PREDICTION OF THE POWERING PERFORMANCE OF SAIL-ASSISTED SHIPS

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Abstract. The paper deals with the performance of conventional commercial ships with wind-assisted propulsion. Mathematical model of the powering performance of a ship with wind-assisted propulsion is formulated and discussed. An algorithm implementing the mathematical model is developed. Case study with a specific ship in real wind conditions is carried out that proves the feasibility of wind-assisted propulsion in terms of fuel oil consumption. The fuel savings in the specific case study amounted to 11% for a round trip Varna–Poti–Varna.

Keywords: energy efficiency, renewable energy resources, wind propulsion.

1. INTRODUCTION

The increased environmental concerns of the society initiated the introduction of increasingly stringent environmental regulations. Wind energy as an auxiliary form of propulsion for commercial ships seems to be an obvious solution to meet the requirements of these regulations [1]. The physical reason for the attractiveness of wind propulsion lies in the fact that the wind power is utilized directly without energy conversions and losses thereof.

Sound performance prediction tools for wind-assisted ships are essential for the further development of this promising technology. Such a tool is presented here.

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The paper comprises three parts:

– Mathematical model of the powering performance of a ship with wind-assisted propulsion;
– Algorithm implementing the mathematical model;
– Case study with a specific ship in real wind conditions.

2. EQUATIONS OF SHIP MOTION

The equations of motion of the ship moving in clam water with constant forward speed and no angular velocity were solved accounting for the external hydrodynamic and aerodynamic forces.

Figure 1 is a sketch of the coordinate system, wind parameters and wind forces and some relevant geometrical parameters. Z-axis is directed upwards and all angles are considered positive when they are in counter-clockwise direction with respect to the corresponding axis.

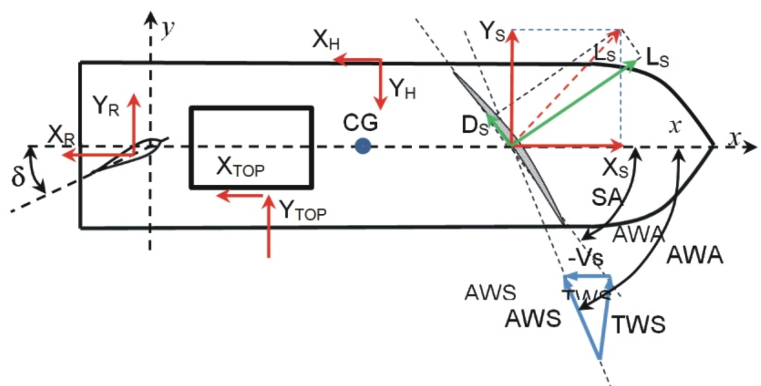

Fig. 1. Coordinate system

The equations of motion in the $x - y$ plane express the balance of the X and Y forces and yawing moments N:

$$\sum_i X_i \left(V_S, AWS, AWA,\ \beta, \delta\right) = 0, \tag{1}$$

$$\sum_i Y_i \left(V_S, AWS, AWA,\ \beta, \delta\right) = 0, \tag{2}$$

$$\sum_i N_i \left(V_S, AWS, AWA,\ \beta, \delta\right) = 0. \tag{3}$$

The arguments in the equations are: V_S is the ship speed, AWS – apparent wind speed, AWA – apparent wind angle, SA – trim angle of the sail, β – leeway angle, δ – rudder deflection angle.

The equation of roll is also relevant to the situation, since, on the one hand, the heel changes under the action of all forces, and on the other hand, the heel affects the hull forces. The roll equation is neglected in this hand, i.e. roll is decoupled from the other motions. The reason is that for large merchant ships the heel due to wind action will be insignificant. Nevertheless, heel is also calculated as a collateral result.

The following external forces are taken into account:

$$R_{TH} + X_{TOP} + X_R + X_H + X_S = 0, \tag{4}$$

$$Y_{TOP} + Y_R + Y_H + Y_S = 0, \tag{5}$$

$$N_{TOP} + N_R + N_H + N_S = 0. \tag{6}$$

where R_{TH} is the hydrodynamic towing resistance of the hull in calm water without wind. The meaning of the subscripts is: H is the hull, TOP – above-water part of the hull + superstructures, R – rudder(s), S – sail(s).

In principle the forces and moments included in the equations can be determined in a number of different ways:
– Model tests in a towing tank or wind tunnel (for ship top side and sails);
– Empirical data;
– Computational Fluid Dynamics (CFD) simulations.

3. HYDRODYNAMIC FORCES ON THE SHIP

3.1. Hydrodynamic loads on the hull at constant leeway angle

The hydrodynamic loads due to the leeway angle can be modelled by the approach used usually in manoeuvrability [2]:

$$X_H = \left(\frac{1}{2}\rho V^2 L_{PP} d\right) . \, X'_H, \tag{7}$$

$$Y_H = \left(\frac{1}{2}\rho V^2 L_{PP} d\right) . \, Y'_H, \tag{8}$$

$$N_H = \left(\frac{1}{2}\rho V^2 L_{PP}^2 d\right) . \, N'_H. \tag{9}$$

The non-dimensional coefficients (with the prime symbol) are expressed with the hydrodynamic derivatives with respect to the leeway angle β, neglecting the influence of the associated heel:

$$X'_H = X'_{\beta\beta}.\beta^2 + X'_{\beta\beta\beta\beta}.\beta^4, \tag{10}$$

$$Y'_H = Y'_{\beta}.\beta + Y'_{\beta\beta}.\beta.\left|\beta\right|, \tag{11}$$

$$N'_H = N'_{\beta}.\beta + N'_{\beta\beta}.\beta.\left|\beta\right|. \tag{12}$$

The hydrodynamic towing resistance of the hull in calm water without wind, R_{TH}, is assumed known and excluded from equation (10).

3.2. Hydrodynamic loads on the rudder

The rudder is intrinsically a wing. Hence, the hydrodynamic forces on the rudder can be determined using all the knowledge, data and methods applicable to wings.

The specific feature with ship rudders is that they are operating in the propeller wake, Fig. 2.

The velocity in the propeller wake and the area of the rudder embedded in the wake are functions of the propeller thrust loading coefficient C_{TH}:

$$C_{TH} = T/\left(0.5\rho V_A^2 A_0\right). \tag{13}$$

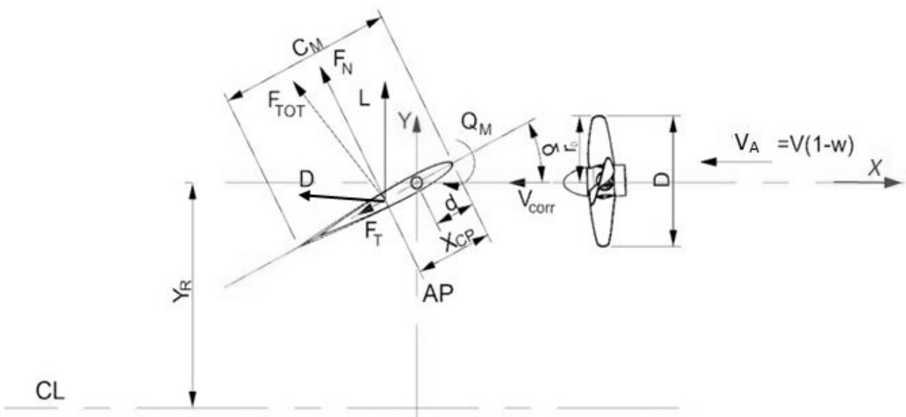

Fig. 2. Rudder–propeller arrangement

4. AERODYNAMIC FORCES ON THE SHIP

4.1. Wind parameters

The aerodynamic forces are a function of the apparent wind that hull and sail(s) experience. The apparent wind is a vector sum of the true wind and the wind due to ship speed – Fig. 3, formulae (14) and (15).

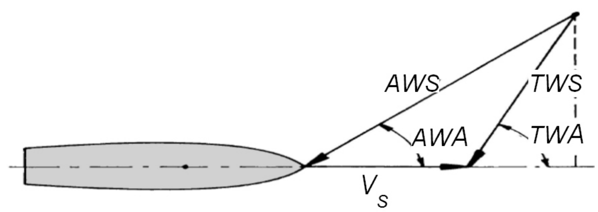

Fig. 3. True wind and apparent wind

$$AWS = \sqrt{V_S^2 + TWS^2 + 2.V_S.TWS.\cos TWA}, \tag{14}$$

$$AWA = \operatorname{arctg}\left(\frac{TWS.\sin TWA}{V_S + TWS.\cos TWA}\right). \tag{15}$$

The True Wind Speed (TWS) is not homogeneous but increases with height above the water surface. TWS is commonly taken at a standard height of 10 m. Assuming logarithmic boundary layer of the air flow, TWS can be represented by the following equation:

$$TWS = \frac{u^*}{k}\log\left(\frac{z}{z_0}\right), \tag{16}$$

where u^* is the shear velocity, which is computed for the speed at $z = 10$ m, k is the Karman constant and z_0 is the water surface roughness height.

Wind is also variable in time. The wind reports are usually reported as average over 1 hour for 10 m height. This 1-hour average is rather steady as to speed and direction. The gusts of wind depend on seasons and navigation area and are estimated on the basis of statistical observations.

4.2. Aerodynamic forces on the top part of the ship

The aerodynamic forces essential for the ship motion (in non-dimensional form) Fig. 4 are:

Longitudinal force coefficient

$$C_{X\_TOP} = \frac{X_{TOP}}{1/2\rho_{AIR}.AWS^2.A_T}; \tag{17}$$

Lateral force coefficient

$$C_{Y\_TOP} = \frac{Y_{TOP}}{1/2\rho_{AIR}.AWS^2 A_L}; \tag{18}$$

Yaw moment coefficient

$$C_{N\_TOP} = \frac{N_{TOP}}{1/2\rho_{AIR}.AWS^2 A_L.L}; \tag{19}$$

Heeling moment coefficient

$$C_{K\_TOP} = \frac{K_{TOP}}{1/2\rho_{AIR}.AWS^2\, A_L^2\,/L}. \tag{20}$$

Figure 5 illustrates the wind force coefficients as functions of AWA determined by CFD.

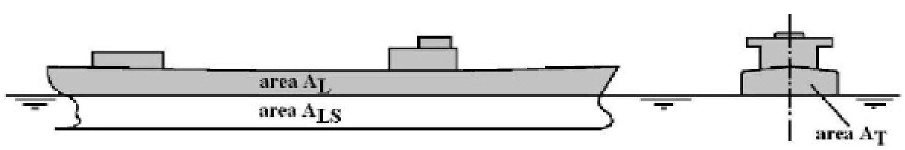

Fig. 4. Areas used in normalizing the forces

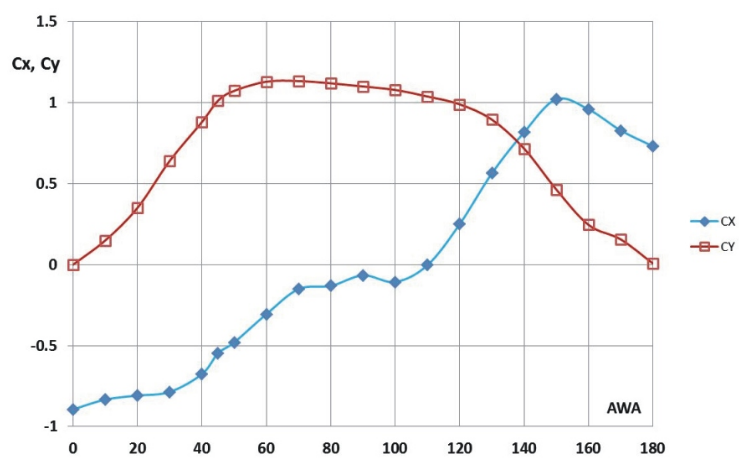

Fig. 5. Wind forces coefficients

4.3. Aerodynamic forces on the sail

The major purpose of the sail is to generate aerodynamic thrust for the ship (X_S in Fig. 1). The air flow around the sail causes also a side force (Y_S) which, depending on the size and position of the sail, leads to yaw and heeling moments.

The theory of wings usually investigates the lift, L_S, perpendicular to the flow, and the drag, D_S, in the direction of the flow, Fig. 1. They are computed as functions of the angle of attack, α.

The relation of lift and drag with lateral and longitudinal forces depends on AWA:

$$X_S = L_S(\alpha) \,.\, \sin AWA - \ D_S(\alpha) \,.\, \cos AWA, \tag{21}$$

$$Y_S = L_S(\alpha) \,.\, \cos AWA + \ D_S(\alpha) \,.\, \sin AWA, \tag{22}$$

$$\alpha = AWA - SA. \tag{23}$$

Figure 6 presents the lift and drag coefficients of a soft sail with mast and rigs computed with CFD for varying angle of attack.

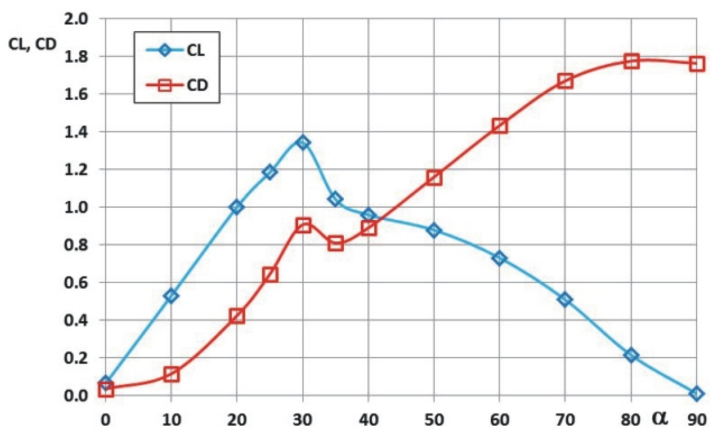

Fig. 6. Lift and drag coefficients of a sail with mast and rigs

In contrast to other applications of wing shapes (airplanes, propeller blades, etc.) where maximum Lift/Drag ratio is searched for, the sails can operate in two modes: (i) like a wing and (ii) like an air dam. The two options can be explained by the following. Figure 6 shows that above a certain value of the angle of attack the drag (D_S) exceeds the lift (L_S). And from formula (21) it can be deduced that for different combinations of apparent wind angle and sail trim angle either lift or drag is dominating.

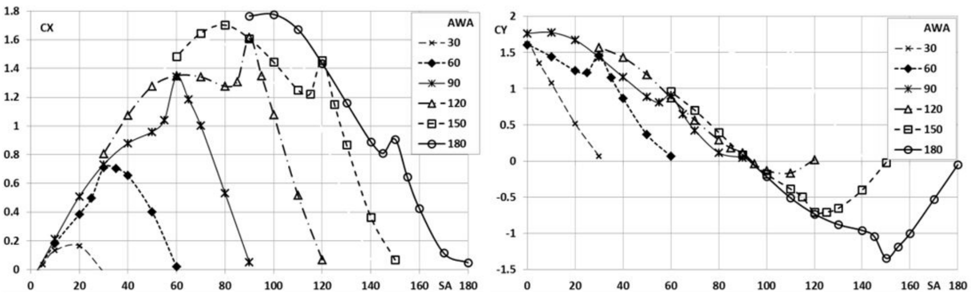

Fig. 7. Sail forces variation with sail trim angle
at different apparent wind angles

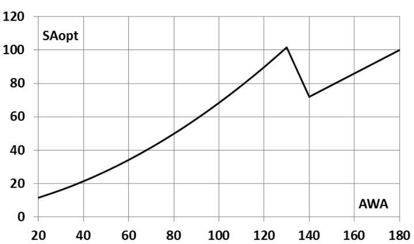

Fig. 8. Optimum trim angles

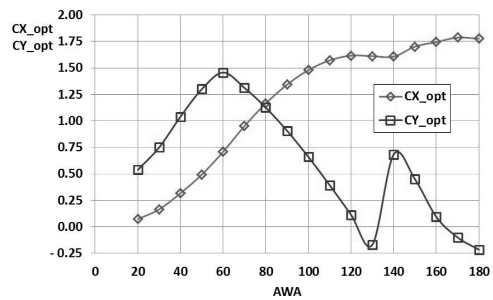

Fig. 9. Sail forces coefficients
at optimum trim angles

Figure 7 presents results of investigating the sail forces variation with sail trim angle at different apparent wind angles. It can be seen that for AWA larger than certain value (about 130 degrees in this case or downwind headings) the curve of C_X has two local maxima: one at lower angles of attack corresponding to the most efficient action of the sail as a wing, and a second one at higher angles of attack corresponding to the action of the sail as an air trap.

Collecting the data corresponding to the absolute maxima of the C_X curves produces the relationships illustrated graphically in Figs 8 and 9. These force coefficients values are used for each specific apparent wind angle.

5. BALANCE OF HYDRODYNAMIC AND AERODYNAMIC FORCES

The steady sail-assisted motion of the ship requires a force balance for six degrees of freedom, and the ship will get a constant heel and leeway angle to generate the necessary reaction forces, Fig. 10.

In particular, the yaw balance of the ship is an essential issue for wind-assisted conventional commercial vessels. With relatively small-size rudders as the only appendage these ships are essentially unfit for sailing. Such hulls will operate with greater leeway angles, and with 'weather helm' as a consequence of this inefficient side force generation. The use of the rudder to oppose this destabilising moment is associated with resistance increase.

Fig. 10. Balancing hydrodynamic and aerodynamic forces (sketch credit [3])

The auxiliary thrust generated by the sails changes the operating conditions of the existing engine and propeller. The propeller will operate in a light-loaded condition, but in an oblique flow. The implementation of a sail-system will only benefit the vessel if the net thrust gained outweighs losses in efficiency and increase in resistance.

Reliable and practical methods of predicting powering performance of wind-assisted ships are needed accounting for the influence of the sailing condition on resistance, yaw balance, propeller efficiency and stability.

The algorithm of such a powering performance predictor comprises:

1. Input data for the ship:
   – Hull geometry and hydrostatics;
   – Geometry and location of rudder and sail(s);
   – Propeller open-water characteristics (K_T, K_Q, η_0);
   – Engine power, RPM, SFOC;
   – Hydrodynamic towing resistance in calm water, straight course.
2. Compute hydrodynamic coefficients of hull, topside, rudder, sail(s).

3. Wind parameters: TWS, TWA.
4. Set ship speed. Calculate AWS, AWA.
5. Force balance. Solve equations (2) and (3) with respect to leeway angle β and rudder angle δ for specified ship speed and wind parameters.
6. With β and δ found solve equation (1) to find the resistance of the ship under the action of the external loads.
7. Compute inclining moment and heel angle.
8. Using updated total resistance and the propeller open water characteristics calculate the delivered power, the brake power and the Fuel-Oil Consumption (FOC).

To estimate the fuel savings for a specific voyage, the route can be broken into sections with relatively constant wind conditions and steps 3 to 8 are repeated consecutively.

6. TEST CASE

The mathematical model and the algorithm are tested on a specific ship and route [4].

A ferry-boat was chosen for the simulation. It was deemed suitable for wind-assisted propulsion for the following reasons:
– Fore ship location of the navigation deck not to be obstructed by sails;
– Relatively clear deck;
– Regular trip destination and schedule.

A system of two soft sails was designed and fitted at both sides to be used alternatingly one at a time, depending on the apparent wind direction, Fig. 11.

Fig. 11. General view of the investigated ship

The Black Sea route Varna–Poti–Varna was investigated. Actual wind data along the route were taken from [5].

In this simulation the following methods were applied for the elements of the algorithm:

– The wind loads (X_{TOP}, Y_{TOP}, N_{TOp}) coefficients on the topside of the ship (above-water part of the hull + superstructures) were computed by CFD code STAR CCM+.
– The rudder forces and moment ($X_{RUD}, Y_{RUD}, N_{RUD}$) were calculated by empirical formulae from [6–7] accounting for the influence of the propeller.
– The forces and moment due to leeway angle ($X_\beta, Y_\beta, N_\beta$) were determined by empirical formulae from [2] for the hydrodynamic derivatives using the main particulars of the ship.
– The forces on the sail (X_S, Y_S) were calculated by CFD code STAR CCM+.
– The force balance equations were solved using the Excel add-in SOLVER.

The FOC of the two engines with the calculated power, speed and time for each section of the route were accumulated to estimate the fuel savings Table 1. During the voyage the leeway angle varied within −0.2 to 0.8 degrees, the rudder angle between −3 and +4 degrees and the heel angle between −0.1 and 0.5 degrees.

Table 1

	Varna–Poti	Poti–Varna	Round trip
No wind, no sales	13.6 t	13.6 t	27.2 t
Wind, no sales	13.5 t	12.8 t	26.3 t
Wind, with sales	12.0 t	11.4 t	23.4 t
FOC savings	11.1%	10.9%	11%

7. CONCLUSION

The developed procedure for predicting the powering performance of ships with wind-assisted propulsion can be used for feasibility studies of sail systems to specific ships and conceptual design of such systems.

The procedure will be further developed by improving the methods used in each element of the algorithm including CFD simulations and model testing procedures.

ACKNOWLEDGEMENTS

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