EXPERIMENTAL AND NUMERICAL INVESTIGATION OF ASYMMETRICAL BEHAVIOUR OF RUDDER / PROPELLER FOR TWIN SCREW SHIPS

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THE PRESENT WORK ADDRESSES THE ASYMMETRICAL FUNCTIONING OF RUDDER/PROPELLER COMPLEX OF TWIN SCREW/TWIN RUDDERS SHIPS. A SERIES OF FREE RUNNING MODEL TEST RESULTS ARE ANALYSED, WITH THE AID OF SOME SIMPLIFIED NUMERICAL CALCULATIONS. THIS ANALYSIS ALLOWS TO SHOW THE ASYMMETRICAL PROPELLER LOADING DURING MANOEUVRES AND THE CONSIDERABLY DIFFERENT RUDDER FUNCTIONING. A POSSIBLE SIMPLIFIED MODEL TO INCLUDE THESE EFFECTS IN MANOEUVRING SIMULATORS IS PROPOSED AND DISCUSSED, ALLOWING TO DEFINE THE NEEDS FOR FUTURE RESEARCH ACTIVITIES TO FURTHER IMPROVE THE UNDERSTANDING OF THE DIFFERENT PHENOMENA SHOWN.

INTRODUCTION

Twin screw ships may experience considerably asymmetrical rudder / propeller functioning during manoeuvres [1][2]. This phenomenon may result in large power fluctuations due to asymmetrical propeller functioning during tight manoeuvres, with increases of shaft torque up to and over 100% of the steady values in straight course and considerable unbalances. In parallel to this, also rudder forces and torque may present significant unbalances. The first effect may affect significantly the propulsion system behaviour, especially for those ships having complex configurations, such as some modern naval ships in which a unique prime mover is connected to the two shaftlines by a cross-connected reduction gear. The second effect may be important for a correct design of the rudder and of its machineries. Both effects may affect, more generally, ship manoeuvrability, even if the extent of their importance has still to be investigated.

Considering this, a series of studies have been carried out by CNR-INSEAN, CETENA, UNIGE and Italian Navy during years to have a better insight in the phenomenon. At first, in [3], a series of turning circle manoeuvres at different speeds and rudder angles performed during sea trials for different twin screw ships was analysed. Following this, a joint research project supported by the Italian Navy (PROSSIMA - PROpulSion StrategIes in MAnoeuvrability) has been conducted in the past years. In this project, extensive campaigns of free running model tests and simulations have been carried out in order to provide an insight into these phenomena. At first, the effect of different control strategies during tests (constant RPM, constant torque and constant power) was analysed, providing the results reported in [1]. In this case the analysis was focused mainly on the asymmetrical propeller loading, and led to the development of a simplified correction to be utilised in ship propulsion system and manoeuvrability simulators [4][5], as briefly described in the following sections.

In parallel (and further) to this, a series of direct numerical analyses by means of URANS simulations were carried out by CNR-INSEAN in order to have a further insight into the problem [6]. Despite these calculations were only qualitative, they showed that very complex phenomena are present, with a superimposition of different effects (inclined flow, vortices, ship wake, etc), not considered separately in the simplified model mentioned above, which is built mainly in order to simulate the asymmetrical functioning of the shaftlines during manoeuvres. In order to better investigate this problem, a further joint research project supported by Italian Navy (PROSSIMA2) has been set up, including in this case also the measurement of the asymmetrical rudder functioning. In particular, an additional experimental campaign on the same free running model of a twin-screw ship previously utilised was carried out, measuring torque on the rudder shaft during standard manoeuvres. The results of this campaign are analysed and discussed in the present work, allowing to deepen the understanding of the asymmetrical phenomena which take place at stern of a manoeuvring twin screw ship.

TEST CASE CHARACTERISTICS

The ship selected for present analysis is a fast twin screw / twin rudder ship, whose main characteristics are reported in table 1, where L is ship length, B is ship beam, T is draft, CB is block coefficient. It is not possible to provide complete data of the ship for confidentiality reasons.

TABLE 1 – MAIN DATA OF TEST CASE

L/B	7.5
B/T	3.25
C_B	0.5

EXPERIMENTAL FACILITY AND SETUP

In present section, experimental facility and instrumentation adopted by CNR-INSEAN is briefly described, then the complete list of tests performed is provided.

The experimental activities are carried out on the Nemi's natural volcanic lake located 40 km far from the main CNR-INSEAN branche. It is an ideal location where long-term dead-calm water conditions are frequent in a non-anthropic natural and environmentally protected area. The water surface is large enough to allow the execution on any kind of manoeuvring test regardless the model size and speed. On-board the unmanned model (schematized in Figure 1), each propeller shaft is driven by a dedicated electric brushless motor; in order to simulate a possible cross-connect configuration at the highest speed, both shafts may be linked by a chain and a suitable reduction gear; this was not adopted in present campaign. The whole instruments energy demand is provided by a diesel electric generator. Each shaft line is equipped by a dynamometer for the measurements of propeller loads, namely torque and thrust. The self-propelled unmanned free-running model usually is fully equipped with all the technical devices (DGPS, IMUs, torque and thrusts meters on the propeller axis, dynamo-tachometers, real-time data transmission devices, etc.) necessary to carry out the experimental activities. As an addition, with respect to previous test campaigns, one of the two rudder shafts has been equipped with a torque-meter, in order to have an insight (tough not direct) into the rudder force variation during manoeuvres.

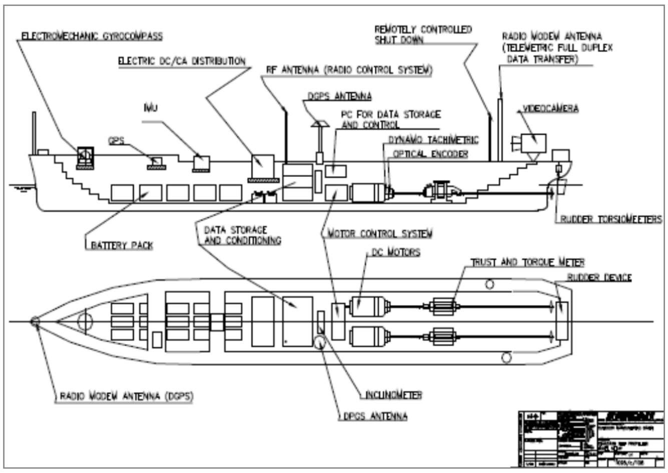

FIGURE 1 – MODEL LAYOUT

The following set of manoeuvres has been carried out at two different speeds (F_N equal to about 0.25 and 0.375):

- Turning circle (± 15°, ± 25°, ± 35°)
- Zig-Zag 10°/10° and 20°/20°

All tests are carried out at constant propeller RPM configuration, which is the standard approach for this type of tests. Since the manoeuvres are the same already considered in [1], tests results may be directly compared with those obtained in the previous campaign, providing a sort of repeatability analysis. Moreover, attention is now given to the rudder torque, which provides a further insight into the asymmetrical functioning during manoeuvres, considering in this case rudder.

EXPERIMENTAL CAMPAIGN RESULTS

As mentioned in previous section, the present experimental campaign reproduced a set of tests carried out previously, allowing to have an insight into the repeatability of results. In the present section, attention is given only to the asymmetrical propeller loading and to rudder torque while some comparative results in terms of main kinematic characteristics are reported in next section when discussing simulation results.

ASYMMETRICAL PROPELLER LOADING

The asymmetrical propeller loading has been analysed with the same approach proposed in [1], which is also the one utilized (though with some modification) in the simulator described in following sections; in particular, asymmetric variations of wake fraction and thrust during manoeuvres are considered.

The asymmetrical wake fraction is given as function of the ship drift angle β and ship speed V, as reported in following equations, where w is the usual wake fraction (during manoeuvre and in straight motion) and Δw is the asymmetrical variation. By means of this corrected wake fraction, the propeller functioning point during manoeuvres is varied.

$$(1-w)_{MAN} = (1-w)_{STRAIGHT} - \Delta w(\beta, V)$$

EQUATION 1

In addition to this, the propeller thrust is further corrected by means of the factor Γ, again function of the drift angle.

$$T_{STRAIGHT} = K_T \rho \bar{n}^2 D^4$$

$$T_{MAN} = T_{STRAIGHT} \Gamma(\beta, V)$$

EQUATION 2

The results in terms of asymmetrical variation of wake fraction and of thrust correction are reported in following figures, comparing results of the two experimental campaigns.

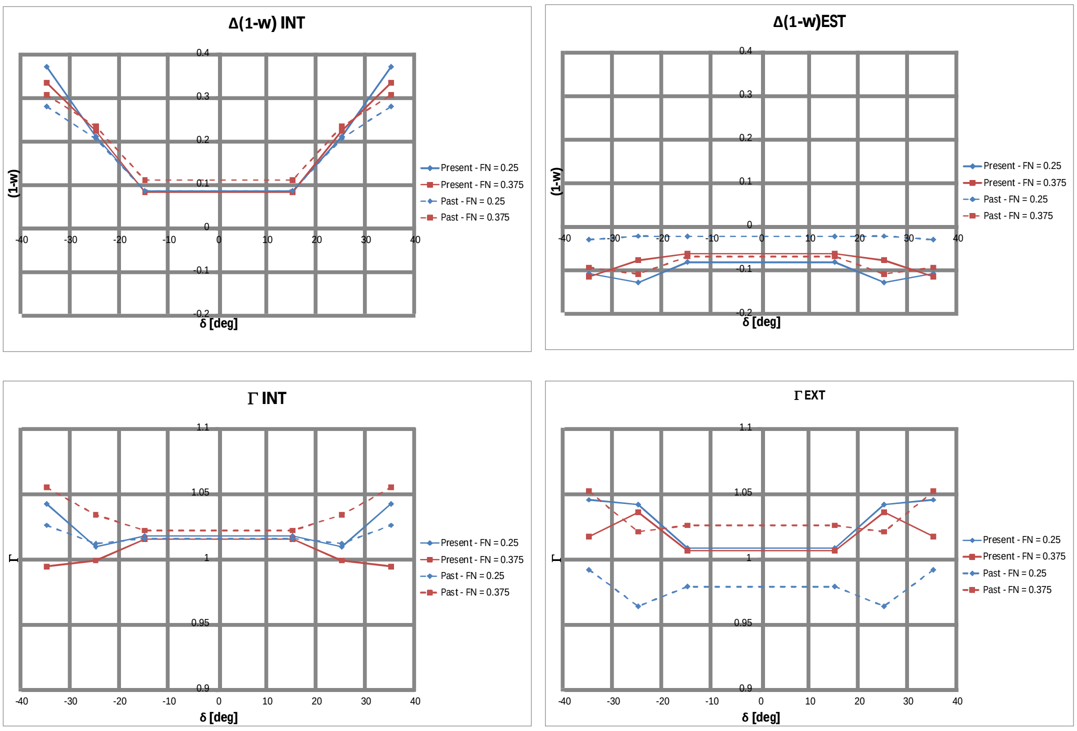

FIGURE 2 – ASYMMETRICAL SHAFT FUNCTIONING

Considering Figure 2, a rather good correspondence between results of present and previous analysis is clear; differences for the two asymmetrical coefficients are small, and in the worse cases around 5%. Considering results, the unbalanced thrust coefficient (1-t)$_{unbal}$ is definitely limited, being lower than 5%. The asymmetrical wake fraction Δ(1-w) is more pronounced, especially for the internal shaft, with values up to about 0.35, while internal shaft presents slightly negative values.

It is worth mentioning that, as already anticipated, the asymmetrical wake fraction variations may be subject to criticism, since their values are opposite to a physically sound behaviour. As already discussed in [1], these values have to be considered only as a simple correction which includes many effects (axial flow variation, effect of tangential flow, oblique flow effect, etc). This approach is useful and straightforward if the purpose is the evaluation of the asymmetrical functioning of the shaftlines from the propulsion system point of view, however it does not allow to represent the real propeller inflow, not even in terms of mean velocity.

The direct introduction of very complex flow characteristics in a manoeuvring simulator was not considered at the moment, however the approach has been modified (see section about the manoeuvring simulator) in order to avoid these unphysical values, keeping in parallel the same characteristics in terms of propulsion system.

RUDDER TORQUE MEASUREMENTS

As already explained, one of the main aims of the present campaign was to measure rudder torque in correspondence to different manoeuvring conditions. The results of the turning circle manoeuvres, in terms of nondimensional torque, are reported in the following figure 3. In particular, torque is nondimensionalised as in equation 1, where Q_{rud} is measured torque, V is ship speed, A_R is rudder area and $\bar{C}$ is the mean chord; in the figure, a positive rudder angle represents the external shaft, while a negative angle represents the internal one. Considering torque signs, a sign concordant with the axis sign represents a torque moment whose effect is to increase rudder angle (center of pressure forward with respect to rudder shaft) and vice versa.

$$C_M = \frac{Q_{rud}}{{}^1\!/_2\,\rho V^2 A_R \bar{C}}$$

EQUATION 3

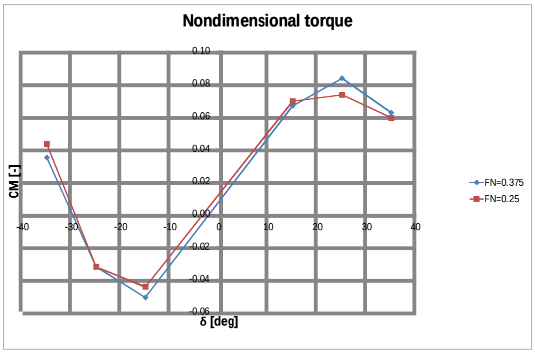

FIGURE 3 – TORQUE MEASUREMENTS

As it can be seen, once made nondimensional, the measured data at the two velocities are in good accordance, confirming that the inflow characteristics are similar for the two cases. It may be remarked that it would be more correct to consider the effective flow at the rudder (inclusive of propeller accelerating effect), however this would need some assumptions (as in the simulator for example) for its calculation, thus it was preferred to consider only ship speed (including velocity reduction in the turn). Since however the percentage of flow acceleration given by the propeller at constant rudder angle is very similar, the nondimensionalisation works properly in making similar the two curves at the two speeds.

As it can be seen, the behaviour of the torque, despite presenting analogies between internal and external shaft, is very asymmetrical. Considering the lower angles, it is clear that the center of pressure is initially located fore with respect to the rudder shaft. With an increasing rudder angle, torque does not increase, due to the effect of a shift aft of the center of pressure (and to a nonlinear increase of lift at highest angle considered). Considering the maximum rudder angle the behaviour is completely different; in the case of the external shaft, torque slightly reduces, even if keeping a nearly constant value; in the case of the internal shaft, torque even changes sign, indicating thus a significant shift towards stern of the center of pressure. The different behaviour is clearly represented in the following figures.

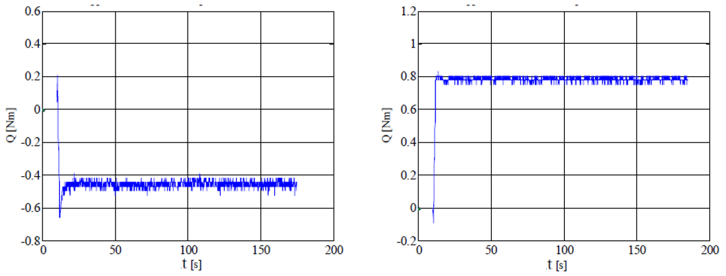

FIGURE 4 – TORQUE SIGNAL – FN = 0.25 - $\delta = 15^\circ$ – LEFT: INTERNAL – RIGHT: EXTERNAL

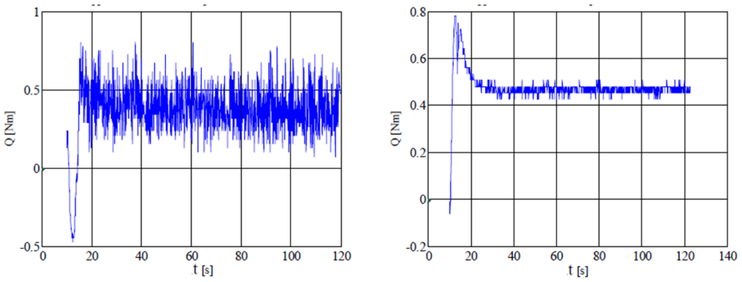

FIGURE 5 – TORQUE SIGNAL – FN = 0.25 - $\delta = 35^\circ$ – LEFT: INTERNAL – RIGHT: EXTERNAL

In order to have a better insight (at least from a qualitative point of view) into this phenomenon, an analysis has been carried out, using some direct numerical calculation (obtained with a simplified RANS model of the rudder-propeller) and the simulator developed during years at UNIGE [5][7].

RUDDER TORQUE ANALYSIS

The analysis of rudder torque results is not simple, since unfortunately rudder torque is, obviously, dependent on two parameters, i.e. rudder normal force and force lever arm, thus infinite (in principle) combinations of them may provide the same result. Moreover, rudder functioning is also affected by the inflow characteristics, which in their turn are due to ship kinematics, effect of hull on the wake and propeller asymmetrical functioning. In order to partly overcome this problem, a further campaign is already planned, in which the rudder force will be directly measured, while in the present campaign only the torque measurement was carried out. Nevertheless, since results are already interesting, they have been analysed by means of some assumptions, summarized in the following.

In general, the asymmetrical results may be due to different causes:

- different behaviour of internal / external propeller due to different inflow
- different behaviour of the rudders due to different inflow (with interactions with propellers and hull)
- different location of the rudder center of pressure

The asymmetrical behaviour of the propellers and its effect on the rudder have been considered by means of the modified mathematical model for the shaftlines unbalance (see next section). The rudder / hull interaction is taken into account by means of the well known flow straightening coefficient, which is used in order to reduce the local drift angle; the local drift angle, in its turn, is used in order to evaluate the effective rudder angle, as reported in following formulations, where δ_{eff} is he effective rudder angle, δ is the geometrical rudder angle, β_R is the local drift angle at rudder location, evaluated as a function of sway speed v, yaw rate r, longitudinal speed at rudder c (inclusive of propeller accelerating effect) and of the two flow straightening coefficients γ_v and γ_r.

$$\delta_{eff} = \delta - \beta_R$$
$$\beta_R = \frac{(\gamma_v v + \gamma_r X_{RUD} r)}{c}$$

EQUATION 4

On the basis of the previous results, it could be hypothesized that the flow straightening effect for the two rudders is asymmetrical, thus the analysis has been focused on this. At first, open water rudder/propeller functioning has been simulated by means of direct numerical calculations carried out with a commercial RANS code, allowing to evaluate rudder normal force and force lever arm in correspondence to different rudder angles.

Then, the manoeuvring simulator (or rather its mathematical model) has been adopted, imposing rudder forces provided by RANS calculations, kinematic parameters recorded during tests and considering the flow acceleration effect of the propeller. Data have been then compared considering various (and asymmetrical) values of the flow straightening coefficient, in order to find those which allow to match better the results. This analysis is clearly very simplified and affected by many uncertainties, however it allowed at least to show a tendency, which needs to be further confirmed in future activities.

MODIFIED MATHEMATICAL MODEL

The simulator consists of a set of differential equations, algebraic equations and tables that represent the various elements of the propulsion system and manoeuvrability behaviour of the model, including the propulsion system.

The following differential equation, where J_p is the shaft line polar inertia, Q_e is the engine Torque, Q_p is the propeller Torque, Q_f is the torque due to the friction, n is the shaft line revolution, is used to simulate the shaft lines behaviour, in terms of time histories of propulsion system behaviour (power, torque, RPM, etc.).

$$2\pi J_p \frac{dn(t)}{dt} = Q_e(t) - Q_p(t) - Q_f(t)$$

EQUATION 5

Ship kinematics are evaluated as usual by means of the three differential equations for surge, sway and yaw ship, where u is the surge velocity, v is the sway velocity, r is the yaw velocity, m is the ship mass, I_{zz} is the mass moment of inertia with respect to vertical axis, x_G is the longitudinal position of the center of gravity, X, Y and N are longitudinal and lateral force and yaw moment (the subscript H, P and R representing hull, propeller and rudder parts), $X_{\dot{u}}$, $Y_{\dot{v}}$ and $N_{\dot{r}}$ are acceleration derivatives.

$$
\begin{aligned}
X_H + X_P + X_R &= (m - X_{\dot{u}})\dot{u} + m(-vr - r^2 x_G) \\
Y_H + Y_P + Y_R &= (m - Y_{\dot{v}})\dot{v} + m x_G \dot{r} + mur \\
N_H + N_P + N_R &= m x_G \dot{v} + (I_{ZZ} - N_{\dot{r}})\dot{r} + mux_G r
\end{aligned}
$$

EQUATION 6

The complete description of the model is reported in [5][7] and is omitted in present work for the sake of shortness, while the model used for propeller rudder asymmetrical functioning is briefly described. As mentioned, the approach proposed in [1] was slightly modified in order to limit some unphysical effects on the rudder: a sort of hybrid approach has been used, in which asymmetrical wake fraction and thrust deduction factor are used for the propulsion system part, allowing to consider the propeller loading and thus shaftline thrust/torque and engine load, but not for the evaluation of rudder inflow.

In particular, for the evaluation of the flow velocity at the rudder, the flow at propeller is evaluated without any wake fraction variation and the asymmetrical effect is only given by the thrust, which is evaluated as proposed in [1]; this approach, despite being very simplified and also partially not coherent for propeller and rudder, allows to avoid unwanted effects on the rudder (e.g. with accelerated flow on the internal shaft).

In order to evaluate the longitudinal speed at the rudder including propeller effect, Equation 7 is adopted, in which A_P is the rudder area in the propeller slipstream, A_R is the rudder area, u_{corr} is the accelerated flow in the propeller race.

$$
c^2 = \frac{A_P}{A_R}\left[u_{corr}(x)\right] + \frac{A_R - A_P}{A_R}\left[u(1-w)\right]^2
$$

EQUATION 7

The value of u_{corr} is obtained evaluating at first the propeller slipstream acceleration by means of actuator disk theory, where $u_{A\infty}$ and u_{RUDDER} are the velocity at infinite downstream and at the rudder respectively.

$$
u_{A\infty} = \sqrt{(1 - w + \Delta(1-w))^2 \cdot u^2 + \frac{8}{\pi} \cdot \Gamma(\beta, \mathrm{V}) \cdot K_T \cdot (n \cdot D)^2 - (1 - w + \Delta(1-w)) \cdot u}
$$

$$
u_{RUDDER} = K \cdot u_{A\infty} + (1-w) \cdot u
$$

EQUATION 8

Equation 8 in particular shows the hybrid model, where it can be seen that the flow acceleration is computed considering asymmetrical propeller functioning (by means of corrected thrust), while the velocity at the rudder is then evaluated adding the propeller acceleration to the rectilinear velocity, which includes only the usual wake fraction (not modified by the asymmetrical wake).

Then the following corrections due to turbulence effect [8] are added.

$$\Delta r(x) = 0.15 \cdot x \cdot \frac{u(x) - u(1-w)}{u(x) + u(1-w)} \qquad u_{corr}(x) = [u(x) - u(1-w)] \cdot \left(\frac{r}{r + \Delta r} \right)^2$$

EQUATION 9

NUMERICAL CALCULATIONS

As anticipated, a series of preliminary RANS calculations adopting the commercial code StarCCM+ have been carried out in order to simulate the rudder functioning in different conditions. In particular, rudder (plus fixed basement) alone and rudder / propeller configurations have been considered; in the second case a uniform inflow speed has been adopted; propeller RPM have been set in order to have thrust identity with the experimental measurements in the steady rectilinear approach phase before maneuvering. From this point of view, obviously during manoeuver the ship speed changes, as also propeller thrust and in general inflow to the rudder/propeller system, however the analysis was carried out in order to have a first insight into the problem. In future, further analyses and improvements are certainly needed, but the present approach is considered already acceptable for an initial investigation.

In the numerical calculations, the propeller effect has been simulated by means of an actuator disk with radially varying load. This configuration, despite being simplified and “computationally cheap” has proven to be able to provide reasonable results in term of global and local force, as discussed in [9], where approaches of different complexity (from simple uniform actuator disk to full RANS) were compared. A polyhedral unstructured mesh was adopted, considering a domain extending about 4 chord lengths upstream of the rudder, about 6 chord lengths downstream, about 4 chord lengths in the lateral direction and 3 times the rudder span below the rudder. The domain dimension have been set in accordance with the boundary non influential condition. The side, top and bottom boundaries are considered as walls with slip condition, while upstream and downstream a velocity inlet and a pressure outlet are imposed. For a better resolution of flow around the rudder/propeller geometries different refinements have been adopted, as visible in Figure 6. A total of about 850k cells was adopted in the resultant mesh for a mean cell value of 4 mm near the blade. Even if the mesh used is still rather coarse, the set-up is comparable with the one adopted in [9] where a similar geometry has been successfully compared with experimental results. To reduce the computational cost each simulation has been carried out with a steady solver. This assumption can be used also for the propeller presence due to the simplified model adopted. In the stall region the unsteadiness can obviously generate some discrepancy but, as showed in [9], within the expected confidence for a preliminary analysis.

In Figure 7 the results in terms of non-dimensional normal force and lever arm at the rudder shaft (in model scale) are reported for the two cases of rudder alone and rudder in the propeller slipstream. The normal force coefficient is calculated as reported in equation 10, where N is the rudder normal force, while the position of the center of pressure along the chord CP_c is given as a percentage of the mean chord; in this case, the reported distance is measured with respect to the rudder shaft.

$$C_N = \frac{N}{{}^1\!/_2\,\rho V^2 A_R}$$

EQUATION 10

As it can be seen, in both cases (with and without propeller effect) the rudder stall is clear due to the sudden decrease of force; the propeller effect tends obviously to increase the rudder force and also to slightly delay stall, which occurs at about 25° rudder angle. Considering center of pressure position, a very fast shift aft of the center of pressure after stall is evident, as expected. Due to this, slightly above 30° rudder angle the torque changes sign, with the center of pressure moving aft the rudder shaft.

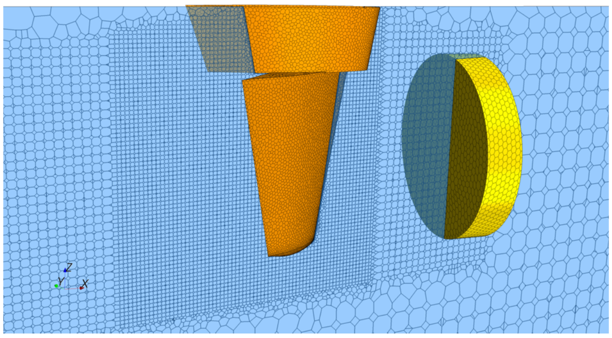

FIGURE 6 – RUDDER/ACTUATOR DISK CONFIGURATION: MESH SETUP

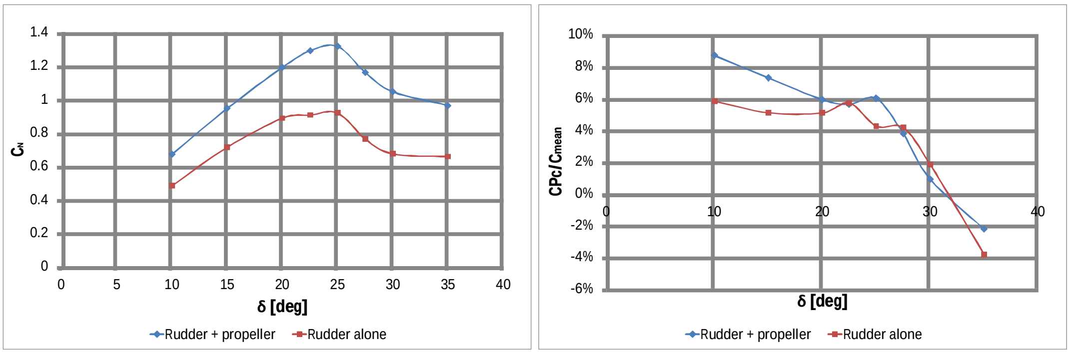

FIGURE 7 –NORMAL FORCE COEFFICIENT (LEFT) AND CHORDWISE CENTER OF PRESSURE (RIGHT)

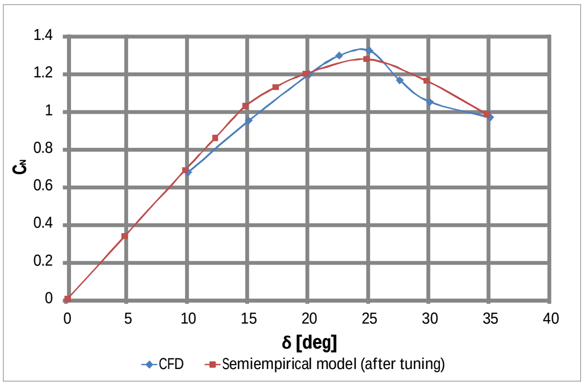

FIGURE 8 –COMPARISON BETWEEN NORMAL FORCE FROM CFD CALCULATIONS AND SIMPLIFIED MATHEMATICAL MODEL (AFTER TUNING)

The results of the CFD calculations have been used to tune the semiempirical model adopted in the simulator, in which rudder stall is considered in a simplified way (see [5]). The normal force provided by the tuned mathematical model in correspondence to different rudder angles is reported in Figure 8, together with the CFD results. The analysis of the experimental results was carried out using the tuned mathematical model and considering the force lever arm at different rudder angles as a term of comparison, as reported in following paragraph.

APPLICATION TO EXPERIMENTAL RESULTS

The mathematical model previously described has been adopted, together with some of the numerical results previously described, in order to analyse the experimental results. In particular, as anticipated, it has been assumed that the tuned mathematical model is able to provide reasonably accurate rudder forces, taking into account the influence of the propeller slipstream in different conditions. Then, knowing the experimental value of torque on the rudder shaft for the different manoeuvres carried out, the required lever arm needed in order to obtain it given the rudder force was evaluated; this, in its turn, was compared with the numerical result. In particular, the stationary part of the turning circle manoeuvres was considered for this analysis, and the flow straightening coefficient values were varied, trying to obtain a similar trend for the lever arms required in the semiempirical model and the ones resulting from the CFD calculations. It has to be remarked that this analysis was carried out modifying the original flow straightening coefficient values (evaluated according to [10]) by means of a unique factor K, considering the general trend and not the various rudder angles individually.

Different values of the K factor were tested; those which provided the best tendency (tough still not completely satisfactory) are K=0 for the internal shaft (complete straightening, i.e. effective rudder angle equal to geometrical rudder angle) and K=0.7 for the external shaft. In the following Figure 9 the lever arms obtained in correspondence to the two Froude numbers considered are reported. In the two figures, the tendency lines are also reported, for a better comparison. As it can be seen, for the internal shaft the tendencies are respected, with the lever arm changing sign, even if at lower rudder angles a difference of about 2% of the mean chord is present, progressively reducing towards the maximum rudder angle. For the external shaft a better correspondence seems to be present.

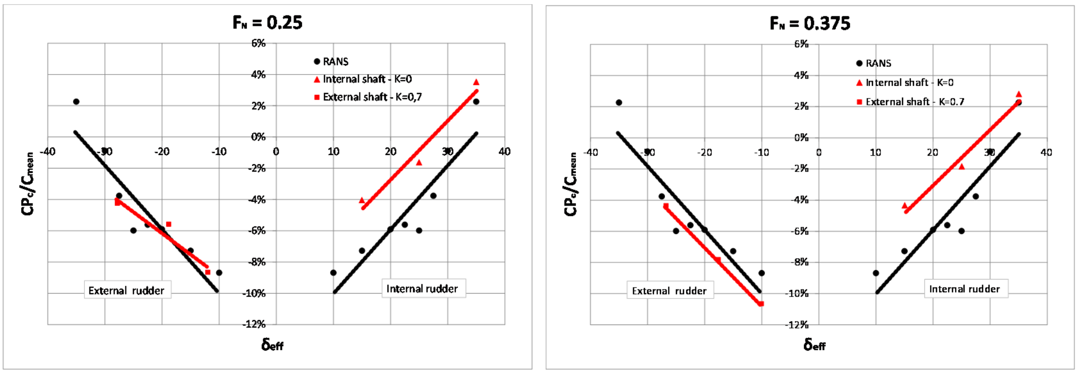

FIGURE 9 –LEVER ARMS EVALUATED BY CFD AND SEMIEMPIRICAL METHOD

It has to be remarked that, as anticipated, the results presented are only a qualitative analysis, with residual differences still present. A more detailed calibration for each individual condition, however, would have led to strongly variable values of the flow straightening coefficients, probably due to the presence of different effects, thus it was decided to avoid it in present work.

As a general trend, the tendency towards a very marked straightening for the internal shaft seems reasonable, since the effect of the hull on the internal shaft may result in a strong reduction of the lateral flow components. However, obviously the analysis completely neglects the effects on the ship wake, which are certainly significant for the internal shaft.

For what regards the external shaft, the result is not in line with what was expected. In this case, the external position of the shaft would suggest a rather low straightening; on the contrary, the resultant K factor tend to further reduce the coefficients proposed in [10]. It has to be remarked that similar results might be obtained also without modifying the original flow straightening coefficients (K=1), however also this is not in line with the expected low straightening.

As a matter of fact, therefore, it is again evident that the present analysis, despite providing already useful results, has to be further deepened. This leads to the necessity of additional experimental campaigns and / or numerical investigations. The experimental setup should be further enhanced, including rudder lateral force to avoid the ambiguity of present data; in addition to it, direct flow measurements could provide unvaluable data for numerical calculation validation and in general for a better understanding of the flow at stern. Numerical calculation complexity should be significantly increased, including at least the effect of a constant oblique flow in the results; this, however, would be probably not sufficient, with the necessity of complete numerical calculations, at least considering the kinematics in the steady turn (in terms of longitudinal and lateral velocity and yaw rate).

Since anyway the present analysis already provided some indication, a series of simulations have been carried out, allowing to compare the initial model with the modified one, including also the asymmetrical values of the flow straightening coefficient.

SIMULATIONS

In order to analyse the possible effects of the discussed phenomena on ship manoeuvrability, a set of simulations with modifications to the mathematical model has been carried out.

In particular, following models have been considered:

- Model 0: original model (asymmetrical wake fraction for propeller and rudder inflow)
- Model 1: modified asymmetrical wake fraction: effect only on propeller inflow, rudder inflow dependent on straight line wake fraction plus asymmetrical propeller acceleration
- Model 2: as model 1, plus asymmetrical flow straightening coefficient.

In figures 11 and 12 some parameters of the two manoeuvres (in correspondence to the lower velocity) are reported, namely advance and tactical diameter as a function of rudder angle for the turning circle and overshoot angles for the ZigZag (actual numerical results are not provided for confidentiality reasons). In all cases, the models do not include any effect of roll on the manoeuvre and the rudder model adopted is not tuned.

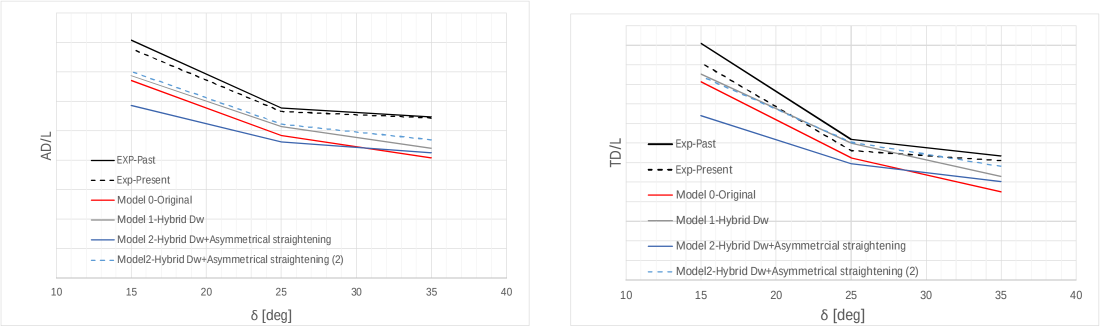

FIGURE 10 – TURNING CIRCLE MANOEUVRE - COMPARISONS OF DIFFERENT MODELS – F_N = 0.25

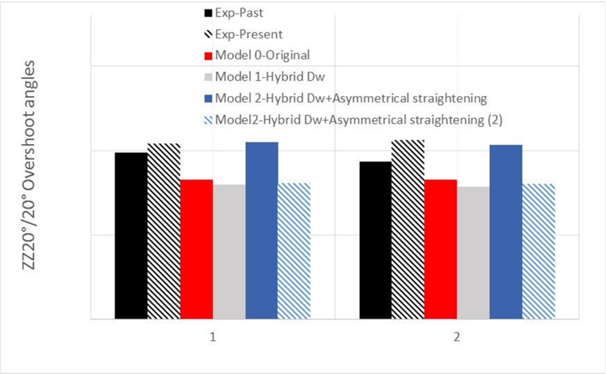

FIGURE 11 – ZIGZAG MANOEUVRE - COMPARISONS OF DIFFERENT MODELS – F_N = 0.25

Results from the different models are compared to each other in order to appreciate the relative variation; in particular, the original model is represented by the red curve, the modified model (with the hybrid use of the asymmetrical wake fraction) is in grey, the model with the asymmetrical flow straightening (as obtained from the analysis reported in previous paragraph) is in blue. For what regards Model 2, a further set of simulations is reported with modified values (dotted blue lines) for the external shaft, as reported in the following. Moreover, also the experimental data of the two campaigns are reported, in order to appreciate their repeatability.

As it can be seen, the mathematical model adopted, with the regressions developed for twin screw ships [11], which in different cases behaved very satisfactorily [7], is not completely satisfactory in the present case, leading to narrower turning circle manoeuvres and to lower values of the overshoot angles; these two tendencies, moreover, are opposed to each other from ship manoeuvrability point of view, being typical of a more unstable and a more stable ship respectively. The two variations applied result in different modifications of the results; the initial change of the effect of the asymmetrical wake fraction results in a globally less accelerated flow to the rudders (due to the elimination of the fictitious flow acceleration for the internal shaft); this, in its turn, results in a reduction of the rudder force, and thus in a global increase of the turning circle parameters, progressively more marked at higher rudder angle due to the higher values of the asymmetrical wake fraction. For what regards the asymmetrical flow straightening coefficient, it results in an internal rudder stalling at maximum rudder angle, while at lower rudder angles the main effect is to increase the effective rudder angle. As a consequence, at lower rudder angles turning circle is narrower, while at larger rudder angles the manoeuvre is almost not changed. Despite still presenting a considerable discrepancy with respect to experimental results, it is clear that the relative tendencies at different rudder angles are better captured. Possible reasons for the discrepancies are both a not correct simulation of the hull and rudder forces and a wrong value of the external shaft flow straightening, which as discussed before appears too large. In order to investigate qualitatively this effect, a further set of simulations has been carried out, imposing an extreme value of 1 to the flow straightening coefficient of the external shaft (no straightening). This simulation allows to underline the importance of this parameter on the ship manouevrability, with considerably larger turning circle trajectory and results more in line with experiments, with a residual discrepancy in the advance.

Regarding the ZigZag manoeuvre, the introduction of the first two modifications of the model result in a better capturing of the overshoot angles. On the contrary, the artificial modification of the flow straightening coefficient of the external shaft in this case results in a worsening of the results. It is worth mentioning that in all cases a further discrepancy between the simulated and experimental manoeuvre is present (tough not reported) since the simulated period is lower (by about 15%) than the experimental one. This result, together with the higher discrepancy in the advance of the turning circle manoeuvre, suggests that the model is not fully capable of capturing some dynamic effects in the transient.

CONCLUSIONS

In present work, the problem of twin screw ships asymmetrical functioning of the rudder-propeller complex has been considered. In particular, results of an experimental campaign (free running model tests) have been presented, focusing attention on manoeuvre parameters, asymmetrical shaft functioning and asymmetrical torque on the rudder shaft.

Rudder torque data have been analysed with the aid of some numerical calculations, allowing to remark an evident asymmetrical behaviour, leading to different flow straightening effects on the two rudders. The results seem qualitatively correct for the internal shaft, with a considerable straightening; for the external shaft, for which a rather low straightening could be expected, results are not satisfactory, with too large apparent straightening effects. The latter result could be due to the oversimplified analysis carried out, in which the rudder / propeller forces in open water are considered, without taking into account the possible influence of oblique flow and, in general, of hull wake. Notwithstanding this, the simulation results show that the tendency provided by the simplified analysis, at least in correspondence to the higher rudder angles, seems qualitatively good. The introduction of a more sound (even if probably exaggerated) value of the flow straightening coefficient for the external shaft confirms the results obtained. However, significant differences are still present in simulations, especially for what concerns the transients showing that the regressions analysis adopted in this case partially fail to correctly capture the hull and rudder forces, contrarily to previous experiences [7]; results are in this case in line with worst possible cases indicated in [11], showing the need for further developments.

In order to enhance the analysis presented in this work, in future further experimental tests will be carried out, including also the direct measurement of rudder force in addition to torque. Moreover, the effect of lateral propeller force, already measured in [12] will be analysed, substituting the current simplified approach which adopts Ribner theory and considering also alternative methods.

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