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A numerical method for the design of ships with wind-assisted propulsion

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ABSTRACT

The present paper presents a numerical investigation on the potential of wind-assisted propulsion for merchant ships. In particular, a KVLCC2M hull was equipped with a set of wingsails inspired from those used in the 34th America's Cup. The combined thrust due to the propeller and the wingsails required to achieve a given cruising speed was computed by solving the equations of motion. For every wind direction, the wingsail trim was optimised with a genetic algorithm in order to minimise the thrust of the propeller. The aerodynamic forces and moments due to the hull and the wingsails were computed with Reynolds-averaged Navier–Stokes simulations, while the hydrodynamic forces on the hull and rudder were computed by adapting formulations developed for manoeuvrability applications. It was found that the aerodynamic efficiency of the wingsails is critical in order to gain a meaningful thrust contribution. The propeller thrust was decreased by about 10% when sailing crosswind, and the maximum benefit was achieved by sailing at low speed in strong wind conditions. The oil saving was found to be particularly sensitive to the wingsail aspect ratio, suggesting that an efficient wingsail should employ several tall wingsails rather than a few short and larger wingsails.

1. Introduction

1.1. Wind assisted propulsion

In the 1980, oil price suddenly increased significantly and this led to the exploration of potential alternative propulsion systems that took advantage of the possibilities of sail technology. The research effort that was undertaken at that time towards wind-assisted propulsors is shown by several contributions that were presented at the International Symposium on Windship Technology (Satchwell, 1985). After several months the oil price dropped again and from 1980 to 1998 the continuous decrease of oil prices made conventional engines affordable again and developments in wind technology were abandoned. Oil prices started increasing again in 1998 and, since then, it has shown an almost constantly increasing upward trend. Today, the nominal price of oil has already doubled from the price peak in 1980. All experts agree that oil prices will continue to increase at least for the next ten years. The dependency on oil cost leads to the constant increase of the shipping cost for the approximately 90% of the goods that are traded in the world and shipped by sea. In trying to reduce their oil consumption, since 2008 many ships have reduced their cruising speed from 25 to 20 knots. A 20% speed reduction allows for a saving of about 40% in fuel consumption. With oil prices continuing to increase, many major companies have recently reduced the speed further to 12 knots. However, speed reduction is in conflict with the necessity of delivering the goods in a timely fashion to meet market demands and as such cannot decrease significantly further when the oil price increases. Therefore, wind power, which has been proven to be able to provide efficient auxiliary propulsion, is becoming attractive again.

On top of the need to uncouple shipping cost from oil price, there is a convincing environmental argument suggesting that the use of wind power must increase. The worldwide merchant fleet produces more than 3% of the total global carbon emissions (International Maritime Organisation, 2009). This merchant fleet emission is as much as the entire output of Japan, which is the 5th highest producer of carbon emissions (United Nations Statistics Division, 2011). These emissions have increased exponentially since the middle of the last century and may rise by a further 30% by 2020 (International Maritime Organisation, 2009). A significant and sudden reduction of these emissions is clearly urgently needed and existing sustainable technologies must be broadly used while new long-term highly innovative solutions are developed.

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In order to quickly motivate the market towards using greener propulsors, legislation will bring about increasing taxes on carbon emissions. In the next few years, with oil price increases and the necessity of decreasing carbon emissions, the usage of sail technology is likely to increase fairly.

1.2. Potential savings and impact

The amount of fuel oil that can be saved using wind technology is widely debated. In 1986, a cargo wind-ship with rigid wing sails was built and she generated an average annual saving of between 15% and 30% of the previously consumed fuel rate (Cross, 1986). In 2000, a product carrier with rigid wing sails was designed for the Danish Ministry of Environment and Energy and she was estimated to enable an annual saving up to 15% of fuel (Rosander and Block, 2000). In 2007, full-scale tests showed that kites used together with conventional engines could enable an annual saving of up to 35% (Skysail website, 2011). Although the use of kites has an interesting potential, the wide air space necessary to fly the kites efficiently and the difficulties in launching and landing the kites make this technology rather less attractive than sail technology. More recently, B9, the largest independent operator of wind-farms across the UK and Ireland with 49 sites and 750 turbines under its management, estimated that flexible sails fitted to ships could supply 100% of their thrust for 60% of the time (B9 Energy website, 2011). These various numbers show that sail technology can be used to different operational extents. Also, the consideration of reduced average cruising speeds allows sails to be more efficient and, at the same time, the reduced speed increases the ratio of the wind thrust over the thrust that is generated by the conventional engines.

Ocean-going low-speed bulk carriers and oil tankers can particularly benefit from wind-assisted propulsion. These ships can accommodate additional superstructures on deck. The low-speed operation increases the spectrum of wind directions where sails and wing sails can generate useful thrust. The long distances covered decreases the percentage of overall voyage time that is spent in restricted waters where sail-power might affect the freedom for manoeuvrability. There are 11 000 bulkers and 8000 tankers of 5000 DWT (Dead Weight Tonnage) or greater that are operating worldwide and these two ship types together represent about 75% of the global ocean-going fleet in DWT (Lemper, 2011).

1.3. Velocity Prediction Program

The use of wind-assisted propulsion increases the complexity of the design process because many design parameters are strongly coupled. For instance, a sail area increase leads the thrust force to increase but also the side force, the yaw moment and the heel moment to increase, therefore also the resistance increases. Because both the thrust and the resistance increase, it is not trivial to compute whether a larger sail area is beneficial. A common approach in high-performance sailing yachts is to solve the coupled equations of motion with the aid of a computer program, namely Velocity Prediction Program (VPP). The first VPP was developed in 1970s to predict the performance of different sailing yachts in order to identify a handicap system for yacht races (Kerwin, 1978). Today VPPs are essential design tools to compare different candidate design solutions, for instance see Larsson (1990). Based on computation fluid dynamics (CFD), experimental fluid dynamics (EFD) or analytical formulations (AFD), models of how the aerodynamic and the hydrodynamic forces and moments vary with the key design parameters are used to solve all, or some, of the six equations of motion of the yacht (surge, sway, heave, roll, pitch and yaw). Most of the VPPs solve the surge, sway and roll equation.

On ships with wind-assisted propulsion, VPPs have been implemented (Rosander and Block, 2000; Ouchi et al., 2013) solving the yaw equation instead of the roll equation. This allows the significant effect of the rudder to be taken into account, while the maximum heel angle of ships is smaller than on sailing yachts and thus the heel equation can be uncoupled from the other equations of motion. In particular, Rosander and Block (2000) adopted a VPP developed by the Danish Meteorological Institute for the Modern Windship (Fig. 1a), while Ouchi et al. (2013) developed a VPP to design the Wind Challenger (Fig. 1b). Unfortunately, the algorithms implemented by these previous authors have not been published. In the present paper a VPP solving the surge, sway and yaw equations is presented, including the description of the flow and the models based on CFD and AFD.

In order to compute the sail forces, 3D models of the sails are typically tested with EFD or CFD, for instance in Fujiwara et al. (2003) and Altosole et al. (2014). Conversely, in the present approach, horizontal 2D wing sections are modelled with CFD and the computed aerodynamic coefficients are integrated along the span to estimate the total wingsail forces. The novelty of the proposed study is also how the boundary conditions are set for the CFD simulations and how the computed aerodynamic coefficients are scaled based on the apparent velocity wind profiles.

The rest of the paper is organised as Method (Section 2), Results (Section 3) and Conclusions (Section 4). The Method includes the description of ship and wingsail geometry (Section 2.1); the VPP algorithm (Section 2.2); the hydrodynamic models of the hull (Section 2.3) and rudder (Section 2.4); the aerodynamic models of the wind (Section 2.5), topsides (Section 2.6) and

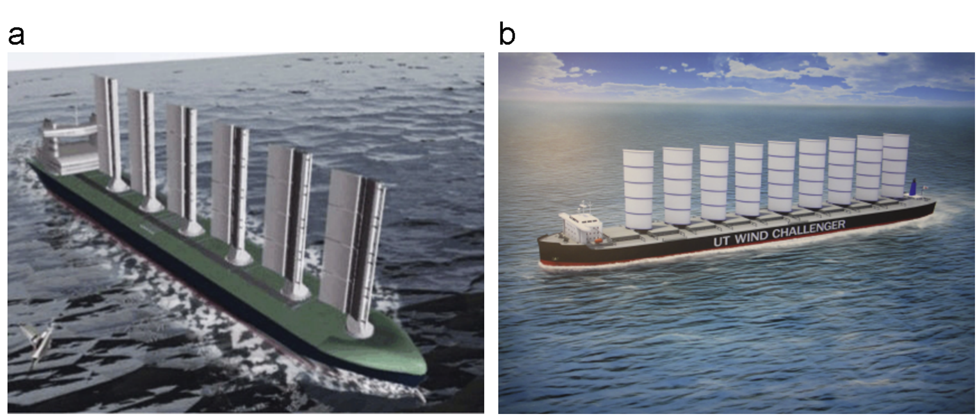

Fig. 1. Example of ships with wind-assisted propulsion. (a) The Modern Windship. (b) The UT Wind Challenger.