COMPARISON OF EXPERIMENTAL AND CFD RESULTS FOR A TANKER LIKE VESSEL

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ABSTRACT

The turning circle manoeuvre of a self-propelled tanker like ship model is numerically simulated through the integration of the unsteady Reynolds Averaged Navier-Stokes (uRaNS) equations coupled with the equations of the motion of a rigid body. The solution is achieved by means of the unsteady RANS solver developed at CNR-INSEAN. The model considered is a twin screw single rudder vessel. Each propeller is taken into account by a model based on the actuator disk concept; anyhow, in order to correctly capture the turning manoeuvring behaviour of the model, a suitable description of the propeller performance in oblique flow operations should be considered. The effects of the stern appendages (shaft lines and brackets) on the vessel's manoeuvring capabilities is analysed. Comparison with experimental data from free running tests will demonstrate the feasibility of the CFD computations and in particular of the proposed model for the propeller side force estimation.

1. INTRODUCTION

The prediction of the dynamic stability and manoeuvrability behaviour of a ship are among the most challenging problems in naval hydrodynamics; the main difficulties arises in the accurate evaluation of the hydrodynamic forces and moments which characterize the dynamic response of the vessels and its motion. Traditional approaches, like system based manoeuvring mathematical model or potential based methods are extensively utilized since decades; the negligible computational resource requirements can be considered as the key of their success. These approaches are widely used for preliminary evaluations in the first design phase. However, despite they guarantee a satisfactory compromise among resource demanding and reliability of results, they are prevented from providing detailed information about the flow field developing along the hull and necessitate continuous verification and validation in case of novel hull forms (Simman 2008 [14] and Adgrup *et al.* [15]). On the other hand, computational fluid dynamics tools have reached a noticeable level of accuracy in predicting ship propulsive performance in straight ahead conditions and its application to study ship manoeuvrability provides a challenging aspect for both the development, and the verification and validation of this powerful technique. The key of the success of this approach lies in the possibility to provide the complete solution of the flow field; indeed, they are based on a mathematical model characterized by a negligible simplification assumptions. The availability of the flow field allows the analysis of the complex flow field around a ship in manoeuvre, which is characterized by large vertical structures shed from the hull and the appendages, as well as by flow separations that can be rather massively. Moreover, the possibility to analyse the complex hull/appendages/propeller interaction makes this technique unique. The main cons for these techniques are the large computational resources reside in CPU time and computational resources requirements; anyhow, the application of computational fluid dynamic to ship manoeuvrability, stability and control is an attractive alternative because it could be a complementary aid and, at the same time, enrich results obtained by means of experimental techniques.

1.1 Work's purposes

In this work, the unsteady Reynolds averaged Navier-Stokes solver *χnavis* developed at CNR-INSEAN (Di Mascio *et al.* [3], Di Mascio *et al.* [4], Di Mascio *et al.* [4] and Broglia *et al.* [2]) coupled with the equations describing the 6DoF motion of a rigid body is applied to the analysis of the turning behaviour of a single rudder, twin screw tanker like vessel. One of the main purposes of the present work is to explore the capability prediction of the CFD solver for a complex geometry (complete appended hull) performing tight motion. Moreover the study is aimed to assess the reliability of numerical techniques for capturing the complex flow features and the complex hydrodynamic interactions which affect profoundly the vessel dynamic response; a detailed analysis of the forces which develop on the different part of the hull is also investigated. In particular, a deeper insight into the propeller contribution to the manoeuvring properties of the vessel is investigated; detailed measurements of hydrodynamic loads and flow features by Atsvanapranee *et al.* [1] around a twin screw frigate type vessel during a steady turn, have shown that the side forces generated by the propeller can be rather relevant (*15-20%* of the total lateral force), therefore, contributing noticeably to the total hydrodynamic loads acting on the hull and, consequently, to its manoeuvring behaviour. Simulations presented in this work provide an interesting insight into propeller lateral force contribution to vessel's manoeuvring and the need of its inclusion into simplified propeller models usually adopted in RANSE solvers is emphasized. Moreover, in Di Mascio *et al.* [5], it has been demonstrated that, in case of twin screw vessels, stern appendages are a crucial element affecting the manoeuvring response. In particular, it has been demonstrated that the most widely accepted system based regression method achieve a poor prediction of the manoeuvring behaviour of the same vessel considered in this study; on the contrary, results for the same vessel equipped with a large amount of stern appendages (namely twin rudder plus a central skeg) were satisfactory. The reliable modelling and inclusion of stern appendages into regression method was the primary reason for the failure in the former case. On this basis, the effect of stern appendages on the vessel's manoeuvring behaviour has been analysed considering separately hydrodynamic force and moment developed by each appendage during the different phase of the turn. Stern appendages represent a key aspect of manoeuvring behaviour for twin screw vessels and CFD can be a valuable tool for quantifying reliably their contribution and, moreover, improve traditional manoeuvring mathematical models extensively widely accepted in this field.

2. NUMERICAL MODEL

The numerical solution of the governing equations is computed by means of the solver χnavis, which is a general purpose simulation code developed at CNR-INSEAN; the code yields the numerical solution of the unsteady Reynolds averaged Navier Stokes equations for unsteady high Reynolds number (turbulent) free surface flows around complex geometries (the interested reader is referred to [3], [4], [4], [7] and [2] for details). The solver is based on a finite volume formulation with conservative variables co-located at cell centre. The spatial discretization of the convective terms is done with a third order upwind based scheme, whereas the diffusive terms are discretized with second order centred scheme and the time integration is done by second order implicit scheme (three points backward). The solution at each time step is computed iteratively by a pseudo-time integration, that exploits an Euler implicit scheme with approximate factorization, local pseudo time step and multi-grid acceleration [8]. Although several turbulence models have been implemented in the code, in all the simulations reported the turbulent viscosity has been calculated by means of the one-equation model of Spalart and Allmaras [13]. Free surface effects are taken into account by a single phase level-set algorithm [4]. Complex geometries and multiple bodies in relative motion are handled by a dynamical overlapping grid approach [7]. High performance computing is achieved by an efficient shared and distributed memory parallelization [2].

2.1 Propeller Model

In usual marine CFD simulations the presence of the propeller is taken into account by a model based on the actuator disk concept, according to which body forces are distributed in the flow field within a disk of finite thickness. Both axial and tangential forces are used in the computation in order to simulate both the acceleration and the increase in swirl that the flow undergoes when passing through the propeller. Such distributions are obtained by blade loads averaging in both time and space. Usually, time averages are taken over one period of revolution, whereas space averages are obtained by distributing blade loads in circumferential direction over the whole propeller disk. Both axial and tangential body forces depend on the actual velocity field; this results in the sum of the nominal wake velocity and the propeller-hull interaction velocity, namely the effective wake; the body forces distribution and the velocity field are mutually dependent, therefore, in order to take into account for the effective wake, an iterative procedure is required. In this work the propeller is modelled by means of an hybrid model: thrust and torque are evaluated by means of a modified Hough and Ordway model, whereas the in plane forces are computed by means of the semi-empirical method proposed by Ribner [12], which is derived from a blade element approach. In the following subparagraphs both the modified Hough and Ordway [9] and the Ribner [12] models will be briefly recalled, the interested reader is addressed to the cited papers for more details.

2.1.1 Thrust and Torque (Hough and Ordway Model)

In this model, the propeller loading is computed following the idea proposed by Hough and Ordway (Hough and Ordway [9]): given the advance, thrust and torque coefficients (J, K_T, K_Q in the following), the axial, radial and tangential force distributions are computed under the assumption of an optimal distribution for the circulation along the blades. The original model was modified to take into account for the axial flow reduction at the propeller disk; in particular, at each time step the advance coefficient is estimated by keeping the number of the revolution constant and by using the instantaneous average axial velocity at the propeller disk inflow section. Then, new values of $K_T(J)$ and $K_Q(J)$ are estimated from the propeller characteristic curves; the resulting load (longitudinal and tangential) is then distributed over each cell of the propeller disk as volume forces in order to simulate the action of the propeller.

2.1.2 In Plane Loads (Ribner Model)

Ribner’s model [12], a widely accepted one in the aeronautic field for the evaluation of airplanes’ stability qualities, was developed on the basis of two main physical phenomena which characterise the propeller behaviour in oblique flow, and therefore, are strongly related to loads acting in the propeller plane. When the propeller works with an angle of yaw with respect to the incoming flow, it accelerates the flow behind the disk reducing the angle of attack with respect to the shaft axis; simplifying this problem, it could be assumed that the propeller tends to align the flow behind the propeller itself. This angle variation results in a lateral momentum provided to the flow by the propeller, and consequently, as a reaction, the propeller experiences a lateral force with the same direction of the incoming flow; moreover, part of the propeller lateral momentum is spent by the slipstream to move in a transverse motion with respect to the flow, so that an additional lateral force is generated. These physical phenomena are accounted for in Ribner's theory by means of a hybrid blade element (for the estimation of the loads acting on the propeller blades) – actuator disk approach (for the evaluation of the effective incidence angle due to propeller induction effect). In the following only the core of the model is presented, and its inclusion in the numerical solver; the interested reader is referred to Ribner [12] for details of its derivation.

A propeller moving in the horizontal plane at incidence with respect to the flow (the treatment is analogous in the vertical plane) experiences a lateral force (in the same direction of the in-plane component of velocity) defined by the relation:

$$Y'_{PROP} = C'_{YPROP}\,\beta \approx C'_{YPROP}\,\frac{v_{PROP}}{V} \tag{1}$$

where C'_{YPROP} is the propeller lateral force hydrodynamic derivative, β is the local angle of attack of the flow with respect to the propeller disk, v_{PROP} is the lateral speed at the propeller and V is the total speed at the propeller disk (velocities in (1) are referred to the nominal conditions, i.e. propeller induction is not considered, its effect being included in C'_{YPROP}). The lateral force derivative is expressed by the following relation:

$$C'_{YPROP} = k_S Z \frac{3}{4\pi}\frac{\partial C_L}{\partial \alpha} A_{SIDE} \frac{F(a)}{1 + k_a \dfrac{3}{4\pi}\dfrac{\partial C_L}{\partial \alpha} A_{SIDE}} \tag{2}$$

where Z is the number of blades, A_{SIDE} is the lateral blade projected area, $\frac{\partial C_L}{\partial \alpha}$ is the sectional lift coefficients which has been derived from thin airfoil theory, $F(a)$ is the propeller load factor, defined as:

$$F(a) = \frac{(1+a)\left[(1+a)+(1+2a)^2\right]}{1+(1+2a)^2} \tag{3}$$

where a is the induced factor. It is evident that the lateral force is strictly related to the propeller geometry, namely lateral projected area, i.e. the propeller can be viewed as an additional fin whose contribution is analogous to those provided by a rudder or a central skeg. Correction factors k_a and k_S are introduced in order to account for the non-uniformity of the load over the propeller disk induced by the slipstream and the presence of the propeller hub, respectively. This model has been added to the modified Hough and Ordway model; the only term that must be evaluated at every time step are the induction factor a and the resultant lateral speed at the propeller disk; in particular:

- the induction factor a is easily determined from momentum consideration once the instantaneous thrust coefficient K_T has been determined;
- the resultant lateral speed is evaluated by averaging the local lateral speed over the disk; moreover, in order to take into account for the nominal wake, i.e. without considering the propeller induction effect, a suitable procedure have been included for separating the contribution of swirl induced effect.

It should be emphasized that the addition of the side force model does not increase the computational resource demanding; this makes the hybrid Hough and Ordway/Ribner model very attractive for those problems where the details of the flow field around the propeller are not relevant, but only the main effects of the propeller on the flow field are required. Ship maneuvering is a typical framework, being the key issue the correct estimation of forces and moments developing on the hull whose magnitude could have a strongly effect on the vehicle's response.

3. GEOMETRY AND TEST CONDITION

A twin screw single rudder tanker like model reported is considered for the numerical simulations (see Figure 1).

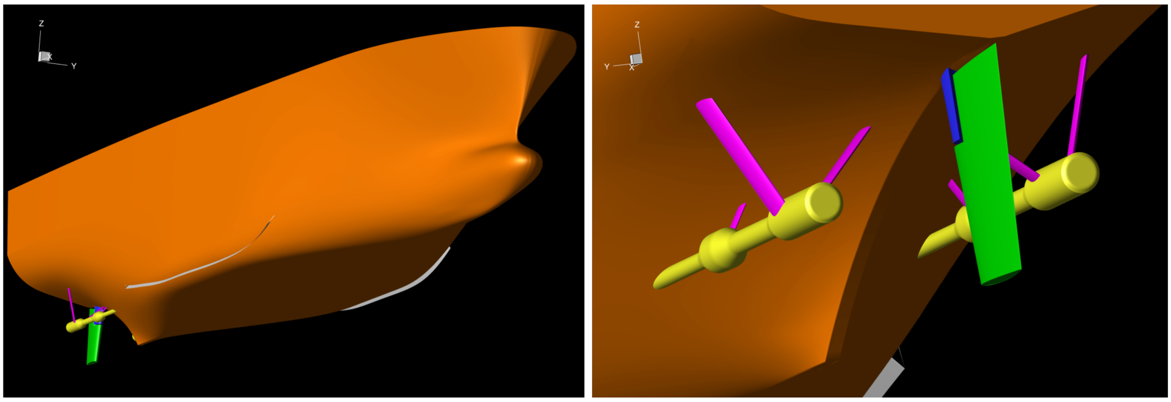

Figure 1. *Views of the model. Top: 3D global; bottom, transom region.*

The model is fully appended with bilge keels, struts, A-brackets and shafts for two propellers and a horn-type rudder. For this model an extensive free running test program has been carried out at the lake of Nemi [10] and [11]; this will allows a comparison in terms of both trajectories and kinematic characteristics. The main non dimensional characteristics are reported in Table 1. All the quantities in the following are made non dimensional by a reference length L_{PP} and the approach velocity U_0 (at model scale). This gives a Reynolds number $Re=5 \cdot 10^6$ (at model scale) and a Froude number $F_N=0.217$. The turning circle manoeuvre test is carried out at fixed turning rate of the propeller; the propulsion point is chosen by means of an unpropelled steady state simulation at the given speed with fixed trim and sinkage.

Symbol	Value
Displacement	$5.0987 \cdot 10^{-3}$
CB	*0.6*
Propeller Diameter	$3.2609 \cdot 10^{-2}$
Number of blades	*4*
J	*0.915*
K_T	*0.19140*
K_Q	*0.03817*

Table 1. *Main particulars.*

The simulation of the turning circle manoeuvre is carried out leaving all the six degree of freedom free; the turning rate of the rudder is *12.23* degrees per non dimensional time unit (at model scale), a turning circle with the rudder deflected of *35* degrees is considered. The manoeuvre is carried out at fixed turning rate of the propeller; the propulsion point for the single rudder configuration is chosen by means of an unpropelled steady state simulation at the given speed with fixed trim and sinkage.

The physical domain is discretized by means structured blocks with partial overlap; overlapping grids capabilities are exploited to attain a high quality mesh and for refinement purposes. The whole mesh counts for a total of about 6.2 million of computational volumes. Grid distribution is such that the thickness of the first cell on the wall is always below 1 in terms of wall units ($y^+=O(1)$ i.e. $\Delta/L_{PP}=O(20/Re)$, Δ being the thickness of the cell, L_{PP} the length between perpendiculars and *Re* Reynolds number). In Figure 2 a detailed view of the mesh is shown.

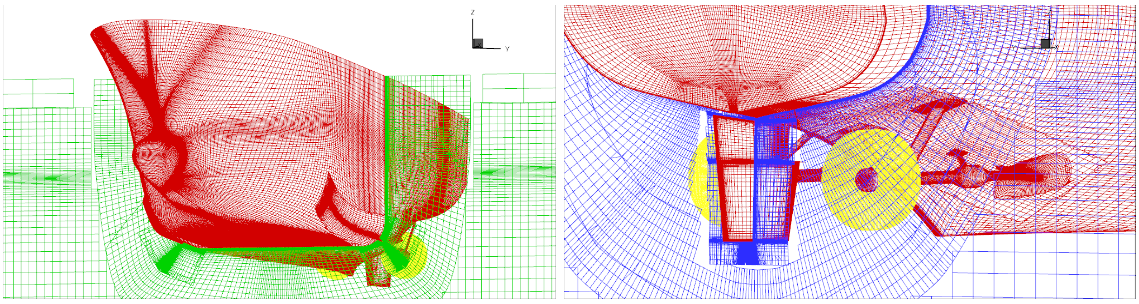

Figure 2. *Computational mesh; top, frontal view, bottom, rear view.*

4. RESULTS

In the following paragraphs numerical results will be presented; in particular the predicted turning qualities will be analysed in terms of trajectory and kinematic parameters; particular emphasis will be given on the effect of propeller behaviour and stern appendage effect on the manoeuvring behaviour. To this aim, time history of force and moments acting on different components of the hull have been analysed and discussed. The predicted turning parameters will be compared with experimental data from free running tests. Grid dependency solution is investigated by the comparison of the results obtained on the medium and the finest mesh.

4.1 Manoeuvre analysis

In Figure 3 the predicted trajectory and the time histories of kinematic parameters (speed of advancement, drift angle and yaw rate) during the turning circle manoeuvre are presented and compared to the free running experimental manoeuvre. In the reported results *t=0* is the time at which the rudder starts its *35°* rotation; the origin of the earth fixed system of reference is taken as the position of the model at *t=0*; in the analysis which follows, the velocity of the ship is normalised with respect to the velocity at *t=0*, i.e. the nominal approach speed.

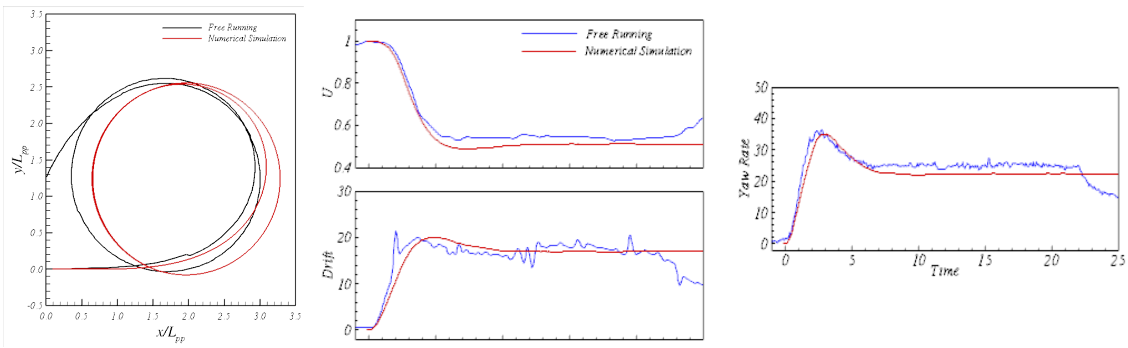

Figure 3. *Left: predicted trajectory; right: time histories for the speed of advancement, the drift angle and the yaw rate.*

As it can be observed from this figure, the overall agreement between experiments and numerical results is rather satisfactory; to properly estimate the quality of the numerical simulations, an analysis in terms of the kinematics parameters like transfer, advancing, tactical and turning diameters is reported in Table 2; comparison error between numerical and experimental data are reported as well. In the same table, for an estimation of the grid dependency for the numerical results, values obtained on the medium mesh are also provided.

	Numerical Results		Experiments
	Medium	Fine	
Advance	3.33 (16.84%)	3.02 (5.96%)	2.85
Transfer	1.11 (10.00%)	1.02 (2.00%)	1.00
Tactical Diameter	2.67 (4.30%)	2.48 (3,13%)	2.56
Final Diameter	2.89 (14.68%)	2.60 (2.44%)	2.52

Table 2. *Trajectory parameters and comparison with experiments.*

From Figure 3, it is evident that in the transient phase the course keeping stability of the vessel is slightly overestimated, i.e. the ship is less reactive to the rudder deflection (heading angle less than 90°). After the initial transient phase, the manoeuvring behaviour is well reproduced. This is evidenced by the comparison of the maximum transverse position and the steady turning phase; it is rather clear that, the main difference resides in a slight shift ahead of the trajectory, mainly due to the overestimation of the heading stability.

Time histories of kinematic parameters (speed drop, drift angle and yaw rate) are also in good agreement with respect to the measurements, thus revealing the high fidelity level of present computations in reproducing the dynamic behaviour for this challenging configuration. The attitude of the vessel with respect to the incoming flow, i.e. the drift angle is in excellent agreement with experiments, while speed drop and yaw rate are slightly underestimated. However, it should be pointed out that the effects of these two terms are opposite, i.e. speed drop provide a destabilizing character, which is counteracted by the higher resistance to rotation, which causes a lower yaw velocity; as a results, these effects cancels out and the final dynamic behaviour is captured. Further work and efforts are necessary to study in deep this phenomena and to quantify these cancellation effects.

4.2 Propeller behaviour during turning

In Figure 4 the thrust variation during the manoeuvre and the time histories of the lateral force/thrust ratio are reported. It is worth to note that during the manoeuvre lateral forces for the leeward and windward propellers act in opposite direction; the windward one provide a stabilising effect, vice versa the leeward one.

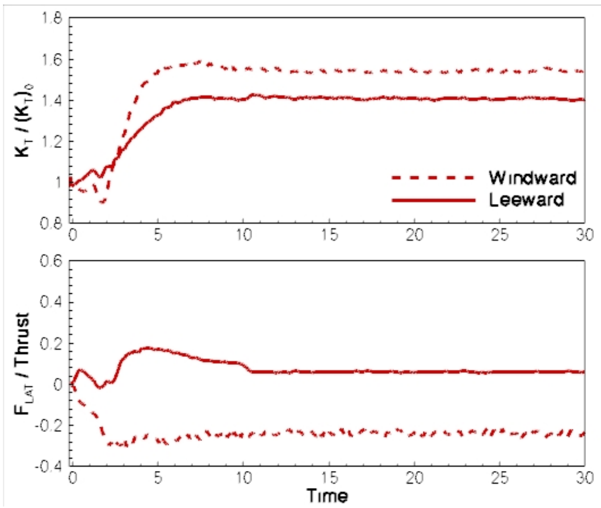

Figure 4. *Propeller thrust and lateral force/thrust ratio time histories.*

This apparently unexpected behaviour depends on the stern fineness characteristics, which strongly affects the local flow field features. In particular, in this case the windward propeller experiences a strong oblique flow from the wind to the leeward side, whereas the leeward propeller experiences an oblique flow from the leeward to the windward side. It could be observed that after the rudder is executed, the thrust (and torque, which is not reported) developed by both propellers increases; this is consequent to the decrease of the advance coefficients, consequent to the speed reduction experienced by the vessel in the drift-yaw motion. Moreover, this phenomenon is not symmetrical, i.e. the external/windward propeller develops higher loads with respect to the leeward one, because the wake, and consequently the inflow in correspondence of the propeller plane, is asymmetrical.

4.3 Stern appendage effects

In order to gain a deeper insight into the effects of propulsion system and stern appendages on the manoeuvring behaviour, an analysis on the forces experienced on the different part of the vessel is reported. To this aim, time histories of hydrodynamic force and moment (in the horizontal plane) on the various components (hull, appendages, rudder and propellers) and their sum during the turning circle are reported in Figure 6 and Figure 7. Horizontal loads are considered in the reference moving with the vessel (see Figure 5).

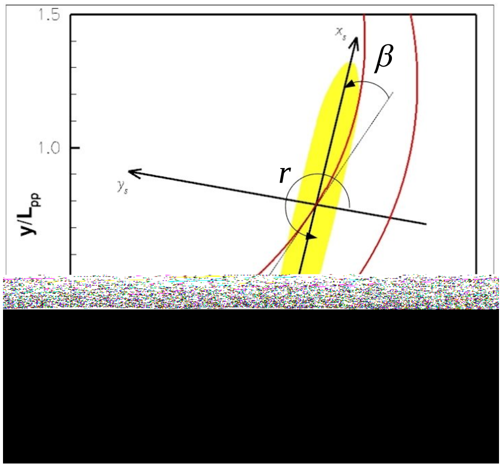

Figure 5. *Earth fixed and body fixed system of references.*

In particular, it has been evaluated the contribution due to: the bare hull, the mobile part of the rudder and the appendages (i.e. the bilge keels, the axis lines (including the brackets) and the fixed part of the rudder). In the upper panel of Figure 6 and Figure 7, the contribution due to the bare hull, the mobile part of the rudder and the hull including the appendages are reported, whereas the contributions due to each individual appendage are reported in the bottom panel of the figures.

At the begin of the manoeuvre, the rudder force (and moment) is predominant to the other contributions; in this transient rudder force provides the necessary disturbance to initiate the turn and to lead the hull to reach an angle of attack with respect to the incoming flow. When the hull is at incidence, hydrodynamic loads on the hull rapidly increase and overwhelm the force and moment provided by the rudder. During this early transient phase (up to around two non-dimensional time units) stern appendages do not have any significant effects; on the other hand, the global propeller lateral loads provide a stabilizing contribution (see Figure 4). By the comparison between the time histories of the yawing moment due to the bare hull and the hull including the appendages, it is evident that the hydrodynamic loads on the appendages reduce the turning quality of the vessel. This is due to the position of the centre of pressure of the hull forces, which is shifted towards the stern, providing a stabilizing moment which counteracts the vessel motion. This is clearly evident observing the moments time history in Figure 7: the hull is unstable (yawing moment is positive) and the appendages modify dramatically the vessel's inherent unstable behaviour. After the rudder action, hydrodynamic forces and moments experience a transient before reaching a stabilized value in correspondence of the steady phase of the turn.

During the stabilized phase, the resultant hydrodynamic moment acting on the vessel is zero, whereas, the resultant lateral force converge toward the apparent centrifugal force (when considering the vessel reference frame) whose contribution is not represented. Regarding the contribution from the stern appendages (bottom panels in Figure 6 and Figure 7), it can be observed that the appendages on the starboard (external) side develop a higher lateral force with respect to the port side ones; this is clearly due to the asymmetric flow field which affects the effective angle of incidence on the two sides. In particular, appendages on the port (inner side) are located in the hull's wake, experiencing a higher ``hull masking effect'', which reduces the effective angle of attack and, consequently, the force developed.

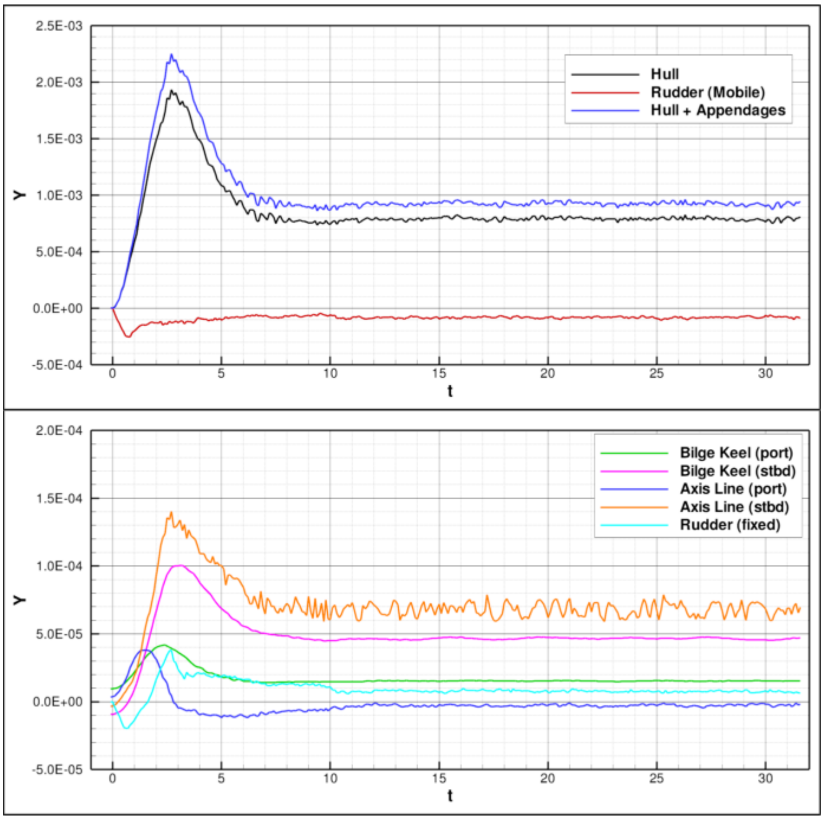

Figure 6. *Time histories of lateral forces developing on hull and appendages.*

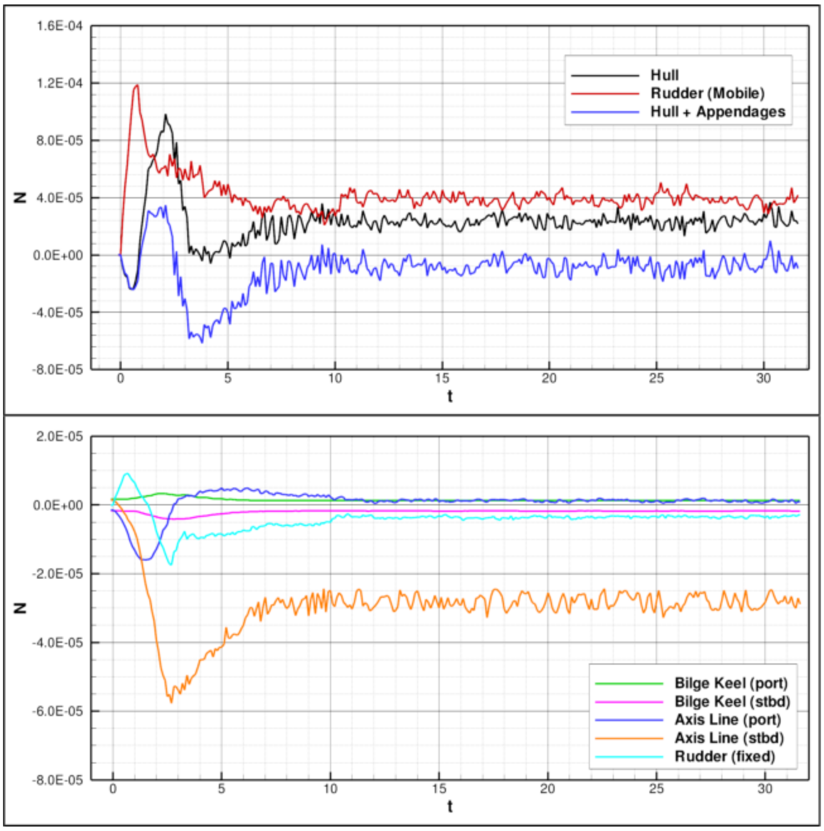

Figure 7. *Time histories of yawing moment developing on hull and appendages.*

In this case, the contribution of the appendages on the internal side is destabilizing, except for the shaft line, whose effect can be considered negligible. Moreover, it should be noticed in Figure 7 that starboard bilge keel does not contributes to the stabilizing moment, because its force is distributed in the central part of the hull and the net stabilizing moment is of the same order and opposite with respect to the internal side one.

For the sake of completeness, in Figure 8 and Table 3 appendages contributions in the stabilized phase are further explained in terms of ratios of appendage force and moment with respect to the hull ones; in the upper panels, partial contributions for each port/starboard appendages and rudder is considered, in the bottom panels total contributions on each side of the vessel are reported. It can be remarked that the internal side globally provide a slight destabilizing effect, vice versa, the appendages on the external side (in particular propeller shaft and propeller) provide a stabilizing effect; moreover, it should be emphasized that, despite the appendages on the starboard side exert a relatively low contribution with respect to the hull force (about *20%*), the resultant moment is of the same order of magnitude of the hull's one. This element further stresses the extreme importance of stern appendages on the manoeuvring behaviour of twin screw vessel, in particular of inherently unstable vessel.

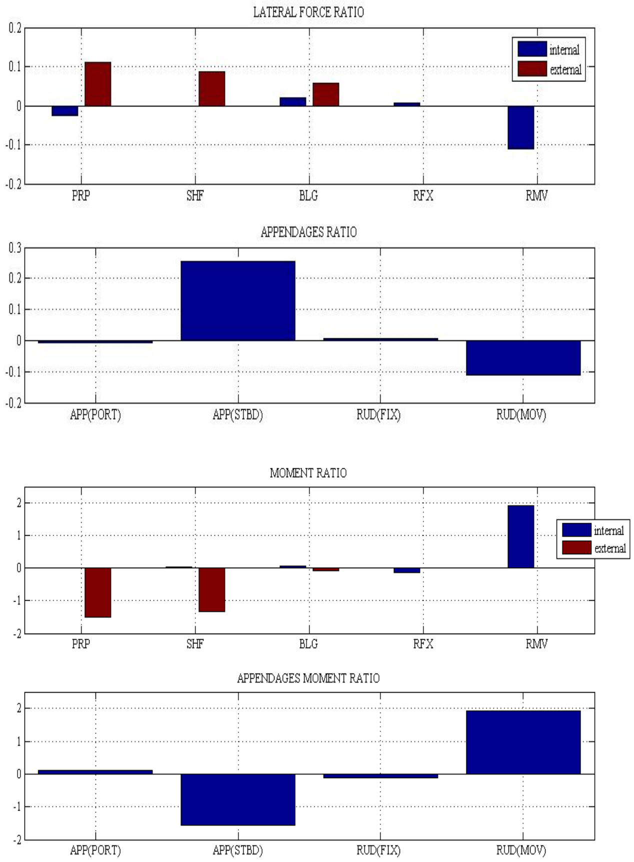

Figure 8. *Lateral force and yawing moment ratios.*

6. CONCLUSIONS

Capabilities of CFD techniques for the prediction of the manoeuvring behaviour of a tanker like vessel characterized by a single rudder twin screw configuration have been analysed. To this purpose, a finite volume unsteady RaNS solver that couples the Navier--Stokes equations to the solution of the dynamic equations of a rigid body have been used. In order to account for the propeller in-plane forces arising during tight manoeuvres, a novel approach has been followed by coupling a generalized actuator disk model with the simplified lateral force model proposed by Ribner. Comparison with experimental results demonstrated that this component should be considered in order to improve the prediction of the ship manoeuvring qualities. Stern appendages contribution to the manoeuvring capabilities of the vessel has been considered by analysing separately lateral forces and resulting yawing moment developing on each appendages. Further studies and research is needed for gaining more insight into propeller off design conditions, like a tight manoeuvre could be considered, in order to develop simplified and computationally efficient models which can be included in CFD solvers in order to improve their ability in evaluating ship's stability and manoeuvring behaviour.

	FORCE RATIO		MOMENT RATIO	
APPENDAGE	STBD - external	PORT – internal	STBD - external	PORT – internal
Propeller (PRP)	*0.11*	*-0.02*	*-1.51*	*0.0*
Bilge Keel (BLG)	*0.058*	*-0.0023*	*-0.08*	*0.0613*
Shaft Axis (SHF)	*0.087*	*-0.0023*	*-1.32*	*0.0379*
Rudder Fixed (RFX)	*0.0077*		*-0.13*	
Rudder Moveable (RMV)	*-0.11*		*1.91*	
Appendage total	*0.256*	*-0.008*	*0.0992*	*-2.91*

Table 3. *Lateral force and yawing moment ratios.*

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