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Off-Design Propulsion Power Plant Investigations by Means of Free Running Manoeuvring Ship Model Test and Simulation Techniques

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ABSTRACT

Twin screw vessels' propulsion system experiences strong off design conditions during tight manoeuvres due to the propellers inflow asymmetry arising from the coupled yaw-drift motion. Unfortunately, simplified mathematical models based upon statistical data or ad hoc executed captive model test (PMM or CMT) do not provide such a detailed information. Indeed, free running model tests are the best mean in order to get ship's trajectory and kinematics parameters data and propulsion behaviour by recording the loads (thrust and torque) on the shafts. More insight into this complex aspect is desired in order to improve and generalize the application of existing manoeuvring mathematical models for the preliminary design of unconventional propulsive configuration control system.

KEY WORDS: Twin screw vessels manoeuvring, Free running model tests, Propulsion, Propeller asymmetrical loading modelling, Blade element momentum model, simulation.

INTRODUCTION

In last years ship manoeuvring has reached increasing interest among the Naval Architects community due to strict safety requirements during navigation and during critical operations such as manoeuvring in restricted areas; moreover naval vessels should be provided by a suitable manoeuvring behaviour in order to accomplish their task. In order to satisfy minima requirements provided by international regulations (such as IMO and ANEP 70 for naval ships), ship manoeuvrability has to be properly evaluated since the first design phases; in recent years semi-empirical based simulation tools have been refined and provided invaluable help to the designer. However, due to extreme complex phenomena involved in a such extreme off design condition and to the lack of information provided by simplified semi-empirical methods, free running model test experimental activity is the best way to obtain the closest prediction in terms of trajectory geometrical characteristics recorded during the ship trials. Moreover, the marked variation of the flow field around the hull, due to the coupled yaw-drift motion, changes significantly the propeller inflow and as a consequence, the propulsion power plant working regime: during tight manoeuvres propeller loading could increase to values critical for the various components of the propulsion system (shaft, shaft bearings, reduction gear, prime mover). In this work the principal features of free running model tests carried out at the INSEAN Manoeuvring Basin on a limited series of multi-screw naval vessel will be described and the results will be discussed. The main task of this work is devoted to gain more insight into the strong interaction between ship dynamics and propulsion power plant during manoeuvring; to accomplish this task, each shaft is equipped with a torque dynamometer installed between the electrical prime mover and the propellers and the loads are recorded during the manoeuvres (turning circle and zig-zag). Due to the recent interest to analyse systematically this complex aspect, further experimental data relative to an enlarged set of twin screw vessels are needed in order to statistically define the asymmetrical shafts overloading. In order to include such a complex phenomenon in simplified mathematical models mainly utilised for trajectory predictions (whose characteristic parameters are ruled by international regulations), propeller hydrodynamic description by means of sole open water test and propulsive coefficients evaluated at straight ahead condition should be improved. This can be ahcieved, modelling more realistic (but, at the same time simplified for their inclusion in system based manoeuvring models) wake distributions that arise during a general manoeuvre in the stern leeward and windward side. Moreover, the effect of oblique flow on propellers hydrodynamic performance may be also added. A simple representation of this complex phenomenon could provide invaluable aid during the first design phases for reliable and safer sizing of the complete propulsion system devices (including the control system mean), and, moreover, could provide an improvement of traditional manoeuvring mathematical models and extend their use for a broader analysis of the ship manoeuvrability problem.

SHIP MODELS OVERVIEW AND RESULTS

Free running model tests provide the best estimation of the ship manoeuvring capabilities, because of its fidelity to the full scale trials, except for inevitable viscous scale effect due to Froude similarity. In fact, simplified system based mathematical models are valuable tools in the preliminary design phases, however they could lead to misleading predictions in case of novel hull configurations, in terms of hull form and stern appendages configurations (the latter property has been shown to be of particular importance in case of twin screw vessels (*Viviani 2009*)). CFD, despite being very promising, is too time consuming to be systematically applied in the first design phases for numerical simulation of free running numerical (virtual) manoeuvres;

this novel technique may be successfully applied for the computation of hydrodynamic loads (hydrodynamic coefficients) employed in the traditional manoeuvring mathematical model, performing numerical oscillatory tests whose execution needs much less computational effort. Moreover, as introduced above, being the model self propelled, propulsive off design conditions could be systematically investigated in order to determine the most critical loading conditions encountered by the ship during its operational life. In particular, propulsion system behaviour is hardly stressed during turning circle at the highest rudder angle or during crash-stop manoeuvre, due to the modified propeller inflow character.

In this work only turning circle manoeuvres are considered, because of their safer systematic execution during an experimental campaign and because of their higher frequency during ship operation, in particular in the case of naval vessels. In recent years various authors attempted to gain more insight into propulsion system off design conditions: Kuiper (2002) attempted at investigating propeller inflow during tight manoeuvre of a three screw frigate by means of PIV, Nagamoto (1992) carried out LDV measurements of the propeller inflow on a ship model executing the first transient phase of the a turn. Atsavapranee’s (2010) PIV measurements show clearly the structure of the flow near the stern region of the fully appended DDG51 model while performing a turn by means of the Circular Motion Tests (CMT). In Viviani (2007)(2010) it has been concluded that the external and internal shafts could reach overloading up to 90% and 30-50% respectively at full scale; these values are reduced at model scale (70% and 10-20%). In Viviani (2008, 2010) interactions between a manoeuvring vessel and the propulsion system is investigated by means of simulation techniques; in particular, the propulsion device is modelled and opportunely included into a hydrodynamic based module describing the ship motion under rudder action in order to develop a reliable tool in the first design phases of automation control system of unconventional propulsive configurations.

In Tab. 1 the main dimensional characteristics and approach speed in terms of F_N of a limited set of twin screw naval vessels are reported. It should be remarked that the principal aim of this work is to show the improvement and development of a suitable free running model experimental set up in order to deepen knowledge about off design conditions arising during critical operational phases of ship’s life; therefore it is believed that the data set shown is adequate for this purpose.

Table 1. Non dimensional geometric characteristics and tested Fn

SHIP	**L/B**	**B/T**	**C_B**	**F_N**
A	7.87	3.6	0.492	0.23-0.4
B	6.76	3.35	0.469	0.38-0.66
C	7.55	3.05	0.5	0.25

Power propulsion plant demand is dictated principally by the instantaneous operational propeller working condition. During a tight manoeuvre, the flow around the hull is strongly modified because of the lateral and rotational motion; in particular, in the case of a twin screw ship, the asymmetrical wake distribution among the leeward and windward side determines the propellers’ asymmetrical behaviour. Indeed, propeller loading condition is strongly correlated to the hull manoeuvring behaviour and consequently to its attitude during the stabilized turning phase in terms of kinematics parameters. In Tab. 2 principal results of turning circle manoeuvres performed at various F_N are summarized; shaft revolution during all the manoeuvre are maintained constant. It should be noticed that a larger number of parameters are usually considered when evaluating the turning performance (like advance, transfer, time to reach 90° and 180° heading); however, in this case only those terms affecting mostly the dynamic behaviour during the stabilized turn phase and, consequently, the propulsion system response have been considered. It could be evidenced by previous Tab.1 and Fig.1 (where only turning circle manoeuvres at low Fn are reported), analysing ship A results, that turning circle diameter and speed drop experience slightly variation in the range of F_N analysed; however, this is not the case for ship B, which experience a loss of turning ability at the highest F_N.

Table 2. Geometrical and kinematics turning circle results

SHIP	**D_T/L**	**r’**	**U_S/U_0**
A F_{Nmin}	3.455	0.583	0.71
A F_{Nmax}	3.58	0.577	0.69
B F_{Nmin}	2.755	0.735	0.657
B F_{Nmax}	3.5	0.509	0.685
C	4.294	0.486	0.742

It is believed that this marked behaviour could be related to a variation of the wave generated lateral force distribution along the hull. Finally it is also clear that ship C is the more stable one (higher turning circle). Despite its geometric similarity with ship A, manoeuvring capabilities denote a marked difference, in particular determined by stern form and stern appendages configurations (rudders type and size, presence of centreline skeg).

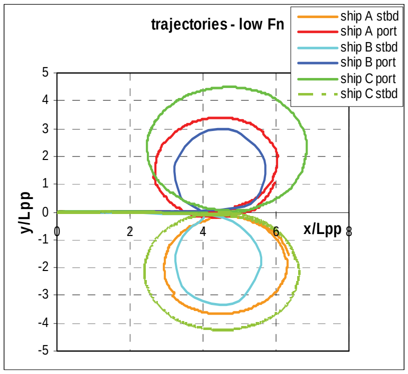

Fig. 1 – Turning circle trajectories (free running model tests)

Turning properties deduced from turning diameter are confirmed by the non dimensional absolute speed (relative to the approach value) and turning rate in the following Figs.2-3, respectively; the speed reduction during turn is evident, similar in case of ship A and C, and higher in case B; speed drop is strictly related to the hull geometric drift with respect to incoming flow during the stabilized phase of the turning: the lower the ratio, the higher the drift angle and the yaw speed, and consequently the turning ability. Moreover, despite the similar speed reduction, the marked difference in turning diameter is caused by discrepancy in yaw speed (higher for the former one).

In case of ship A, moreover, the model has been equipped with transducers between the shafts and the two electrical propulsion motor, in order to analyse prime mover power demand during critical off design conditions. In Fig. 4 non dimensional propeller torque absorption (with respect to the approach phase value) for internal and external shaft at the two F_N tested is reported. For the sake of clarity, the internal shaft is the leeward one, i.e. the one closer to the turning centre; viceversa, the external shaft is the windward one; this convention will be maintained in the following description.

It could be evinced that during a manoeuvre a different torque demand is experienced; in particular, at both F_N the external shaft is more loaded with respect to the internal one. Moreover, it could be noticed that the torque demand is higher for both shafts at the higher F_N, despite their unbalancing is approximately halved in comparison to the lower speed case. Similar results have been confirmed in previous works (*Shulten 2005*)(*Viviani 2007*), where the external shaft experienced higher torque demand with respect to the internal one.

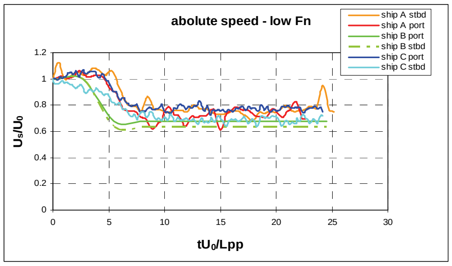

Fig. 2 – Speed reduction (with respect to approach speed) during turns

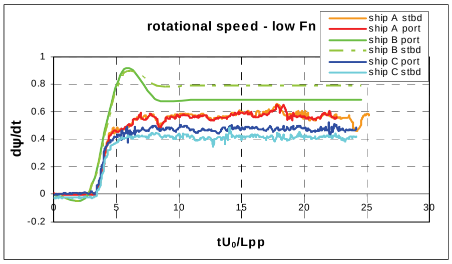

Fig. 3 – Turning rates (non dimensional) during manoeuver

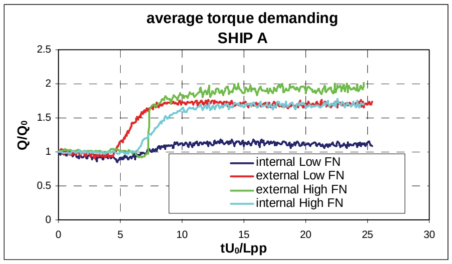

Fig. 4 – Torque demand increase during turn – vessel A

This behaviour has been detected in both cases of inboard (from above) and outboard propeller rotation (when seen from astern). On the contrary, in the valuable work of Atsavapranee (2010), propellers experience an opposite unbalancing trend, namely the internal one is more loaded with respect to the external; in this case propeller rotation is opposite with respect the one adopted in the present model, which seems to be a determinant effect. However, further systematic experimental work is needed in order to understand and generalize the propeller's unbalancing behaviour during manoeuvres, and relate it to hull/stern geometric features. As an example, on the basis of data from sea trials on a ship with propeller rotation equal to the one in Atsavapranee, a trend in torque increase similar to the one evidenced in this work has been experienced.

EXPERIMENTAL SETUP IMPROVEMENT AND PRELIMINARY RESULTS

In order to improve measurements system, as a preliminary attempt, model C has been installed with shaft dynamometers aiming at investigating thrust variation during a tight manoeuvre.

In Fig. 5 it is evidenced that external shaft's thrust obeys to a different increment with respect to torque because of differences in K_T and K_Q slopes and thrust deduction factor increase; on the contrary, internal shaft seems to be not affected during the manoeuvre in terms of both loads, despite in the first transient phase a trough can be easily evinced.

This improved configuration has been adopted for an extensive campaign of free running manoeuvring tests on a twin screw model similar to this one, and are still on course. Due to particular propulsion power plant installed at full scale (gas turbine connected to the shaft via a reduction gear), an accurate knowledge of propellers asymmetrical overloading phenomenon is demanded in order to design the more suitable automation control system in order to preserve the integrity of the propulsion system. In fact such a configuration is critically stressed during a tight manoeuvre because the reduction gear is characterised by alternating loads (due to the propellers asymmetrical loading) and, as a consequence, the automation control system action is vital in order to prevent possible damages.

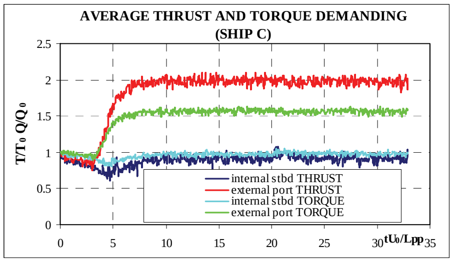

Fig. 5 – Thrust and Torque demand increase during turn – vessel A

In order to obtain results more similar to the full scale trials, simulating machinery and automation behaviour, a novel controller has been included in the model propulsion system; in this case, in addition to the usual constant RPM test, manoeuvers obtained with constant prime mover torque and power could be carried out in order to have more insight into automation control strategy and its influence on the manoeuvring performance, a fundamental aspect mainly for multi purpose naval ships.

SIMPLIFIED MATHEMATICAL MODEL

Because of stringent requirements imposed by international regulations about manoeuvring capabilities, simplified system based manoeuvring models are continuously under development contemporarily to improvements in measurements techniques and model testing procedures in order to predict reliably ship manoeuvring capabilities in the first design phases.

It is common practice to consider a manoeuvring ship as a 3DOF body in the horizontal plane governed by the following equations of motions:

$$\begin{cases} X_H + X_P + X_R + X_{HPR} = \Delta\left(\dot{u} - vr - x_G \cdot r^2\right) \\ Y_H + Y_P + Y_R + Y_{HPR} = \Delta\left(\dot{v} + ur + x_G \cdot \dot{r}\right) \\ N_H + N_P + N_R + N_{HPR} = I_{zz}\dot{r} + \Delta x_G\left(\dot{v} + ur\right) \end{cases} \tag{1}$$

where the right term is the inertial term and in the left one X, Y and N are hydrodynamic forces (surge, sway) and moment (yaw) respectively; subscripts H, P, R and HPR refer to hull, propeller, rudder and coupling (interaction effects). Noticeable research effort has been devoted to investigate and consequently develop reliable systematic experimental tests aiming to have more insight into rudder, hull and interaction forces (the most difficult one to be determined); propeller model employed, on the other hand, is usually represented by open water hydrodynamic characteristics and propulsive coefficients (wake fractions and thrust deductions) obtained from the self propulsion tests (*Ankudinov 1993*) because these coefficients are missing in the proper drift – yaw motion in the preliminary design phases, and regression formulae to estimate them, if existent, are limited to a small number of ship typologies. Recent application of MMG models (*Kijima 1993*)(*Stern 2008*) for single and twin screw ships (*Lee 2003*)(*Khanfir 2009*), have improved this aspect by defining the variation of wake factor with respect the ship's angle of drift β:

$$w = w_{P0} e^{-C\beta^2} \tag{2}$$

where C is a constant to be determined experimentally and w_{P0} is the wake factor at straight ahead condition. In particular, ship wake in oblique flow is evaluated by means of a thrust identity procedure; regarding this aspect, propeller thrust curve (obtained from axial symmetric flow condition) is assumed to be valid. Typical results of this analysis (*Lee 2003*) carried out for a twin screw (wide beam) twin rudder vessel is reported in next Fig. 6, where the effective wake is plotted in terms of drift angle (positive drift angle – STBD propeller is the windward propeller, namely the external one).

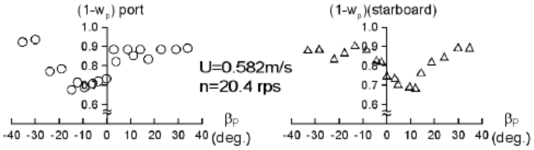

Fig. 6 – propeller wake during oblique motion (from Lee (2003))

Regarding this mathematical model, considerable improvement has been reached thanks to the unique approach to execute systematic manoeuvring tests, devoted to measure each component contribution (H, P, R) and interaction coefficients (HPR) among them separately, as recently proposed in the study of a novel single rudder vessel (*Kang 2008*)(*Kim 2007*). Unfortunately, it has to be remarked that such improved models are not useful as a predictive tool because of the large number of empirical coefficient which need to be determined (by means of expensive experimental campaign), if they could not be estimated by means of reliable statistical regression based upon a sufficient large amount of data. In order to develop a self contained tool useful in the first design phases for analysing this problem, a reliable “propeller unbalancing” model should be included in usual manoeuvring mathematical model. Moreover, to accomplish this task, it should be characterised by a reduced number of parameters directly related to the physical phenomena involved, in order to facilitate their evaluation from experiments. Once determined for a sufficiently extended number of vessels, model’s parameters can be statistically analysed in terms of hull geometric characteristics in order to develop simple regression useful for future preliminary estimations. The authors’ principal aim is to present possible alternatives that could help to discern the main hydrodynamic aspects governing this phenomenon, and at the same time, provide useful suggestion for improvement of free running model tests techniques in order to gain further insight into this problem. It has to be pointed out that in this case, free running model tests have been considered for the preliminary setting of the new propeller model. In the following paragraphs a manoeuvring mathematical model based on Ankudinov model (*Ankudinov 1993*) properly modified (*Viviani 2009*) and its propeller model has been properly modified to manage propeller asymmetrical behaviour experienced by twin screw vessels. Details of the present mathematical model are deeply described in (*Ankudinov 1993*) (*Viviani 2009*) and are omitted in this context because it is preferred to consider in more detail propeller modelling aspects.

PROPELLER MATHEMATICAL MODELS

Propeller performance during a turning circle is strongly related to ship motion and wake features, as it is briefly described in the following three points, referring to Fig.7:

- when the ship advances in the straight ahead condition, both propellers work at J_0;
- when the rudder is acted, the ship starts turning and reduces its speed due to the added resistance and both propellers experience an overloading because the advance coefficient J_0 is reduced (blue arrow).
- ship wake is non symmetric and, as a consequence, each propeller works at a different advance coefficient J; the windward propeller (external) is more loaded and therefore its advance coefficient J_{EST} is lower with respect to J_{INT}.

In traditional twin screw vessel mathematical model, the first two point are usually reproduced, because ship’s speed reduction is captured and, therefore, propellers working state is equal for internal and external side.

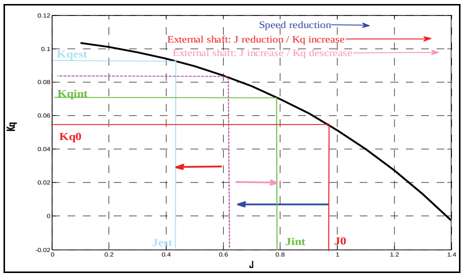

Fig. 7 – Internal and External propeller asymmetric behaviour

In order to represent the last point, propellers’ working regimes should be differentiated during the manoeuver considering more appropriately certain physical features of the flow in the stern of a vessel. In particular, propeller’s inflow during a manoeuvre is strongly modified with respect to straight ahead condition, because of sway-yaw motion, flow separations and the presence of vortex structures interacting with the wake itself and determining secondary separation; other than viscous, also potential effects acts to modify the wake due to hull’s downwash effect (*Ankudinov 1993*). Consequently, the wake is characterised by strong lateral components and it is markedly different among the windward and the leeward side due to the non symmetrical configuration of the vessel with respect to the incoming flow. In order to model properly these effects and, in particular, their influence on propellers working state, the advance coefficient relation should be considered:

$$J = \frac{u_{SHIP}(1-w)}{N_{PROP} D} \tag{3}$$

It is evident that wake fraction *w* and N_{PROP} account for wake effects, and should be differentiated among the two propellers. In this case, N_{PROP} is an equivalent propeller RPS which takes into account transverse flow components, which acts to modify the tangential speed experienced by each propeller section due to the sole shaft rotation. In next paragraphs two simplified wake models are introduced in order to model asymmetrical propeller behavior and results obtained by means of simulation techniques will be presented and discussed.

Asimmetric wake model

In the first method, propeller asymmetric regimes schematized in Fig. 8 are realized by defining asymmetric wake corrections factors Δw_{INT}, Δw_{EST}, whose values could be directly evaluated from shaft torque measured during free running model tests (or full scale trials as described in (*Viviani 2008*)). In this case, advance coefficient is different from windward and leeward propeller:

$$J_{EXT} = \frac{u_{SHIP\_TUR}(1-w+\Delta w_{EST})}{N_{PROP} D}\ ; \quad J_{INT} = \frac{u_{SHIP\_TUR}(1-w+\Delta w_{INT})}{N_{PROP} D} \tag{4}$$

Wake fraction corrections are evaluated by comparing (4) to the effective advance coefficient J* correspondent to torque value measured during the test. In this procedure, a sort of torque identity analysis, similar to the one usually adopted for traditional self propulsion tests, is performed for the stabilized phase of the manoeuvre. In (4) u_{SHIP_TUR} is the longitudinal component of ship speed during turn (stabilized phase), w is the wake factor (determined from self propulsion tests) correspondent to u_{SHIP_TUR}. In order to match J_{EXT} lower than J_{INT} it is evident that:

$$\Delta w_{EST} < 0\,; \Delta w_{INT} > 0\,; w_{EXT} = w + \Delta w_{EXT} > w_{INT} = w + \Delta w_{INT} \tag{5}$$

Values of total wake fraction experimentally derived by means of thrust identity method reported previously confirms relations (5): considering for example the starboard shaft for positive value of β (external propeller) total wake increases in order to lower $(1-w_P)$, otherwise it decreases for opposite drift value (internal propeller). Detailed description of this procedure is reported in (*Viviani 2007*)(*Viviani 2008*) and is here omitted for the sake of brevity. In order to validate the procedure, wake correction factors have been evaluated for ship A considering turning circle manoeuvres (δ=35°) at both F_N by means of the torque identity method briefly described above and are reported in Tab. 3 below:

Table 3. Wake correction factors

$\mathbf{F_N}$	**0.23**	**0.4**
$\Delta \mathbf{w_{INT}}$	0.32	0.04
$\Delta \mathbf{w_{EXT}}$	-0.03	-0.11

Asimmetric flow straightening coefficient models

This method has been proposed by Shulten (*Shulten 2005*) on the basis of extensive LDV (Laser Doppler Velocimetry) measurements performed on a manoeuvring full scale three screw naval vessel (*Kuiper 2002*). In this simplified model N_{PROP} is treated instead of w; moreover, oblique flow effects on propeller hydrodynamic characteristics (K_T and K_Q) are considered by means of the equivalent blade section theory developed by Gutsche. To this purpose, an equivalent advance coefficient is introduced for modelling the flow at the 70% of the blade span, introducing the equivalent propeller rotational speed $n_{\theta,0.7}$:

$$n_{\vartheta,0.7} = \frac{0.7\omega R - v_{TRASV} \sin\vartheta}{0.7\pi D} \tag{6}$$

$$J_{\vartheta,0.7} = \frac{u_{SHIP}(1-w)0.7}{n_{\vartheta,0.7} D} \tag{7}$$

where ϑ is the circumferential position of the blade; it is evident from (6) and (7) that each blade section working point is variable during one revolution because of the second term in the denominator; 0.7 in equation (7) is added in order to evaluate blade loads at 0.7 of propeller radius (in oblique flow) from K_T and K_Q determined from open water tests (axialsimmetric flow) (*Shulten 2005*). In order to differentiate among external and internal propeller working regime, a flow straightening coefficient is introduced, that modifies the transverse speed contribution in (6). In particular, on the basis of detailed measurements of propeller inflow during a tight turn (*Kuiper 2002*) it was evidenced that the lateral flow in the propeller plane v_{TRASV} is determined by a component related to the motion of the ship, and a component related to a transverse components in the wake due to downwash/flow straightening effect of the hull. Advance coefficient defined in (6) is modified as follows:

$$J^*_{\vartheta} = \frac{u_{SHIP}(1-w)0.7}{(0.7)2\pi N r - v_{TRASV} \sin\vartheta\gamma} \tag{8}$$

where γ is a flow straightening coefficient that is different for internal and external propeller: in the internal propeller γ is unity (i.e the transverse flow is not modified), while in the external propeller γ is unity in the upper half of the disk and 1.5 in the lower half; this model simply states that hull wake experience higher transversal flow components in the lower part of the disk because three dimensional effects are dominant with respect to the tendency of the hull to straighten the flow. In the same experimental campaign, a small influence of the motion to the longitudinal component of the wake has been detected and therefore it has been neglected in this simplified approach.

Once J^*_θ is evaluated for the generic circumferential position θ, $K_{T\theta}$ and $K_{Q\theta}$ values can be obtained from the open water characteristics; propeller thrust and torque should then be evaluated by averaging the sectional loads over one complete revolution (torque):

$$\overline{T}_{\vartheta} = \frac{\rho}{2\pi} D^4 \int_0^{2\pi} n_{\vartheta,0.7}{}^2 K_{T\vartheta} d\vartheta \,; \qquad \overline{Q}_{\vartheta} = \frac{\rho}{2\pi} D^5 \int_0^{2\pi} n_{\vartheta,0.7}{}^2 K_{Q\vartheta} d\vartheta \tag{9}$$

It has to be emphasized that this approach permits to take into account for two phenomena: variations of propeller hydrodynamic characteristics for transverse speed and wake asymmetry. Moreover, the flow straightening coefficient can be related to an effective physical aspect; otherwise, in the previous model, wake corrections are not related to the longitudinal wake variation but also to transverse wake components variations.

Asymmetric wake model and flow straightening model – Results

Model A has been considered because a broader set of data have been collected during experiments. In Fig. 8 Torque percentage increase with respect to the value in the approach phase (Q/Q_0) predicted with the two models for the low speed (F_N=0.23) is reported. Simulations with asymmetrical wake model comprise values determined in Tab. 3; in the asymmetrical flow straightening model two couples of values have been considered, (γ_{INT}=1; γ_{EST}=1.5, “met2/1” in the figure) and (γ_{INT}=0.0; γ_{EST}=1.4, “met2/2” in the figure), in order to investigate the sensibility of the model to these parameters. In this case it was not possible to derive their values from experimental data by means of a similar analysis performed above, because only absolute speed has been measured.

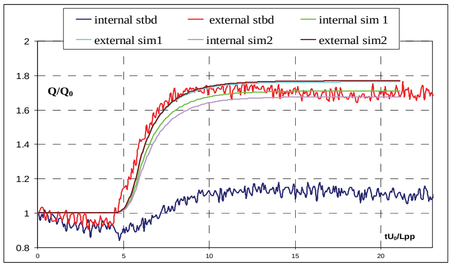

Fig. 8 – Internal and External propeller asymmetric behaviour

It is evident from previous results that propellers’ overloading and unbalances during a manoeuvre are reproduced. Method 1 (wake corrections) predicts torque increase with good accuracy, despite it overestimates the torque for both shafts in the stabilized phase of the turn; on the other hand, method 2 fails in predicting internal shaft behaviour, and moreover, it is evident that the asymmetrical behaviour is less marked with respect to the experimental one. Moreover, it should be noticed that the second couple, with extreme values of flow straightening coefficient (γ_{INT}=0.0; γ_{EST}=1.4) suggests that some effects are still missing, with particular reference to the internal shaft: in this case, the only possible alternative to further increase the internal propeller working point (and therefore to reduce torque demand) is to increase the wake fraction w (similarly to the first method). Finally, in order to test the model as a whole, particular attention should be dedicated to rudders’ loads, because their efficiency is strongly dependent on propellers’ loading effect when located in the propeller slipstream. In Fig. 9 simulated internal and external rudder lateral force (non dimensional) are reported; experimental values are not reported because unfortunately, they were not measured. It should be noticed that in the asymmetrical wake correction, the internal rudder lateral force results higher with respect to the external one; this result is not confirmed in the extensive experimental studies of Atsavapranee (2010), where rudder unbalances with respect to the propellers’ one. In the mathematical model resultant rudder speed is computed by summing speed component inside and outside the propeller slipstream; benefits deriving from the propeller loading (higher in the external propeller due to the lower J) are overcompensated by the speed outside the propeller slipstream (higher velocity in the internal side due to the lower resultant wake, see eq.(5)) and therefore the resultant speed is lower on the windward rudder. Alternatively, in the flow straightening approach rudders’ unbalance is qualitatively similar (despite underestimated), but opposite with respect to the one provided in

Atsavapranee (2010), where the internal rudder is overloaded of about 30% with respect to the external one. Confirmation for present ship should be needed to further investigate these effects.

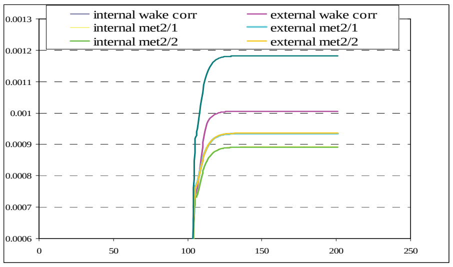

Fig. 9 – Internal and External propeller asymmetric behaviour

ASYMMETRICAL OVERLOADING BY MEANS OF A BEMT PROPELLER MODEL

Form previous results, it has been shown that the asymmetric wake approach, both in terms of wake deduction factor corrections ($\Delta w_{int,\ est}$) and propeller lateral speed flow straightening coefficients provide a simple and efficient alternative for the modelling of propellers' unbalances during turns. However some problems still exists in terms of the flow field definition during a manoeuvre: as it can be seen in Fig. 10, the flow in the windward region seems to be less affected by hull's wake, despite a stronger oblique flow could be present with respect to the internal side where hull could straighten the flow, which is further decelerated because interested by hull's wake. This physical interpretation has been partially provided in the second model presented above, where the lateral flow component is amplified on the external side in order to take into account for the flow passing from windward to leeward side when approaching the stern limit of the ship; however, longitudinal wake variation (like the first model) with drift angle has not been considered. Regarding the first model, Δw should not be given a direct physical interpretation, because it seems unlikely that the flow on the leeward side, more affected by the presence of the hull, is more accelerated with respect to the opposite one. Aiming at developing a simple, and at the same time, physically based model, it seems that oblique flow effects should be considered more appropriately. In particular, it has to be considered that propeller characteristics necessarily changes when the inflow conditions depart considerably from axialsymmetric conditions, in particular during tight turns where propeller disk inflow angle could reach up to 35° (disregarding windward to leeward flow leakages).

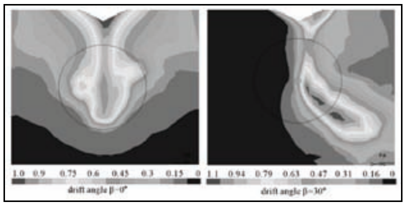

Fig. 10 – Hull asymmetrical wake (Abramowski 2005)

Moreover, in addition to propeller hydrodynamic definition, the following wake characteristics could be present:

- in the *windward side*, absolute speed is not affected by the presence of the hull and, reasonably, flow straightening coefficient is low and consequently, propeller inflow angle of attack is high. In this case, high overloading would arise due to propeller working at significant oblique flow.
- In the *leeward side*, absolute speed is decelerated because of hull "masking" effect; moreover flow direction is strongly straightened by the hull and therefore it works in less critical oblique flow condition.

From the above considerations the propeller inflow angle in the external shaft should overcome the effect of flow deceleration (and the lower oblique propeller inflow) in the internal side in order to match with experimental measurements. In order to test this further hypothesis, a BEMT propeller model extended to oblique flow conditions has been developed in order to analyse more accurately propeller behaviour in oblique flow. The final aim will be then to include propeller characteristics for generic inflow conditions and the above wake model in the simplified manoeuvring mathematical model in order to further analyse this complex aspect.

Description of BEMT model

In the Blade Element Momentum Theory the propeller is modelled as a series of two dimensional airfoils independent from each other; lift and drag acting on the generic section are easily evaluated if two dimensional hydrodynamic properties of the profile are known (in terms of C_L and C_D) on the whole range of incidence angles experienced by the section during a complete blade rotation. Usually, when the propeller is operating during a manoeuvre, sectional incidence angle can be large and stall (at model scale) and cavitation phenomena can arise, affecting the total load developed by the blade. If the 2D section hydrodynamic characteristics are defined for a relatively broad range of incidence angles, these effects can be partially taken into account and modelled. Therefore, this model is an attractive alternative for the purpose of analysing propeller behaviour when operating in an oblique flow with respect to more complicated approaches, i.e. Boundary Element Method or RANSE, the former one unable to capture stall and viscous effect and suffering at high angle of attack, the latter one expensive in term of computing and time resources needed to characterise a complete propeller for a wide range of J and inflow angle β_{PROP}. The traditional BEMT theory has been modified (*Philips 2002*) in order to treat non symmetrical inflow condition; the effect of the transverse component of the flow modifies the tangential component of the flow, as it is schematically represented in Fig. 11 (α_P in the formulas reported on the sketch is the same as β_{PROP} in the main text). In particular, it is evident that the inflow transverse component $V_{INF}\sin\alpha_P\sin\theta$ modifies the tangential velocity ωr due to propeller rotation (θ representing section's circumferential position). In particular, sectional lift and drag are evaluated by means of the following formulas:

$$dL = 0.5\rho V^2{}_{B} c\,\frac{dC_L}{d\alpha}\,\alpha_{eff} \tag{10}$$

$$dD = 0.5\rho V^2{}_{B} c\left(C_{D0} + C_{D1}\alpha_{eff} + C_{D2}\alpha^2{}_{eff}\right) \tag{11}$$

where ρ is the fluid density, c is the profile chord, α_{eff} is the sectional angle of attack, and hydrodynamic coefficient are pre calculated once the profile geometry is defined.

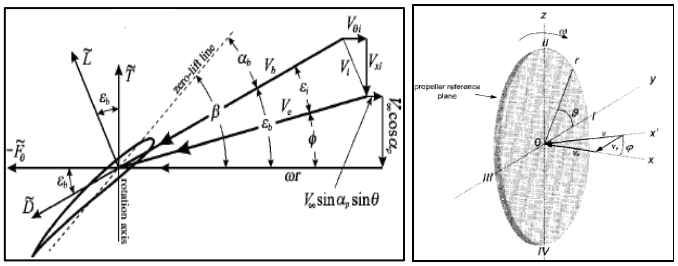

Fig. 11 – Blade section velocities in oblique flow

V_B is the sectional velocity, resultant of longitudinal and transverse speed components, briefly defined below:

longitudinal component:

$$V_{axial} = V_\infty \cos\beta_{PROP} + V_{iax} \tag{12}$$

circumferential component:

$$V_{\tan} = 2\pi N_{PROP} r - V_\infty \sin\beta_{PROP} \sin\theta - V_{i\tan} \tag{13}$$

where β_{PROP} is the inflow angle with respect the propeller axis, r is the radial position of the section, θ is the circumferential position and V_{ii} are the components of the propeller wake induced flow, which could be determined after the induced angle of attack ε_i is evaluated by means of the Betz condition (relation between sectional circulation and transverse speed induced component) and Prandtl-Goldstein tip loss factor, accounting for propeller losses due to three dimensional effect:

$$\frac{Bc}{16r}\frac{dC_L}{d\alpha}(\phi_0-\phi_\infty-\varepsilon_i)=\cos^{-1}\exp\left[-\frac{B(1-x)}{2\sin(\phi_{0T})}\right]\tan(\varepsilon_i)\sin(\phi_\infty+\varepsilon_i) \tag{14}$$

Due to its non linear character, this equation is solved by a common iterative technique in term of ε_i. In this relation, B is the number of propeller blades, Φ_0 is the geometrical pitch angle, Φ_{inf} is the incidence angle without considering induction effect and Φ_{0T} is the geometric pitch angle of the blade tip section. Once this equation is solved, the effective angle of attack can be determined:

$$\alpha_{eff}=\phi_0-\phi_\infty-\varepsilon_i \tag{15}$$

In order to obtain sectional propeller thrust and torque, sectional lift and drag are first projected in the longitudinal and circumferential direction θ; total thrust and torque are calculated integrating sectional loads along the blade span and averaging in a propeller revolution; for the sake of brevity, only the propeller torque is derived:

$$dF_T=L\sin(\phi_\infty+\varepsilon_i)+D\cos(\phi_\infty+\varepsilon_i)$$

$$Q=\int_{R_{HUB}}^{R}\frac{B}{2\pi}\int_0^{2\pi}dF_T\,\sin(\theta)rdrd\theta \tag{16}$$

Computation of propeller hydrodynamic characteristics

In order to describe more accurately propeller behaviour during manoeuvres in order to test the simple wake model previously described, propeller hydrodynamic characteristics have been pre calculated by means of BEMT code for a wider range of advance coefficient (0.1<J<1.5) and oblique inflow angle ($0<\beta_{PROP}<40°$):

$$Kt=Kt(J,\beta_{PROP})\qquad Kq=Kq(J,\beta_{PROP}) \tag{17}$$

It should be remarked that in this case, advance coefficient J is evaluated considering absolute speed instead of its axial component. The complete propeller charts have been included into the manoeuvring mathematical model, as described below.

BEMT inclusion in manoeuvring mathematical model - Description

In Fig. 12 the fundamental structure of the propeller model is schematized; at each time step ship speed and drift are required in order to evaluate propeller state, in particular:

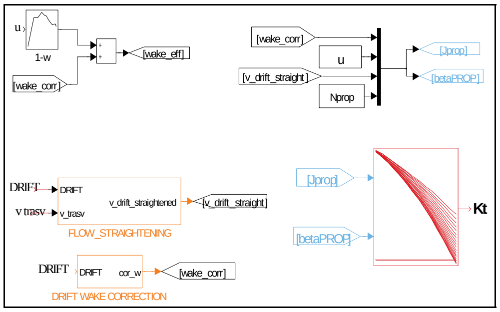

Fig. 12 – Modified propeller model and wake correction

- propeller transversal speed (“v_trasv”) is evaluated considering the combination of ship lateral (v_{SHIP}) and rotational (r_{SHIP}) speed:

  $$v_{PROP}=v_{SHIP}-r_{SHIP}X_{PROP} \tag{18}$$

  where X_{PROP} is propeller longitudinal position from $L_{PP}/2$ (origin of the moving reference system);
- in “FLOW STRAIGHTENING BLOCK” propeller lateral speed is corrected by means of a flow straightening coefficient, whose value is variable if the propeller is windward or leeward with respect to the trajectory. In this block lateral speed is amplified for the external propeller and reduced for the internal one:

  $$v_{PROP\quad INT}=\gamma_{INT}v_{PROP}<v_{PROP} \tag{19}$$

  $$v_{PROP\quad EST}=\gamma_{EST}v_{PROP}>v_{PROP} \tag{20}$$
- in “DRIFT WAKE BLOCK” correction of the wake factor (measured from the self propulsion test) is evaluated on the basis of the propeller’s relative position with respect to the incident flow (external or internal correction is switched on the basis of vessel’s drift angle); the effective wake factor (different from each propeller) is then computed as follows:

  $$w_{PROP\quad INT}=w(1+c_{wINT})<w \tag{21}$$

  $$w_{PROP\quad EST}=w(1+c_{wEST})>w \tag{22}$$
- once both longitudinal and transverse speed have been corrected, the propeller inflow (absolute speed and incidence angle with respect propeller axis) can be easily defined and therefore, propeller hydrodynamic characteristics (K_T and K_Q) could be evaluated in terms of advance coefficient J_{PROP} and local drift angle β_{PROP} defined as:

  $$J_{PROP}=\frac{\sqrt{u^2{}_{SHIP}(1-w_{PROP\_INT/EST})^2+v^2{}_{PROP}}}{N_{PROP}D} \tag{23}$$

  $$\beta_{PROP}=\arctan\left(\frac{v_{PROP}}{\sqrt{u^2{}_{SHIP}(1-w_{PROP\_INT/EST})^2+v^2{}_{PROP}}}\right) \tag{24}$$

  where N_{PROP} are propeller rps, D is propeller diameter, u_{SHIP} is longitudinal component of absolute ship speed.

It is evident from (21) and (22) that wake correction terms $c_{w\_INT/EST}$ act to modify effective hull wake (internal one greater with respect to the external) oppositely to the first model described above (external one greater than internal): it has to be emphasized that in this case it has been attempted to split the global physical information carried up by Δw_i terms, in a longitudinal and transverse component in order to model and identify a reliable wake model more coherent to the hydrodynamic flow field in the stern of a vessel when performing a tight manoeuvre.

BEMT inclusion in manoeuvring mathematical model – Results

Preliminary tests have been carried out in order to analyse the model’s sensibility to the parameters (flow straightening coefficients and wake correction factors) of the asymmetrical wake model are reported in Tab.3. Simulations 1 and 2 adopt same flow straightening coefficient proposed in the second method described above neglecting wake correction factor; this choice could lead to compare both models. In Fig.13 (left) results in terms of torque increase are reported and compared to the experiments for simulations 1 and 2.

Tab.3: Wake parameters tested

simulation	**1**	**2**	**3**	**4**
γ_{INT}	1	0	0	0.5
γ_{EST}	1.5	1.4	1.5	1.5
Δw_{INT}	0	0	0.1	0.3
Δw_{EXT}	0	0	-0.1	-0.2

It could be evidenced that results are similar to those obtained by means of the asymmetric flow straightening method described in previous paragraphs (*Shulten 2005*); despite external propeller performance is well captured, the internal one is over predicted and differences among them is not markedly defined as in the experimental tests. In successive tests, a longitudinal wake component is added as reported in Tab.3 and plotted in Fig. 13 (right) (ordinate scale is changed for the sake of clarity). Increasing the asymmetrical wake effect differences in torque demand between internal and external propeller are further alleviated till a similar behaviour is detected.

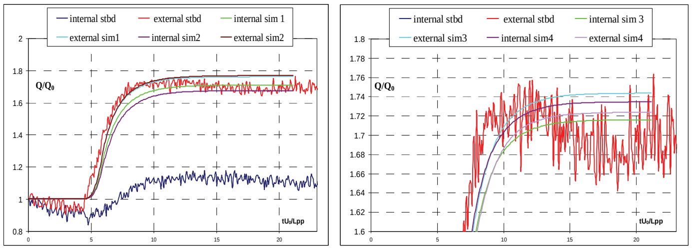

Fig. 13 – Modified propeller model and wake correction

This deficiency of the model is caused by a compensation of two phenomena: drift angle and advance coefficient. The first term acts to increase the windward propeller torque demand, because it operates at a larger value of drift (24) with respect to the internal one; wake correction factors assumed for the model (speed reduction/increment in the internal/external side) cause the leeward propeller to work at a lower J (23) with respect the windward one: as a consequence, despite inflow conditions are markedly different, they determine similar propeller behaviour. Results in terms of rudder loads and unbalances are similar to the second model (Fig.8) (i.e. the rudder behind the more loaded propeller develops an higher load), and are not reported for the sake of text space savings. The proposed model provides reliable results only for the external propeller and proposed wake model coupled to propeller characteristics in oblique flow seems to be adequate; unfortunately, this model is still inadequate for predicting internal shaft behaviour. Presently, original approach with asymmetrical Δw values still allows to obtain best results, despite its oversimplification. It has to be pointed out that present model is two dimensional (it defines a longitudinal and lateral component) and, moreover, both components are considered constant over the propeller disk. As a matter of fact, it is reasonable that the inflow in the internal propeller is completely three dimensional and its component experience strong gradients over the propeller disk. Further studies should be dedicated to the identification of a simple and reliable wake model describing with reliable accuracy the leeward propeller inflow during a manoeuvre in order to develop a reliable tool for analysing critical off design conditions that could affect the integrity of propulsion system. Finally, it has to be remarked that the proposed wake model does not claim to be absolute and general, because opposite unbalances have been detected in other cases for similar hull forms; however, it can be considered a simple physical based attempt for preliminary analysis of this complex aspect.

CONCLUSIONS

In this work propeller load increase and unbalances on twin screw vessels during a tight manoeuvre have been considered. This phenomenon is usually postponed to the latest phases of the design spiral (free running model tests) or during the delivery process, because its evaluation by means of CFD techniques (for the determination of propeller inflow during a manoeuvre) or direct measurements by means of model tests is expensive and time consuming. In order to deal with this aspect by means of simple tools, a system based manoeuvring mathematical model has been modified in order to manage the propeller unbalances during tight turns. To this aim, three different wake models have been included in the propeller hydrodynamic model. Comparisons between calculated and measured torque increase has shown the ability of these models to simulate an asymmetrical behaviour of the windward and leeward propeller. Moreover, the external propeller is quite well described by a two dimensional wake, homogeneous over the disk; on the other hand, this description is not reliable for the internal propeller, due to more complicated flow features which cause the wake to be three dimensional and irregular. It has to be emphasized that the identification of a physical and simple wake model could be helpful for the systematic analysis of propeller unbalances experienced during free running model test and full scale sea trial: the parameters defining the wake model, being strictly related to physical flow features, could be more easily analysed in terms of hull and stern geometric characteristics in order to develop statistical regressions useful in the preliminary design stages as a predictive tool. At the same time, twin screw vessels manoeuvring mathematical models could raise their predictive capabilities because of the inclusion of a physical wake model could help to model hull-propeller (and consequently propeller-rudder) interaction effects otherwise described by semi-empirical coefficients determined from detailed experimental captive model tests.

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