SUMMARY
Marine propulsion plants can experience large power fluctuations during tight manoeuvres. During these critical situations, dramatic increases of shaft torque are possible, up to and over 100% of the steady values in straight course. In the case of a twin-screw ship turning circle, the two shaft lines dynamics can be completely different in terms of required power and torque. This phenomenon, if not correctly considered, is potentially dangerous, especially for propulsion plants with two shaft lines powered via a unique reduction gear, which can be subject to significant unbalances.

The paper presents a simulation approach able to represent the dynamics of a twin-screw ship propulsion plant in these critical working conditions. The numerical model includes the ship manoeuvrability and the dynamic behaviour of prime movers, shaft lines, propellers and propulsion control system. Numerical results obtained have been compared to full-scale measurements in order to validate the proposed simulation approach.

1. INTRODUCTION
As it is well known, ships during maneuvers can experience large fluctuations of required shaft power from the propulsion plant. This is especially true in case of very tight maneuvers, like turning circle at, or in proximity to, maximum rudder angles, and can result in considerable increase of shaft power, or shaft torque if propeller revolutions are kept constant, up to and over 100% of steady values in a straight course recorded during the approach phase to the maneuver.

Despite the fact that this behavior is qualitatively well known, there is not a wide amount of quantitative data available in literature; however, these effects could be potentially dangerous, if not correctly predicted and cared for, for some particular kinds of propulsion plant, in which for instance two shaft axes are powered by the same prime mover via a unique reduction gear, like in some of the latest naval ships (see example in following Figure 1).

![Fig. 1: Propulsion layout with two shaftlines and common reduction gear](image)

In this case, the possibility of significant unbalances of forces on the reduction gear itself and of strongly different power increase for the shaft axes exists; unfortunately, a very low amount of data is available for this kind of propulsion plant, considering also its rather recent introduction and application.

In order to bridge this gap, in a recent work [1] an analysis of data available for the more common propulsion configuration with two completely separated shaftlines and related prime movers (see example in next Figure 2) has been carried out. In particular, standard turning circle maneuvers at different speeds and rudder angles for a series of twin screw naval ships have been analyzed, and a common trend for shaft power increase has been found, as it will be briefly summarized in following paragraph 2.

![Fig. 2:Typical propulsion layout with separated shaftlines](image)
Circle and ZigZag manoeuvres and how the propulsion controller influences the performance of the entire propulsion system. Numerical results obtained have been compared to full-scale measurements in order to validate the proposed simulation approach.

2. SUMMARY OF PREVIOUS RESULTS

As anticipated in previous paragraph 1, in a recent work [1] an analysis of manoeuvring data for 5 different naval ships, whose non-dimensional data is presented in following Table 1, has been carried out. Most of data was taken from full scale sea trials, while for Ship 5 free running model tests were available too.

<table>
<thead>
<tr>
<th>Ship</th>
<th>( C_B )</th>
<th>L/B</th>
<th>B/T</th>
<th>( A_R/LT )</th>
<th>( F_R )</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1</td>
<td>0.64</td>
<td>6.61</td>
<td>2.92</td>
<td>2.1%</td>
<td>0.08-0.28</td>
<td></td>
</tr>
<tr>
<td>1/2</td>
<td>0.64</td>
<td>6.61</td>
<td>2.92</td>
<td>4.3%</td>
<td>0.08-0.29</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.48</td>
<td>5.29</td>
<td>3.21</td>
<td>1.9%</td>
<td>0.11-0.27</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.50</td>
<td>8.61</td>
<td>3.32</td>
<td>4.1%</td>
<td>0.21-0.42</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.48</td>
<td>6.91</td>
<td>3.46</td>
<td>3.4%</td>
<td>0.22-0.44</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.51</td>
<td>7.89</td>
<td>3.63</td>
<td>4.0%</td>
<td>0.14-0.40</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Main non-dimensional data of ships analyzed

In particular, following data are represented:
- block coefficient \( C_B \)
- length to beam ratio L/B
- beam to draft ratio B/T
- rudder area percentage with respect to lateral area represented by LT
- range of ship speed (in terms of Froude number)

Different ship types are included, ranging from rather slow Auxiliary ship and Replenishment and Logistic support ship to fast Frigates and Corvettes. All ships present a twin screw propulsion configuration, with completely separated propulsion plants, however prime movers are various, including Diesel Engines, Electrical Motors and Gas Turbines, or combinations of them; both CPP and FPP configurations are present in the analysis. Finally, two different stern configurations on the same hull for Ship 1 are analyzed, and namely single and twin rudder configuration for Ship 1/1 and Ship 1/2 respectively.

For all ships turning circle maneuvers at different speeds and, when available, different rudder angles, have been considered (for a total of 52 trials), with particular attention to ship speed, propeller RPM and shaft power. Power increase during maneuvers at different speeds and rudder angles with respect to power required for straight course in the approach phase have been evaluated, considering both peak values in the initial transient phase and stabilized values (which in general result about 10-15% lower than peak ones). Since RPM are kept constant during all maneuvers when no automation intervention is present, torque increase is equal to power increase. Despite ships analyzed have significant differences from many points of view, a common trend for all trials (in which automation is not acting) was found, with an external shaft power increase of about 85-105% and an internal shaft power increase of about 30-50% in correspondence of the maximum rudder angles; influence of Froude number seems negligible.

For the highest ship speeds considered, automation plays a key role, limiting power increase by means of RPM or propeller pitch reduction for both internal and external shafts to similar values (different from ship to ship depending on different power margins), since at this speed propulsion plant is already utilized near to its full capabilities.

Stabilized power increases obtained for all ships are summarized in following Figures 3 and 4 for internal and external shafts respectively as a function of rudder angle (tests with automation influence have been omitted). In both figures the mean line is drawn, together with two additional lines shifted up and down by 10%; as it can be seen, despite presenting a certain scatter, a clear tendency results in all cases.

![Fig. 3: Stabilized power - Summary – Internal shaft](image)

![Fig. 4: Stabilized power - Summary – External shaft](image)

Possible reasons investigated in [1] for the shaft power increase, apart from the obvious speed reduction during the maneuver, are oblique flow and asymmetrical variations of longitudinal and tangential speed at the propeller plane; the effect of the first phenomenon is widely covered in literature (see for example [2][3]), while from the analysis of extensive experimental tests at PMM on different hull shapes reported in [4] and [5]
both longitudinal and tangential speed variations during manoeuvres were found.
In view of the development of a simulator including ship maneuvering and automation plant, asymmetrical wake fraction variation has been considered the most straightforward and easy to be evaluated from usual data recorded during sea trials.
A procedure similar to the analysis of a self-propulsion test has been adopted, evaluating new values of the propeller advance coefficient $J$ during manoeuvre in correspondence of recorded values of torque (and consequently $K_Q$), and then calculating the "asymmetrical wake fraction variation".
In particular, variation of $J$ is partially due to reduction of ship speed during manoeuvre, which results in higher torque coefficient $K_Q$ (point $J_1$ in figure 5), then the following effective functioning points $J_{ext}$ and $J_{int}$ are reached by means of the asymmetrical variation of wake fraction.

![Fig. 5: Asymmetrical variation of advance coefficient $J$](image)

The following steps are adopted for the analysis of manoeuvring data:

1. Evaluation of equivalent open water torque on internal and external shafts on the basis of recorded power and propeller revolutions, in accordance to (1)

$$Q_O = \frac{P \eta_r}{2 \pi N}$$

(1)

$$\eta_r = \frac{Q_O}{Q}$$

(2)

where $Q_O$ is the open water torque, $Q$ and $P$ are the delivered torque and power and $N$ are propeller revolutions and $\eta_r$ is the relative rotative efficiency, defined in (2) (adopting value from self-propulsion test),

2. Evaluation of correspondent torque coefficient $K_Q$ for both shafts on the basis of (3)

$$K_Q = \frac{Q_O}{\rho N^2 D^5}$$

(3)

3. Evaluation of advance coefficient $J$ value needed in order to obtain $K_Q$, interpolating from propeller characteristic curves

$$J = \frac{V_a}{ND}$$

(4)

$$V_a = (1 - w)V_s$$

(5)

where $V_a$ is the propeller advance velocity, $D$ is propeller diameter, $w$ is the wake fraction and $V_s$ is the ship speed.

4. Evaluation of correspondent advance velocity:

$$V_a = JND$$

(5)

5. Finally, “effective value” of wake fraction can be computed:

$$(1 - w) = \frac{V_a}{V_{s(evol)}}$$

(6)

where $V_{s(evol)}$ is stabilized ship speed during turning circle maneuver

In the following Table 2 values of wake fraction variation $\Delta w$, defined in (7) are reported in correspondence to maximum rudder angle and for different ranges of Froude Number (where low stands for a value lower than 0.15 and high for a value higher than 0.3).

$$\Delta w = w_{evol} - w$$

(7)

<table>
<thead>
<tr>
<th>Fr</th>
<th>$\Delta w_{int}$</th>
<th>$\Delta w_{ext}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship 1/2</td>
<td>Mean</td>
<td>-0.56</td>
</tr>
<tr>
<td>Ship 2</td>
<td>Mean</td>
<td>-0.38</td>
</tr>
<tr>
<td>Low</td>
<td>-0.34</td>
<td>0.14</td>
</tr>
<tr>
<td>Ship 3</td>
<td>Mean</td>
<td>-0.10</td>
</tr>
<tr>
<td>Ship 4</td>
<td>High</td>
<td>-0.15</td>
</tr>
<tr>
<td>Ship 5</td>
<td>Mean</td>
<td>-0.17</td>
</tr>
</tbody>
</table>

Table 2: Values of wake fraction variation

In most of cases, a similar trend has been found on the basis of this analysis, i.e. flow on the internal shaft appears accelerated (with a reduction of wake fraction value), while flow on the external shaft appears to be decelerated (with an increase of wake fraction value).
However, these data present a significant scatter (see for instance negative value for Ship 1 external shaft), due to the fact that they “incorporate” also other effects whose entity varies from ship to ship; in particular, it is likely that influence of variation of tangential speed has a strong influence on this scatter.

A complete insight of the problem could be obtained only by means of numerical simulations (still very difficult and computationally demanding for such a complex phenomenon with interactions between hull, rudders and propellers) or by means of an extensive experimental campaign with the aim of analysing flow in correspondence to propeller location during manoeuvres. Both these approaches would be very expensive since, in order to have a clear understanding of the problem, analysis of different ships and hullforms should be carried out, thus further multiplying the effort needed.
From this point of view, it is believed that the values of wake fraction variations for different ships which have been computed, despite being affected by errors arising from experimental nature of data analysed and by implicit inclusion of different effects (such as tangential speed), can be already readily applied to similar ships during design phases if required.

In case significantly different ships are considered, free running model tests appear to be probably the least expensive alternative to complicated numerical calculation or experimental campaigns with PMM, providing scale effects are properly considered.

With this aim, a dedicated series of free running model tests has been performed by INSEAN at its facility at Lake Nemi on Ship model n°5 (model scale 1:25) [1], and the results of the comparison with full scale data are reported in following Figures 6 and 7; it has to be noted that, in order to be able to compare results at high speed (in which propeller revolutions are reduced in full scale during maneuvers), P/N° variations are reported in figures instead of power variations.

2. SIMULATOR DESCRIPTION

The ship behaviour is simulated by means of a mathematical model that is able to predict the interactions between the propulsion system dynamics and the ship maneuverability.

This mathematical model consists of a set of differential equations, algebraic equations and tables that represent the various elements of the propulsion system: the automation, the engines, the propellers, the shaft lines and the ship motions (surge, sway and yaw).

In particular, the modelled propulsion plant consists of a twin shaft arrangement with controllable pitch propellers, where each shaft is driven, through a gearbox, by two prime movers.

The schematic of the modelled ship dynamics is shown in Figure 8, where it is possible to see the several main components involved in the simulation process.

The implementation of the numerical code has been made in MATLAB-SIMULINK® software environment, a wide used platform for the dynamic systems simulation.

For each element illustrated in Figure 8, numerical models with different level of accuracy have been developed, taking into account the general objective of a good balance between the reliability of the simulation results and the code performance.
Shaftline dynamics, as anticipated, are governed by equation (8). From this equation, in particular, it is possible to calculate the propeller speed \( n \), where the engine torque \( Q_e \) is evaluated by means of a mathematical model based on the thermodynamic process of the engine, while the propeller torque \( Q_p \) is evaluated by means of the open water propeller tests for several blade positions. Once calculated \( n(t) \) from shaft line dynamics equation and \( V(t) \) from maneuverability equations, it is possible to obtain the propeller advance coefficient \( J(t) \) using the matrix values of the wake fraction \( w(t) \).

![Fig. 9 – Calculation of wake fraction variation](image)

In Figure 9 the calculation process of the wake fraction variation, adopted in the simulation model of each propeller, is shown. The two tables, representing the values of \( \Delta w \) for each shaft, perform 2-D linear interpolation of the two inputs, the ship speed and the rudder angle. At each time instant it is then possible to calculate the proper wake factor variation on the base of the drift angle sign. In fact the “switch” block passes the first input or the third input on the base of the second input, meaning a starboard or port side turning circle of the ship.

As presented in previous paragraph, \( \Delta w \) values are computed from stabilized parts of the manoeuvre. If the scheme indicated in Figure 9 were directly adopted without additional considerations, sudden variations of \( \Delta w \) would occur once a certain rudder angle is given, thus generating erroneous power peaks during transients; this would be particularly significant for manoeuvres in which large parts are in transient mode (e.g. ZigZag). In order to overcome this problem, the effective \( \Delta w \) value adopted instantaneously is evaluated in accordance to following equation:

\[
\Delta w_{eff}(t) = \Delta w_{i}(t) \frac{\beta(t)}{\beta_{evol}}
\]

where \( \Delta w_{i} \) is the value obtained by interpolation, \( \beta \) is the current value of drift angle and \( \beta_{evol} \) is the drift angle value during the stabilized turning circle at the considered speed and rudder angle.

By using this calculation routine, the simulator is able to realize which is the external or the internal shaft during the ship turning circle and then to calculate the proper wake fraction in order to evaluate the propeller advance...
coefficient \( J(t) \). Once \( J(t) \) is known, it is possible to evaluate \( K_Q(t) \) and \( K_T(t) \), respectively for propeller torque and thrust calculation.

3. TEST CASE

3.1 SHIP CHARACTERISTICS

As already anticipated, in order to test the modified simulator described in the previous paragraph 2, a sixth ship, different from those already analysed in [1] and listed in table 1, has been considered.

Main characteristics of this ship are summarised in the following:

- \( C_B \) = 0.585
- \( L/B \) = 7.32
- \( B/T \) = 4.35
- \( A_R/LT \) = 3.7%
- \( F_R \) = 0.17÷0.31

This ship is equipped with a propulsion plant with completely separated shaftlines and two prime movers per shaft (similar to the one schematized in Figure 2).

3.2 SEA TRIAL DATA ANALYSIS

Turning circle and ZigZag manoeuvres with different rudder angle and different ship speed performed during sea trials have been made available for the present analysis, as reported in next Table 3:

<table>
<thead>
<tr>
<th>TURNING CIRCLE</th>
<th>( \delta )</th>
<th>SPEED</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pm 35 )</td>
<td>( \pm 25 )</td>
<td>( \pm 15 )</td>
</tr>
<tr>
<td>( ZIG ZAG )</td>
<td>20-20</td>
<td>Fn=0.17 Fn=0.31</td>
</tr>
</tbody>
</table>

Table 3 – Experimental tests

As a first step, as already performed in [1], Turning circle manoeuvres (for which maximum power fluctuations are experienced) have been considered, in order to obtain values for the simulator. Main physical parameters investigated are ship speed, shaft rpm and shaft power. ZigZag manoeuvres are not considered initially, since they are utilized in order to validate the simulator behaviour in correspondence to manoeuvres different to those used for the simulator itself calibration.

In the following Table 4, results in terms of shaft power increment during turning circle tests are summarized in percentage notation in relation to the values before the rudder execute point.

For a better understanding, these results are visualized in the following figures 10 and 11.

<table>
<thead>
<tr>
<th>( \delta )</th>
<th>( \Delta P% )</th>
<th>( \Delta P% )</th>
<th>( \Delta P% )</th>
<th>( \Delta P% )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \text{EXT} )</td>
<td>( \text{INT} )</td>
<td>( \text{EXT} )</td>
<td>( \text{INT} )</td>
</tr>
<tr>
<td>35</td>
<td>80</td>
<td>15</td>
<td>54</td>
<td>40</td>
</tr>
<tr>
<td>-35</td>
<td>72</td>
<td>38</td>
<td>53</td>
<td>51</td>
</tr>
<tr>
<td>\text{av}</td>
<td>76</td>
<td>26</td>
<td>53</td>
<td>46</td>
</tr>
<tr>
<td>25</td>
<td>64</td>
<td>13</td>
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<td>24</td>
</tr>
<tr>
<td>-25</td>
<td>69</td>
<td>24</td>
<td>52</td>
<td>29</td>
</tr>
<tr>
<td>\text{av}</td>
<td>66</td>
<td>18</td>
<td>49</td>
<td>26</td>
</tr>
<tr>
<td>15</td>
<td>35</td>
<td>9</td>
<td>42</td>
<td>13</td>
</tr>
<tr>
<td>-15</td>
<td>29</td>
<td>10</td>
<td>48</td>
<td>23</td>
</tr>
<tr>
<td>\text{av}</td>
<td>32</td>
<td>9</td>
<td>45</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 4 – Experimental Power Increments

Also in this case, as already found in previous work, an almost symmetrical behaviour for port and starboard maneuvers has been experienced (considering unavoidable external disturbances during sea trials). In particular, external shaft power increase is higher (with maximum values of about 80% in correspondence to \( F_R=0.17 \)) than internal shaft power increase (which is about 35-45% for all cases, except a spurious lower increase for one of the two manoeuvres in correspondence to the lower speed analysed). In the case
of external shaft at higher speed, power increase is lower because of limitations introduced by automation, since maximum allowed power of the plant is reached; in particular, automation acts by means of a reduction of the propeller blade pitch.

Power increase values computed for the present ship (for manoeuvres where automation is not acting) are compared with previous ones and reported in following Figures 12 and 13, which are the same of previous Figures 1 and 2 with the addition of these new data.

As it can be seen, present ship results are generally within the mean ranges already found in [1], especially for the intermediate rudder angles considered, while for the highest rudder angle (35°), power increases experienced in this case are lower.

As a second step, experimental test results have been utilized to calculate the values of $\Delta w$ for internal and external shaft, using the procedure described in the previous paragraphs.

In particular, in order to consider that power recorded for the two shaftlines is not perfectly symmetrical (both in the approach phase with a rectilinear path and during the manoeuvre), $\Delta w$ values have been calculated considering mean power, speed and RPM in the rectilinear phase and during port and starboard manoeuvres.

In following Table 5 and Figures 14 and 15, different values of $\Delta w$ in correspondence to different values of rudder angle and ship speed, evaluated adopting this strategy, are reported:

<table>
<thead>
<tr>
<th>$\delta$</th>
<th>$F_R=0.17$</th>
<th>$F_R=0.31$</th>
<th>$\Delta w_{int}$</th>
<th>$\Delta w_{est}$</th>
<th>$\Delta w_{int}$</th>
<th>$\Delta w_{est}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>-0.254</td>
<td>0.189</td>
<td>-0.34</td>
<td>0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>-0.213</td>
<td>0.105</td>
<td>-0.28</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>-0.076</td>
<td>0.042</td>
<td>-0.107</td>
<td>0.027</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Also in this case, values computed for sixth ship fall in the range already found in [1]. Unfortunately, as already pointed out, it has not been possible up to now to find a common law for all ships, and values of wake fraction variation present a significant scatter from ship to ship, thus obliging to analyse experimental data in order to construct a simulator which behaves correctly.

This fact points out the difficulty to predict this particular behaviour of twin screw propellers ship during manoeuvres, and the need to better understand the complex and variable flow pattern near the two propellers and its relation to stern shape. In particular, main reasons for this scatter are the different drift angles each ship reaches during the manoeuvre and the possible effect of
different tangential speed variation. Both these phenomena are implicitly included in the \( \Delta w \) values, thus generating a certain scatter.

It has to be pointed out, however, that main purpose of this work is to test if the modified simulator is able to reproduce the behaviour recorded during experimental manoeuvres for a determined ship; as already considered [1], in fact, if a ship considerably different has to be simulated, data from free running model tests can be utilised, if proper scale factors are adopted.

4. SIMULATION RESULTS

In following paragraph 4.1, results obtained inserting values reported previously in the modified simulator and reproducing turning circle and zigzag manoeuvres are reported. These results are compared with experimental ones for validation of the model.

In paragraph 4.2, the simulator itself is used in order to analyse a wider range of manoeuvres to investigate the possible propulsion plant behaviour.

4.1 COMPARISON OF SIMULATION RESULTS AND EXPERIMENTAL DATA

In following Figures 16-19, the internal and external shaft stabilized power increments recorded during simulated turning circle manoeuvres at \( Fn=0.17 \) and at \( Fn=0.31 \) are compared with sea trial results. In particular, for experimental data port and starboard manoeuvres results are reported together with the mean values, while for the simulator a single curve is reported due to its implicit symmetry.

It can be seen that the simulator allows to reproduce fairly well the qualitative behaviour recorded during sea trials.

Considering in particular the manoeuvres at the higher speed, regarding the internal shaft a slight overestimation in correspondence to the lower angles and a slight underestimation in correspondence to the higher angles are recorded, while external shaft power is underestimated in the whole range.

It has to be noticed, however, that differences are very low (being less than 10%) and the most important phenomena are captured, with an almost linear power increase for the internal shaft and the automation effect clearly visible for the external shaft.

Considering the manoeuvres at lower speed, the qualitative behaviour is again reproduced, even if for the
external shaft power in correspondence to lower angles a higher error (about 15%) is experienced.

In order to have a better insight in the simulator behaviour, the complete time histories of the most important parameters have been analysed; as an example, in following Figures 20-22 external and internal power and ship speed are reported for the turning circle manoeuvre in correspondence to the lower ship speed and the higher rudder angle.

In following Figures 23 and 24, increments of P/N³ values instead of absolute power values are reported, in order to consider the possible different behaviour in terms of propeller revolution during different manoeuvres and simulations.

It can be seen that the adoption of this alternative representation allows to collapse data for the internal shaft, showing again a very good agreement between simulated and experimental results. Moreover, this representation allows also to improve the results in terms of timing of the power increase for the external shaft.

The unique problem remaining is linked to the initial power reduction for the internal shaft (limited anyway to about 15%), which is probably linked to a too fast introduction of the Δω value. From this point of view, therefore, the assumption of linearity between Δw and β should be further considered, while it seems correct for the external shaft.

Similar results have been obtained for other turning circle manoeuvres, even if they are not represented in the present paper for the sake of simplicity.

A final comparison has been made considering also the overall trajectories obtained using the simulator; in particular, in the following Figure 25 simulated and experimental turning circle trajectories in correspondence.
of the higher rudder angle and the lower ship speed are reported.

![Fig. 25: Simulation results vs experimental data](image)

Also from this point of view, a good correspondence between simulations and experiments has been obtained. In order to analyse the simulator behaviour in correspondence to manoeuvres different from the ones utilised for calibration, two ZigZag manoeuvres have been considered. In particular, 20°/20° ZigZag manoeuvres have been simulated in correspondence to the two speeds analysed.

In following Figures 26-27 and 28-29, P/N\(^3\) and ship speed time histories are reported for the higher and lower ship speed respectively. As an example, moreover, typical ship heading versus rudder angle time history is also reported in following Figure 30 for the lower ship speed. It can be seen that also in correspondence to the zigzag manoeuvre a rather good correspondence has been found, stressing the simulator capability of capturing also manoeuvres different from the ones used for the calibration.

![Fig. 26: Simulation results vs experimental data](image)

![Fig. 27: Simulation results vs experimental data](image)

![Fig. 28: Simulation results vs experimental data](image)

![Fig. 29: Simulation results vs experimental data](image)

Once again, the problem of initial internal shaft power reduction is experienced, while the \(\Delta w - \beta\) linearity assumption seems to allow a good capturing of shaft power time history in the remaining part of the manoeuvre, stressing the capability of the simulator of reproducing manoeuvres with large transients like the ZigZag manoeuvres. In particular, peak increment values are very well captured for both manoeuvres, while slightly larger hollows are predicted.
Regarding manoeuvring parameters, ship speed reduction is well captured as an average, even if a certain difference seems to exist, with correct speed oscillations at twice the rudder frequency for the simulator and lower speed oscillations for the experiments; this difference is probably due to the full scale automation plant behaviour. Overshoot angles are also well captured, and a slight period overestimation (about 5%) is experienced.

4.2 PROPULSION PLANT BEHAVIOUR ANALYSIS
After validating the mathematical model adopted in the simulator, a series of different manoeuvres have been performed in order to analyse the propulsion plant behaviour in correspondence to different conditions. In particular, turning circle manoeuvres in correspondence to maximum rudder angle at different speeds have been simulated, since this is the condition for which the maximum shaft power increases are experienced.

In following Figures 31 and 32, results in terms of power and torque increases at different speeds are reported. In particular, two different curves are represented; the one with continuous line is referred to a possible functioning with one prime mover per shaft up to $F_R = 0.25$ and two prime movers for higher speeds (indicated as Mode 1), while the dotted line is referred to a functioning with both prime movers at all speeds (indicated as Mode 2).

In the first case, automation acts in correspondence to two speed ranges, i.e. the intermediate ones for which one prime mover allowed power is saturated and the maximum ones for which two prime movers allowed power is saturated; in the second case, obviously, automation acts only in correspondence to highest speeds. In both cases, therefore, the two separated shaft lines are controlled by automation, which limits power increase when prime movers allowed power is saturated, while when prime movers are not saturated the power increases at different speeds are almost constant (about 75-80% for the external one and 20-35% for the internal one).

In the following paragraph, some considerations about possible different behaviour in correspondence to different propulsion plant configurations are reported.

4.3 FURTHER CONSIDERATIONS
As presented in previous paragraph 4.1, a mathematical model which allows to consider with a satisfactory approximation the real behaviour of a ship propulsion plant including automation system has been developed and tested successfully against different experimental data.
Moreover, different possible manoeuvres have been simulated for the same ship in order to analyse her behaviour, and the results confirm that the automation plant is able to limit power increases in different propulsive configurations (i.e. one prime mover per shaft or two prime movers per shaft) in correspondence to a propulsion system with completely separated shaftlines.

It is believed that such a model could be of great help in order to simulate the behaviour of the propulsion system in correspondence to a different configuration with shaftlines coupled to their prime movers by means of a unique reduction gear (as in Fig.1).

In such a case, high power (and torque) increases could be experienced by shaft axes if not properly controlled, and the reduction gear itself could experience significant unbalances on the two axes, with possible vibrations and fluctuating loads.

As an example, assuming that the automation controls only parameters of the prime movers and considering a power increase of 80% for the external shaft and 20% for the internal shaft, values of power increase for the two shafts can be estimated.

In particular, in correspondence to a ship speed for which the maximum power of the prime mover(s) is reached during manoeuvres, the external and internal shaftlines would experience a total power 20% higher and 20% lower respectively than their maximum during rectilinear path at 100% power, thus resulting in a considerable overload of a shaftline, and in a difference of about 50% between the unbalanced torques.

As a consequence, the need for a direct control of torque on the two shaftlines is evident, together with a tuning of the automation in order to avoid problems on the shaftlines themselves, not controllable only at the prime mover(s) level.

Regarding maximum power (or torque) on the shaftlines, this could be reduced during manoeuvres by means of a reduction of propeller blade angle (if CPP are equipped) or propeller revolutions (both for CPP or FPP). It has to be underlined that probably a reduction of propeller revolutions is less fast than a pitch reduction, and this has to be carefully taken into account.

Moreover, for what regards the unbalance of torques on the two output shafts of the reduction gear, it has also to be pointed out that in case of CPP automation could decouple the two shaftlines by means of different propeller blade angles, while in case of FPP the possible reduction of propeller revolutions cannot reduce the unbalances, but only the absolute values of the two torques.

From these points of view, it is believed that a complete simulator of the propulsion system, including also a detailed mathematical model of the reduction gear and of the automation control, is necessary in order to simulate the different scenarios that the ship can encounter during her operation and evaluate the correct countermeasures to avoid possible problems and failures.

5. CONCLUSIONS

In this paper a simulation approach able to represent the dynamics of a twin-screw ship propulsion plant taking into account the significant unbalances which can be generated in correspondence to manoeuvring conditions has been presented. The developed numerical model includes ship manoeuvrability, taking into account the effects of manoeuvres on shaftlines load and the dynamic behaviour of prime movers, shaft lines, propellers and propulsion control system.

Numerical results obtained have been compared to full-scale measurements in order to validate the proposed simulation approach, with satisfactory results.

It is believed that this method, despite presenting some simplifications, can be a useful tool for the control system designer for twin screw ships with coupled shaftlines (see figure 1), which can experience shaft overloads or forces unbalances on the reduction gear if the described phenomenon is not properly taken into account.

Next steps needed to gain a further insight into the problem consist in a complete modeling of a ship propulsion plant with coupled shaftlines, with particular attention to the cross connected reduction gear and to the optimization of the automation system strategy, with all necessary controls needed to prevent possible problems.

Moreover, a further analysis and comparison of model tests and full scale trials would allow to have a better understanding of the existing scale effects, allowing to have more reliable predictions of shaft unbalances if ships significantly different from the ones already analysed have to be considered.

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