Hull, Rudder and Propeller Investigation on a Vessel in Free Run Condition

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1. Introduction

The rudder normally operates in the wake of the propeller in the stern of the ship. This is needed in order to create enough lift for its main role, maneuvering, with the high speed flow leaving the propeller. When the ship is in free sailing condition, the rudder is only responsible for doing minor course corrections, normally carried out by the autopilot. Due to the pressure distribution over the rudder, different forces appear, mainly a longitudinal force that could be drag or push force and a transverse force affecting the ship's course.

The wake adapted rudder is normally designed so as to improve the propulsive and maneuvering performance of the propeller – rudder unit. The amount of energy which is recovered will depend on the form and thickness of the profile of the propeller, the aspect ratio, Rn, the spatial distribution of the velocity upstream and the turbulence of the flow [1]. It is expected that a wake adapted rudder has less transverse force than a conventional one at 0º angle when a vessel sails in free run operation, therefore reducing the need for autopilot corrections.

In single screw vessels there are also a force unbalance due to the asymmetry of the propulsion system which modifies the flow differently on port and starboard side depending on how the propeller rotation is.

The flow is not stationary, mainly due to the rotation energy supplied by the propeller; also the presence of the rudder modifies the performance of the propeller compared to the open water case, partially blocking the water flow downstream the propeller. Analyzing this system by CFD means that the behaviour of the flow would imply the solution of an evolutionary problem on a moving mesh. These problems have high computational costs and are not suitable to be solved on a routine basis. A lot of articles consulted in the literature demonstrate that they can be dealt with in a quite precise way by means of Reynolds Averaged Numerical Stationary simulations so as to obtain integral values on the different regions of interest, among other can be cited Caldas et al. [2]

Numerical simulations of a conventional and a twisted rudder with the same area are performed behind the running propeller of a vessel in order to determine how large the transverse forces at 0º angle are. A parametric study was done analyzing small variations of angle in order to search the optimum angle that minimizes net transverse. The simulations carried out included an analysis of the forces from each part of the ship i.e. rudder, propeller and hull. All the calculations are carried out using commercial CFD code STAR-CCM+.

2. General Description

The aim of this study is to investigate, by means of CFD, the interaction between rudder, propeller and hull on a sailing ship at different angles of drift, especially at 0º angle and also, the manoeuvring performance of the twisted rudder fitted compared to a conventional one. To achieve this objective it is necessary to consider two conditions: static rudder and pure drift cases. The static rudder cases are used to compute the hydrodynamic forces and moments varying the rudder angle δ to determine the manoeuvre of the ship. During these cases, an appended model is modelled at constant speed and straight-head course, while the rudder angle is varied systematically, between 0º and 10º. The pure drift cases are used to determine the influence of oblique flow on the forces and moments in the sea course of the ship. In order to simulate these cases, the appended model is modelled at constant speed for a fixed angle rudder of 0º varying the drift angle (β) between -10º and 10º. The drift angle is defined as $\beta=\tan^{-1}(v/-u)$, where u and v are the sway and surge velocities, respectively. The Figure 1 illustrates these conditions.

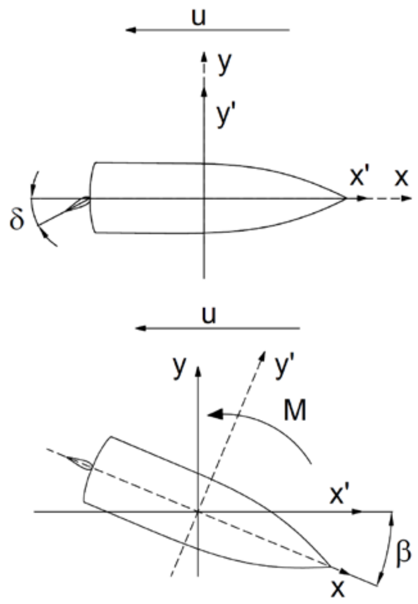

Figure 1. Sketches of the cases: static rudder (up) and pure drift (down).

In this study, several double-body self-propulsion simulations on both configurations at free run condition were carried out, which is defined by a speed of 10 knots and a propeller rotation rate of 205 rpm.

2.1. Geometry

The ship considered in this study is 46.7 m long equipped with a fixed pitch propeller and a central twisted rudder with bulb adapted to the flow. The main particulars of the ship are shown in Table 1.

Lpp	*45.9*	m
B	*10.4*	m
T	*3.9*	m
Propeller Diameter	*2.95*	m
Number of blades	*5*	-
Rudder Chord	*1.9*	m
Rudder Height	*3.3*	m
Lateral Area	*6.27*	m^2
Thickness	*0.2*Chord*	-

Table 1. Main geometric dimensions

The rudders to be analyzed are shown in Figure 2. Both rudders have the same dimensions in terms of chord and span being the only difference given by the lateral displacement on the leading edge for the twisted one. The bulb is the same in both geometries.

Despite the geometry has longitudinal symmetry, this symmetry cannot be applied in the domain as the rudders presence leads to instabilities by means of the introduction of physical asymmetry in the problem (i.e., it produces a flow block at the exit of the propeller).

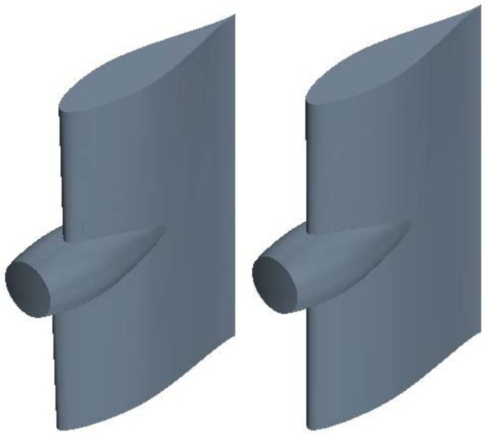

Figure 2. Geometry CAD of simulated rudders: wake adapted rudder (left) and straight rudder (right)

It has to be noted that propeller rotates clockwise, when is viewed from astern facing forward, since it is important to follow the argumentation.

2.2. Numerical model

The mathematical model used for the calculation of the numerical simulations is described by Reynolds Averaged Navier Stokes Equations (RANSE). The Reynolds stress tensor was modelled to close the governing equations by means of a two-equation model, named Two Layer K-Epsilon, with a Two Layers All y+ Wall Treatment for the wall modelling. The problem is closed establishing the initial and boundary conditions on the physical and computational boundaries.

Commercial code StarCCM+ has been used for the numerical solutions of the equations. StarCCM+ solves RANSE equations in their integral form, by means of Finite Volumes methods. The spatial discretization of the convective terms is done with a second order upwind based scheme, whereas the diffusive terms are discretized with second order centered scheme. Velocities and pressures are solved in a segregated manner, and then coupled by means of the SIMPLE algorithm. The rotation of the propeller is modelled used a moving reference frame system, i.e., the velocity is set on propeller blades and centripetal effects are included in additional source terms in the momentum equations. Further details about the code can be found in [3] and about numerical aspects in [4]

The physical domain is discretized by means of non-structured mesh of polyhedral cells [5]. Several refinement zones or volume shapes were located at different parts of the domain, particularly in the wake region, in order to increase the density of cells and improve to the resolution of flow features. The whole mesh consists of a total of about 3 millions of cells, where the rotation region (propeller) has about 800.000 cells and the fixed region 2.100.000.

For all cases, the y+ values were in a range between *y*+=30 and *y*+=150 with an average of 50. A typical stern surface mesh can be seen in Figure 3.

Figure 3. Typical computational mesh

2.3. Figure of merit

The transverse forces and the yaw moment of rudder, hull and propeller were measured for both conditions. The transverse forces were measured locally for each part whereas the yaw moment was measured globally on the model respect to Lpp/2, as functions of rudder angle for the static rudder condition and function of drift angle for the pure drift condition. The positive directions are defined in the Figure 1, where the X-component acts in the longitudinal direction of the ship whereas the Y- component acts perpendicular to this direction. The transverse forces and the moment are non-dimensionalized by means of lateral underwater area of each part separately, the speed U_∞ and the water density. The Lpp is used as characteristic arm for the yaw moment.

$$L' = \frac{F}{0.5\rho U_\infty{}^2 A_0} \quad (1) \qquad M' = \frac{M_Z}{0.5\rho U_\infty{}^2 A_0 L_{pp}} \quad (2)$$

3. Results and Discussions

Pressure distribution around a NACA profile is an important parameter from the hydrodynamic point of view because it determines the lift and drag forces. The pressure distributions are plotted on the rudder surface by means of local pressure coefficient, C_p

$$C_p = \frac{p - p_\infty}{0.5\rho U_\infty{}^2}$$

where $p - p_\infty$ is the local pressure, ρ is the density and U_∞ is the free stream velocity. This figure of merit is used along with the previous ones to have a deeper knowledge on the manoeuvre of the rudder and the performance of the ship in free run condition.

3.1. Static Rudder

As it was mentioned in the previous section, in the static rudder condition the rudder angle is varied between 0 and 10 degrees (to produce a turn to the starboard side) while the ship sails in straight-head course at constant speed. The non-dimensional transverse force and yaw moment are shown in the Figure 4 and Figure 5.

As it is expected (Figure 4), the higher rudder angle the larger transverse force is (at these low angles) for the rudder whereas for the propeller and the hull are kept constant with the variation of the angle. This is due to the fact that the incoming water into the hull and propeller is not modified during the change in the rudder angle. Indeed, due to the symmetrical geometry of hull, the transverse force for straight-head course is negligible. Special attention is paid to 0° rudder angle, where the transverse forces of rudder and propeller have opposite signs. The clockwise rotation of the propeller, along with the wake of the ship produces a positive side force of the propeller. The swirl and acceleration induced by the propeller alters the speed and incidence of the flow arriving to the rudder, giving rise to negative side force in this case, due to the lateral displacement of the rudders profiles.

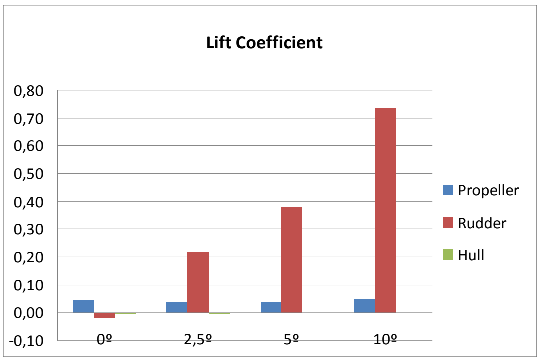

Figure 4. Lift coefficient of propeller, rudder and hull for each rudder angle configuration

The sum of transverse forces at 0° rudder angle leads to negative yaw moment (Figure 5), and hence, a small turn of the ship to the starboard are expected to occur. The pure drift result (above) allows appreciating the influence of this turn on the ship behaviour. As the rudder angle increase, the yaw moment of the rudder has the same sign as the propeller and the values are higher. The values of yaw moment for the rest of rudder angles are large if they are compared to the values of conventional rudders from ships with the same characteristics as the studied one. Therefore, the adapted rudder is able to perform manoeuvres in less time than others.

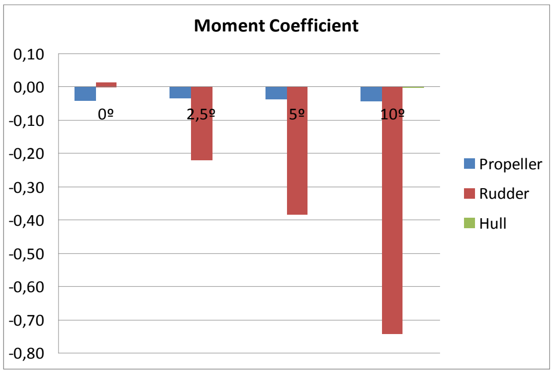

Figure 5. Moment coefficient of propeller, rudder and hull for each rudder angle configuration

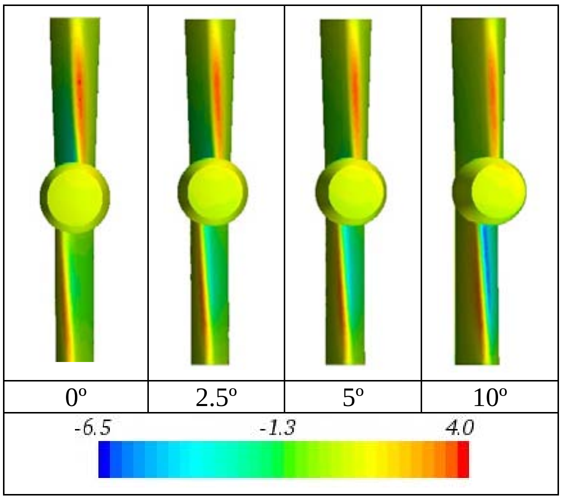

Figure 6. Pressure coefficient for rudder angle

The introduction of the propeller generates high pressure peaks both positive and negative on rudder which causes an increase in transverse forces. The rudder angle modifies the axial and tangential velocities coming from the propeller, leading to lower pressures and high velocities on the port side and higher pressure and lower velocities on the starboard side of the lower part of the rudder. The opposite is produced in upper part of the rudder (Figure 6). As the angle increase from 0° to 10°, gradient pressures in the lower leading edge becomes higher (positive direction) whereas in the upper part becomes lower (negative direction), hence the transverse forces increase (Figure 4).

3.2. Pure Drift

For these cases, the rudder angle is kept fixed at 0° and the drift angle is varied between -10° and 10° whereas the ship is sailing at constant speed, as it was define in previous section. It has to be mentioned that case of drift angle with 0° coincides with studied case of rudder angle with 0°.

Figure 7 shows the transverse forces as a function of drift angle for propeller, twisted rudder and hull. The symmetry of the hull leads to symmetrical values respect to 0°, increasing with drift angle. At drift angle of 0°, the sign of transverse force is negative since the propeller has the higher load between 12 and 3 o'clock (looking from aster) leading an increase of suction on upper left side of stern, which induces a negative transverse force on the hull. Although this physical phenomena has no so much influence as the absolute drift angle increases.

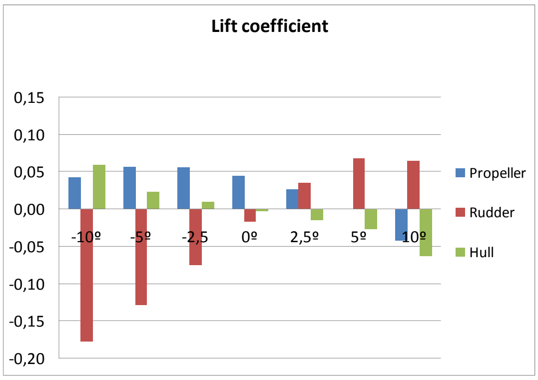

Figure 7. Lift coefficient of propeller, rudder and hull for each adapted rudder angle configuration for pure drift

The presence of the hull in the oblique flow (drift angle different than 0°) modifies the wake, and hence the local angle of attack on the propeller blades leading to a modification of propeller load. Negative drift angle implies higher velocity in the starboard side of the propeller and therefore higher port side propeller loading. This unbalance of loading leads to positive propeller transverse force. Whereas for positive drift angle the starboard side propeller has higher loading and negative propeller transverse force is produced. The propeller rotation along with the wake due to the hull does not allow get a symmetrical results respect to 0° drift angle and the null transverse force is achieved approximately at 5°.

Finally, the rudder performance depends strongly on modification of tangential velocities produced by propeller and hull. The influence of drift angle on rudder performance is explained analysing the pressure coefficient as shown in Figure 9.

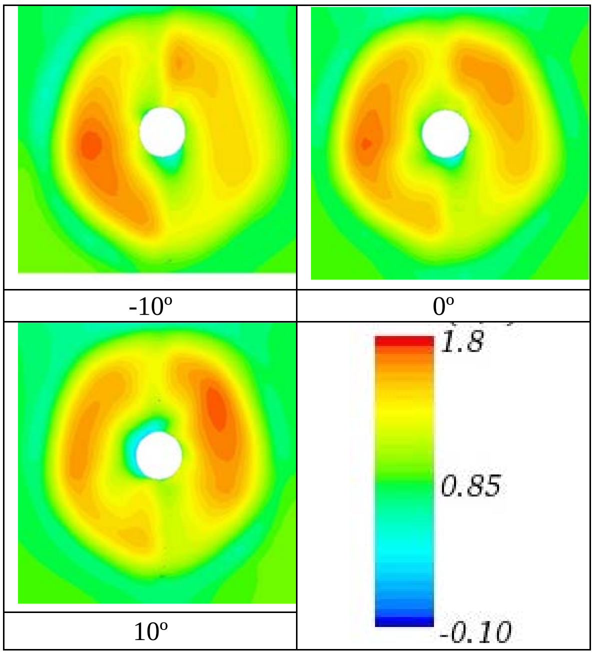

Figure 8. Non dimensional axial velocity on a normal plane to the ship between propeller and rudder (viewed from astern facing forward)

For a drift angle of -10°, the upper leading edge has the largest pressure gradient, given by lower pressures and high velocities on the starboard side and higher pressure and lower velocities on the port side. As the drift angle increases from -10° to 10°, the distribution of pressure and velocities are kept constant but the upper pressure gradient decreases whereas the lower one increases and becomes the largest pressure gradient on rudder. Then, the transverse force goes from negative to positive as the drift angle varies from -10° to 10° (Figure 7).

3.1. Comparison between rudders

The lateral displacement of twisted rudder allows to move the transverse force curve to the left, i.e. the transverse force for negative drift are higher for twisted rudder than straight rudder and vice versa for positive drift angle (Figure 10). The rudder shape has a slight influence on propeller transverse force but the values for the hull are independent of rudder shape.

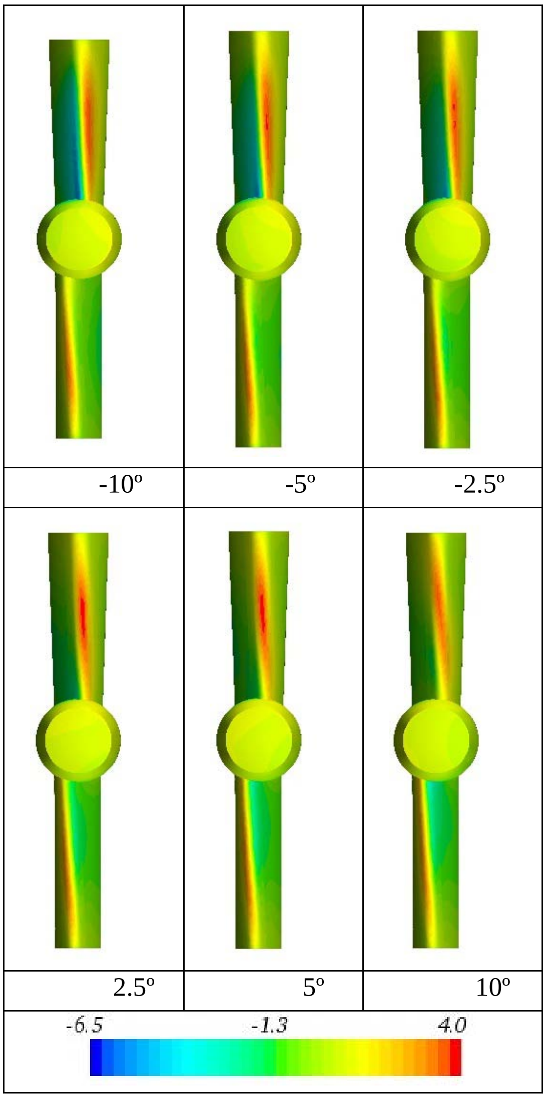

Figure 9. Effect of drift angle on rudder performance

Special case corresponds to 0° drift angle, since straight rudder transverse force is higher than adapted rudder and indeed, it has the same sign of propeller force. Then, straight rudder would develop larger turn to the starboard side than adapted one, leading to more difficulties to keep the course. This can be explained if pressure coefficient for adapted rudder (right) and straight rudder (left) is analyzed (Figure 11). Looking that figure, the only difference between both rudders can be located on the lower leading edge, since the straight rudder has larger pressure gradient than the adapted rudder, giving rise to a higher positive force.

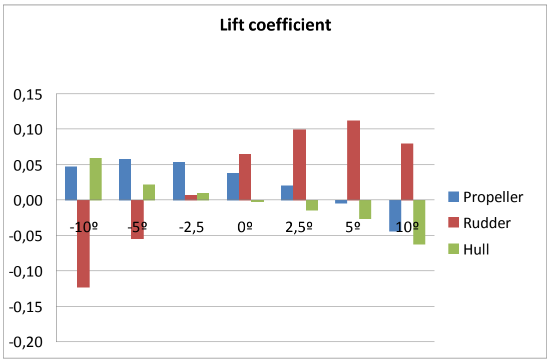

Figure 10. Lift coefficient of propeller, straight rudder and hull for each straight rudder angle configuration for pure drift

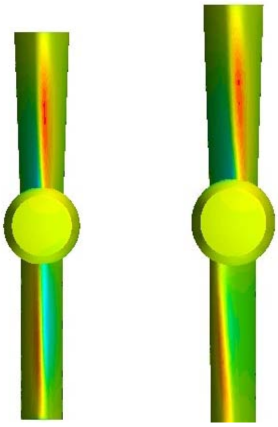

Figure 11. Pressure coefficient for straight rudder (left) and wake adapted rudder (right)

4. Conclusions and Future Works

In the present work RANS CFD has been used to perform numerical self-propulsion test for a vessel 45.9 m long equipped with a twisted rudder with bulb and a single propeller, in order to study the interaction between hull, propeller and rudder and their influence on ship's course and the capacities of manoeuvre, when the vessel sails at constant speed of 10 knots and propeller rotation rate of 205 rpm. Also, a straight rudder with the same bulb has been studied to know the effects of twisted rudder on those issues. Then, two configurations were analysed: static rudder and pure drift.

The numerical simulations for static rudder configuration ($0^{\circ} < \delta < 10^{\circ}$) shows that rudder transverse force increases with increasing the rudder angle and for propeller and hull keeps constant, being hull force negligible. For 0º, rudder force has opposite sign that propeller. Since the sum of moments is not null, a small turn to starboard side is developed.

Effect of drift angle (β) produces a symmetrical response for hull lift forces but not for propeller and rudder, due to interaction between then. For all studied drift angles, lift forces have opposite signs for rudder and propeller, except for small positive angles due to propeller clockwise rotations and lateral displacement of twisted rudder. This performance is due drift angle induces an unbalance of incoming velocities on the propeller, leading a higher propeller loading on blades with lower incoming velocities (enhance or not in function of propeller rotation sense). This asymmetric load distribution produces rudder lift force in the same sign of drift angle, with a little delay due to lateral displacement and rotation sense.

When both rudders are compared, almost the same performance is achieved although the lift curves from both rudders present a shift. For 0º drift angle, straight rudder develops higher yaw moment than adapted one and hence, worse performance from point of view of course keeping. Then, twisted rudders have better performance on ship's resistance and course.

Future work include the use of these forces (propeller and rudder as unit propulsion) in manoeuvring simulator developed by VICUSdt and carry out new numerical simulations in order to get deeper knowledge of the interaction by means of LES modelling.

5. References

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