$$\tilde{v}_A = v_A \sin\left\{ a\cos\left[\sin\theta \left(\cos\left(\beta - \frac{\pi}{2} \right) \right) \right] \right\} \qquad (6)$$

The kite's dinamic wind speed V_{Adyn} is approximated twice the actual true wind speed

$$v_{Adyn} = 2 \cdot v_T \qquad (7)$$

The kite's apparent wind speed V_{Akite} is the root meansquare of $\tilde{v}_A$ and V_{Adyn} acoording to:

$$v_{Akite} = \sqrt{\tilde{v}_A^2 + v_{Adyn}^2} \qquad (8)$$

The towing angle τ can determine the lifting force direction of the kite L_{kite} according to:

$$L_{kite} = L\cos\tau \qquad (9)$$

The percentage of the whole requred power of the engine, delivered by the kite at 15 and 20 knots ship speed is shown in Figure 6.

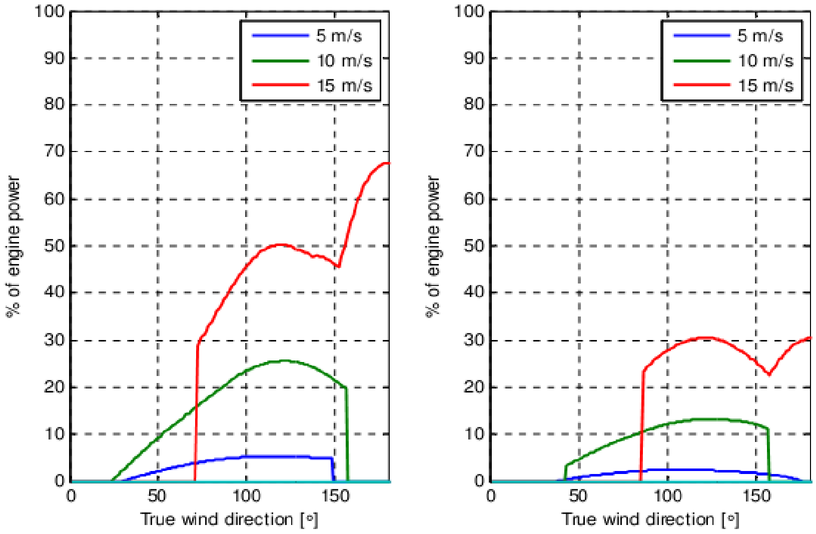

Fig 6 Kite power illustrated as percentage of equivalent engine power at 15 and 20 knots ship speed and different true wind angles and wind speeds, note that 20 m/s is not presented as it is expected to be too windy.

The kite has a good performance but is a more advanced system than the rotor or wing. The kite consists in a realizable system, delivered by Skysails and can be set onboard the ship Fedora. The irregularities which occure in Figure 6 are dependent on the variations in the required engine power, wind velocity boundary values and mode shifting between upwind and downwind direction. In any case, the performance per area, compared to smaller and simpler systems that the rotor and wing system represent is not as efficient.

2 Savings

The vessel is expected to be at sea 220 in a year, but the system is used when weather can provide the necessary conditions. Total savings per year on a worldwide route are about $56.000-220.000 for rotor, $45.000-180.000 for wing system and $50.000-200.000 for kite system at 15 knots depending on the oil price. If the ship's speed increases to 20 knots, the total fuel cost will be larrger from $960.000-3.800.000 to $2.400.000-9.800.000. The profit obtained from the different wind systems at 20 knots will be approximately $100.000-390.000 for rotor, $76.000-300.000 for wing and $62.000-250.000 for kite. The details in Table 1 show the average engine power which depends on the wind values. This fact leads to an average daily fuel consumption which is required to calculate the whole savings.

Table 1. Wind propulsion profit

Ship speed	15 kN(average engine power 5,6 MW)			20 kN (average engine power 13,4 MW)		
Daily consumption [t/day]	22			56		
System	Rotor	Wing	Kite	Rotor	Wing	Kite
Savings [$/tonne]	[$/day] / [$/year]	[$/day] / [$/year]	[$/day] / [$/year]	[$/day] / [$/year]	[$/day] / [$/year]	[$/day] / [$/year]
200	255 56144	202 44528	220 48400	448 98560	347 76384	280 61600
300	383 84216	304 66792	330 72600	672 147840	521 114576	420 92400
400	510 112288	405 89056	440 96800	896 197120	694 152768	560 123200
500	638 140360	506 111320	550 121000	1120 246400	868 190960	700 154000
600	766 168432	607 133584	660 145200	1344 295680	1042 229152	840 184800
700	893 196504	708 155848	770 169400	1568 344960	1215 267344	980 215600
800	1021 224576	810 178112	880 193600	1792 394240	1389 305536	1120 246400

The savings are a little different regarding the systems, with rotor having the optimal performance. For the rotor and wing, a higher ship velocity can cause higher apparent wind speed at profitable wind directions and increases the savings with increased speed. However, the cost of the total fuel is also higher when the ship's speed is high. The kite is decreasing its performance more than the others with increasing the speed of the vessel.

2.1 Installation cost

A thorough economic analysis represents an important measure before making any decision regarding the installation. Analyzing the estimated steel weight, an approximation of the cost of the installation is made. Table 9 shows us the parameters which are used and presents the resulting building/installation cost.

Table 2, price comparison based on steel weight and manufacturer information

	Rotor	Wing	Kite
Area [m²]	2x82	2x150	640
Steel volume [m³] *(thickness 8 mm)*	1,3	2,4	-
Steel density [kg/m3]	7.900	7.900	-
Steel cost + work [$/kg]	4,5	4,5	-
Electrical engine + bearing cost [$]	2x22.500	-	-
Total cost (year 2009) [$]	91.000	85.000	1.596.000

Total cost for wing is exclusively based on steel cost and that includes the work, as well. The rotor requires bearing and electric engine to rotate that is included in the total cost. The bearing can have an estimation cost of $ 10.000 and the 150 kW electrical engine would cost around $ 12.500. Costs are confided by experienced personnel at the Wallenius Marine AB office. The kite is more expensive and the cost origins from Skysails in € where 100.000 € represents the installation cost. Also, the used exchange rate is 1 € = $ 1.33.

2.2 Return on investment

Taking into consideration the oil price, the installation and maintenance costs, the systems will differ in time on the return of investment. Results based on costs calculated in Table 2 are shown in Table 3 and Table 4, Return on investment at ship speed 15 knots.

Table 3. Return on investment at ship speed 15 knots

Ship Speed 15 [knots]	Rotor	Wing	Kite
Total cost (year 2008) [$]	91.000	85.000	1.596.000
Savings/year (oilprice 200$/tonne) [$]	53.000	42.000	48.000
Retur non investment [years]	1,7	2,0	33
Savings/year (oilprice 300$/tonne) [$]	80.000	63.000	72.000
Retur non investment [years]	1,1	1,3	22

Table 4. Return on investment at ship speed 20 knots

Ship Speed 15 [knots]	Rotor	Wing	Kite
Total cost (year 2008) [$]	91.000	85.000	1.596.000
Savings/year (oilprice 200$/tonne) [$]	90.000	70.000	61.000
Retur non investment [years]	1,0	1,2	26
Savings/year (oilprice 300$/tonne) [$]	134.000	104.000	92.000
Retur non investment [years]	0,7	0,8	17

3. Conclusion

The characteristic bow form of the PCTC Fedora highly improves the performance for systems being set in that zone. This analysis is focused on creating a force in the vessels moving direction and establishes that the rotor posseses the optimal performance and lowest payback time. For the wing and rotor, a global drag reducing effect due to a late separation is also expected. Nevertheless, this effect is not considered in this research.

According to the investigation, the rotor posseses the lowest payback time. Despite the fact that it has to be considered that in reality, the rotor can't perform at peak, since it doesen't posses all the working liqud volume it requires. In comparison to the kite, the rotor also represents an easier installation that doesen't need much maintenance. The rotor also has an easy operational system as it only needs to vary its rpm to obtain the best rotational coefficient, no sheet angle has to be modified. Since the power output is guided by the rotation, it is also considered to be resistent against the storms. The rotor might have to be retractable in a cavity in case of agitated weather.

The wing is the least powerful system according to this research. However, it posseses a good payback time. It is also considered to have the easiest instalation and maintanance procedures. In comparison to the rotor, it doesn't need as much free air mass around it to function as thought. The wing might also require to be retractable in case of agitated weather. More efficient performance should be obtainable if using a much more advanced wing with a higher lift coefficient.

The kite system is profitable, mainly because of its dynamical flight mode and higher altitude. On the other hand it has the longest payback time. A strong point consists in the fact that no self-development is required because the whole package is purchased from Skysails. The provider takes care of the installation and fits the whole system onboard. However, a great weak point consists in the maintenance where, the kite needs to be changed at least two times a year. Also, the crew needs to be trained, although the operation is claimed to be totally autonomous. Another weak point ist hat If one controlling system fails there can be serious consequences.

Another weak point is that the kite only works between 4-19 m/s (Beaufort 3-8) apparent wind speed. The design in this research assumes that the dynamic flight speed is 2 times the actual wind speed. This parameter is very decisive for the total power and should be observed. Results should be compared with data from the producer Skysails.

Looking at the big picture, the results conclude that preferable system is the wing system. It assumes to have global drag reducing effects, has good payback investment, its building and maintanance are cheap and it has a measurable performance. In conclusion, the wind turbines are not expected to be profitable.

4. **References**

1. Tupper, Rawson. *Basic ship theory* - Fifth edition. Woburn : Butterworth-Heinemann, 2001. ISBN 0 7506 5398 1.
2. Tolle, Martin. Shiptracker.com. [Online] 27 January 2009. http://images.vesseltracker.com/images/vessels/midres/86256.jpg.
3. Schentzle, P. *Estimation of wind potential*. s.l.: Journal of wind engineering and industrial aerodynamics, 1985.
4. Massey, B:S. *Mechanics of fluids* (sixth edition). Padstow, Great Britain : Chapman & Hall, 1997. ISBN 0 412 34280 4.
5. Ticu, I. *Analiza calitativă a surselor de energie neconvențională utilizate la propulsia navelor*, Constanta 2012
6. Kuttenkeuler, Jakob. *Segling - så funkar det*. Stockholm : KTH - Center for Naval Architecture, 2007.
7. Hanson, T.F. *Sail assist and the Spins'l*. 1986.
8. Gernez, Etienne. DNV. 27 January 2009.
9. Gatenfjord, Göran. *GGRail.* 8 October 2008.
10. Flettner, A. *Mein weg zum rotor*. Leipzig : Köhler & Amelang, 1926.
11. Eliasson, Lars Larsson & Rolf. *Principles of yacht design*. Midsomer Norton : Adlard Coles Nautical, 2002. ISBN 0-7136-5181-4.
12. Carbonaro, M. *Flow visualizations*. Rhode Saint Genèse : von Karman Institute, 1994.
13. Bergeson, Lloyd and Greenwald, C. Kent. *Sail Assist Development 1979-1985*. Amsterdam : Elsevier Science Publishers, 1985. 19 (1985) 45-114.
14. Andersson, J.D. *Introduction to flight*. Third edition. s.l. : McGraw-Hill, Aerospace Science series, 1989. ISBN 0-07-100496-3.
15. International Energy Agency. World Energy Outlook 2008. 2008.
16. DSME, Daewoo shipbuilding and marine engineering co.ltd. *Trim & Stability booklet*, H.NO 4445. 2007.
17. *Skysails.* Technology information. Hamburg : Skysails, 2008.
18. Quiet Revolution. [Online] 2008. http://www.quietrevolution.co.uk/faq_qr5.htm#qr3.
19. New Scientist. [Online] 2009. http://www.newscientist.com/data/images/archive/2488/24881601.jpg.
20. Knud E. Hansen; Bloch, Martin Rosander and Jens O.V. *Modern Windships*. Copenhagen : Knud E Hansen, 2000.
21. Oklahoma state university; *Fluid mechanics* . Lecture notes Chapter 9 Lecture 4. 2008. ENGSC 3233.
22. Martin Hepperle. *Javafoil.* [Online] 2 5 2007. [Cited: 21 1 2009.] www.mh-aerotools.de/airfoils/javafoil.htm.
23. Marten Silvanius; *Wind assites propulsion fo pure car and truck carriers*, Master Thesis,KTH Centre for Naval Arhitecture, Jauary 2009.
24. Enercon. *Christening and launch of "E-Ship 1" in Kiel*. Aurich : Enercon, 2008.
25. Bergey. *BWC Excel 10kW Class wind turbine*. [Online] [Cited: 12 October 2008.] www.bergey.com/Products/Excel.Spec.Frt.pdf.
26. Danish wind industry association. Betz' law. [Online] [Cited: 22 Januari 2009.] www.windpower.org/en/tour/wres/betz.htm