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Fuel economy assessment tool for auxiliary kite propulsion of merchant ship

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ABSTRACT. – A tool dedicated to assess fuel economy induced by kite propulsion has been developed. To produce reliable results, computations must be performed on a period over several years, for several routes and for several ships. In order to accurately represent the impact of meteorological trends variations on the exploitability of the kite towing concept, a time domain approach of the problem has been used. This tool is based on the weather database provided by the ECMWF[1]. Two sailing strategies can be selected for assessing the performance of the kite system. For a given kite area, the simulation can be run either at constant speed or at constant engine power. A validation has been made, showing that predicted consumption is close from in-situ measurement. It shows an underestimation of 11.9% of the mean fuel consumption mainly due to auxiliary consumption and added resistance in waves that were not taken into account. To conclude, a case study is performed on a 2200 TEU container ship equipped with an 800m² kite on a transatlantic route between Halifax and Le Havre. Round trip simulations, performed over 5 years of navigation, show that the total economy predicted is of around 12% at a speed of 16 knots and around 6.5% at a speed of 19 knots.

Keywords: wind propulsion, kite, fuel economy, time domain simulation, ship, route, containership

Outil d'évaluation d'économies de carburant pour la propulsion par cerf-volant des navires marchands

RÉSUMÉ. – Un outil dédié à l'évaluation des économies de carburant faites par cerf-volant a été développé. Pour être fiables les calculs doivent porter sur des périodes longues de plusieurs années, sur différentes routes et différents navires. Afin d'appréhender au mieux les effets de l'alternance des phénomènes météorologiques sur l'opérabilité du système, une approche temporelle a été retenue. Celle-ci se base sur l'utilisation d'une base de données mise à disposition par l'ECMWF[1]. Les performances du système de propulsion par cerf-volant peuvent être évaluées via deux stratégies de navigation différentes qui sont à vitesse constante ou à puissance constante et ce pour une surface d'aile souhaitée. Une validation a été réalisée et montre que la consommation du navire prédite par le programme est proche de celle mesurée en mer. Elle montre une sous-estimation de 11.9% sur la consommation moyenne, principalement liée au fait que les consommations auxiliaires et la résistance ajoutée dans les vagues ne sont pas prises en compte. In fine, un cas d'étude est présenté pour un porte-conteneurs de 2200 EVP et une aile de 800m² sur une route transatlantique reliant Halifax au Havre. Les résultats montrent sur une période simulée de 5 ans, une économie globale aller-retour d'environ 12 % pour une vitesse de 16 nœuds et d'environ 6.5% pour une vitesse de 19 nœuds.

Mots-clés : propulsion éolienne, cerfs-volants, économies de carburant, simulation temporelle, navire, porte-conteneur

I. INTRODUCTION

Kite propulsion, like many other wind propulsion devices, has been considered with interest for reducing greenhouse gases and fuel consumption. In order to demonstrate the efficiency of the system, focussing only on aerodynamic properties is not sufficient. As suggested by Naaijen and Koster [2007], system performances highly depend on the considered maritime route. Thus, kite operating context should be of prime concern. To get the most insight into the kite propulsion efficiency, a dedicated simulation tool based on Leloup *et al.* [2016] previous work, has been especially tailored at ENSTA Bretagne. This paper presents the leading concepts of the simulation tool, and its validation and results from a case study on a transatlantic route.

II. GENERAL PRINCIPLE

The algorithm developed for this program is based on spatial and temporal discretization of meteorological data encountered by the vessel along its journey. The great circle route between two ports of destination is discretized in a sufficient number of points to get a fair depiction of meteorological events. If required, control points can be added to impose a specific path or avoid obstacles (coastline, breakers, etc.). This is illustrated in Figure 1. Meteorological data associated to each point of the route are from ERA-Interim data base, provided by the ECMWF [Dee *et al.,* 2011]. Thus, simulation can be run for a specified number of trips (round trip), over the desired period of time. The balance of forces acting on the ship is computed for every spatial and temporal update of the meteorological data. This gives an understanding of the kite propulsion behaviour at a trip level, such as the flying time evolution or the flying mode selected.

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[1] European Centre for Medium-Range Weather Forecasts

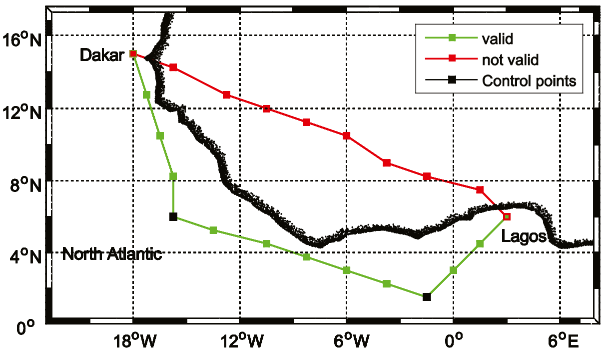

Figure 1: *Route discretization*

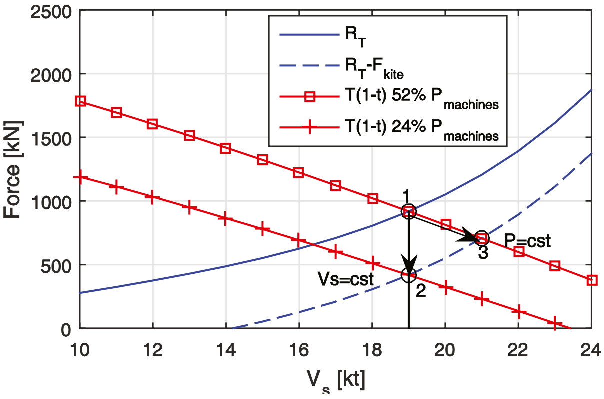

Figure 2: *Propulsion – resistance balance*

III. SHIP AND KITE MODELLING

Only longitudinal forces are considered. Equation (1) gives the balance of the considered forces.

$$(1-t)T + F_{kite} = R_H + R_A \qquad (1)$$

R_H is the hydrodynamic resistance of the hull, which can be obtained by towing tank tests or sea trials, CFD analysis or from parametric model. It does not include the added resistance in waves. R_A is the aerodynamic resistance, it can be obtained by wind tunnel tests or CFD analysis. In this study, aerodynamics data were provided by Blendermann [1986]. The open water propeller thrust T is computed thanks to associated K_T and K_Q open water curves. The relation between thrust and torque for a given ship speed can be deduced from these curves. Consequently, engine power and fuel consumption can be computed based on the engine specific fuel consumption.

Kite towing force is denoted by F_{kite} and depends on true wind speed, true wind direction and ship speed. This force, originally computed with the kite propulsion optimisation program developed earlier by Leloup *et al* [2016], is now obtained from a database. This new approach induces a dramatic drop in the computing time by a factor 60 and makes this program suitable for fast computation over numerous trips. A more detailed description of the database technic is given by Podeur *et al* [2016].

IV. SIMULATION CASE

Depending on the specified scenario, the ship can experience a variation in speed at constant power or a variation of engine power at constant speed. Both operating solutions are illustrated in Figure 2. Constant speed option is represented by the motion of the equilibrium point from point 1 to point 2. Constant power option is represented by the motion from point 1 to point 3.

V. VALIDATION

Program validation is based on in-situ measurements made on 2200 TEU container ships operating on the Le Havre–Pointe-à-Pitre route. These data, provided by CMA CGM, cover a 3.5 year period of time and give ships daily fuel consumption. After modelling this specific type of container ship, a total of 94 round-trip were simulated over the same period of time at a rate of one trip every 15 days and at a constant speed of 19.13 knots. The considered path is the most likely one to be followed and is obtained by performing a 2nd order polynomial fit on dataset of ships positions. Results from this simulation are given in Table 1.

Table 1: Validation results, $\overline{FC}/24$ *denotes the daily mean fuel consumption in tonnes*

Container carrier 2200-EVP	Simulation	Simulation corrected (+auxiliary consumption)	Measure
$\overline{V_s}$	19.13 knots		
$\overline{FC}/24$ (without kite)	56.5 t	65.7 t	64.1 t

A difference of 11.9% can be seen between predicted and measured daily fuel consumption. This discrepancy can be justified by solely considering auxiliary fuel consumption, which represent on average 14% of the total fuel consumption on the measured data. As showed by Minsaas [1983], added resistance in waves could also represent up to 10% of the total consumption. Based on these corrections and considering the relatively small difference observed between computed and measured data, the model implemented can be considered reliable enough regarding the aims of the present work.

VI. CASE STUDY

This case study is performed on a transatlantic route between Le Havre and Halifax harbours. The same container ship as for the validation was considered and with the same kite area of 800m². Ship and kite characteristics can be found in Podeur *et al* [2016]. Two sets of simulation were run at 16 and 19 knots, for a total number of 250 trips over a 5 years period of time. Table 2 sums up results from those simulations.

Table 2: Case study results
W-B denotes west bound leg Le Havre-Halifax, E-B denotes east bound leg Halifax-Le Havre. $\overline{FC}$ *denotes the mean fuel consumption in tonnes per trip.* $\sigma / \overline{FC}$ *denotes the normalised standard deviation of* $\overline{FC}$ *.*

speed	16 knots		19 knots	
leg	W-B	E-B	W-B	E-B
Mean economy of HFO / Trip	13.8 t	42.3 t	10.2 t	33.6 t
of HFO/ Trip with kite	221 t	188 t	324 t	295 t
$\sigma / \overline{FC}_{kite}$	6.06%	14.9 %	3.92 %	9.56 %
of HFO/ Trip without kite	235 t	230 t	334 t	328 t
$\sigma / \overline{FC}$	2.02%	1.94 %	1.51 %	1.13 %
% Mean flying time / Trip	59.4%	81.3%	50.5%	74.5%
Mean percentage of economy	5.87 %	18.4 %	3.05 %	10.2 %
Total mean percentage on round trip	**12.1 %**		**6.62 %**	

Table 3 : Dispersion evolution of $\overline{FC}$ *per trip with kite*

W-B / 16 kts $\sigma / \overline{FC}$=6.06%	→ 0.646 →	W-B / 19 kts $\sigma / \overline{FC}$=3.92%
↓2.46↓		↓2.44↓
E-B / 16 kts $\sigma / \overline{FC}$=14.9%	→ 0.641 →	E-B / 19 kts $\sigma / \overline{FC}$=9.56%

Fuel economy of 5.87% and 3.05% on the Le Havre – Halifax leg at 16 and 19 knots are predicted. These figures noticeably increase to 18.4% and 10.2% on the Halifax – Le Havre leg. It can be observed that fuel economy depends on both ship speed and considered leg. Reducing speed on both legs increases the fuel economy. Economy also increases when sailing on the east-bound leg compared to west-bound leg. In both cases, this is due to more favourable relative wind angles. Regarding normalised standard deviation $\sigma / \overline{FC}$ of fuel consumption per trip, it can be noticed that kite propulsion introduces a higher dispersion than without kite. As detailed in table 3, ship speed and the considered leg have a significant impact. Increasing the speed from 16 to 19 knots induces a factor of about 0.64 on the normalised standard deviation $\sigma / \overline{FC}$ on both legs. A factor of about 2.45 on $\sigma / \overline{FC}$ also appears between east-bound and west bound legs, at both 16 and 19 knots. Table 3 sums up the multiplication factor between each values of normalized standard deviation regarding the variation of speed or sailing direction. A remarkable symmetry can be observed about multiplication factors.

VII. CONCLUSION

A fuel economy assessment tool for merchant ship assisted by kite propulsion was presented. This fast tool allows massive computations over a long period of time. The fuel consumption model was compared to in-situ measurements made on a transatlantic route over a 3 year period and gives satisfactory results. A case study was presented for a container carrier of 2200 TEU, sailing between Halifax and Le Havre harbours and equipped with a 800m² kite. This study shows that, over a 5 year period, a potential fuel economy of around 12% and 6.5% can be reached respectively at 16 and 19 knots on a North Atlantic crossing.

VIII. ACKNOWLEDGMENTS

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