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NUMERICAL ANALYSIS OF THE SHIP PROPULSION CONTROL SYSTEM EFFECT ON MANOEUVRING CHARACTERISTICS IN MODEL AND FULL SCALE

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Abstract. A comprehensive approach to simulate the interaction between the ship propulsion system and manoeuvrability, during transients and off design conditions, is presented.

The increasing attention on the manoeuvring features of the vessel has forced designers to consider this aspect already in the preliminary stages of the project.

Data about manoeuvring characteristics may be obtained by means of several model tests (at planar motion mechanism or with free running models). However, differences between model tests and full scale trials exist. From the hydrodynamic point of view, some disagreements are due to the scale effects but also the effect of the propulsion control system, highly non-linear, may provide a considerable contribution to such differences.

These dynamical aspects cannot be taken into account with traditional methodologies and purely stationary approaches. For these reasons, the ship dynamic behaviour is evaluated by time domain simulators, developed by the authors, which include the ship dynamics, the propulsion plant dynamics and the propulsion control system logics.

At the end of the paper some simulation results are shown in order to better understand the effects and the differences of the propulsion control settings on the ship manoeuvrability in model and full scale.

1 INTRODUCTION

The dynamic behaviour of the propulsion system is mainly affected by the control system performance, in particular by the strategies adopted to perform the required task within the boundary conditions imposed by machinery or environment constraints. This is particularly evident when fast transients are present, as experienced in the case of tight manoeuvres.

To prevent possible failures, the control system must be properly set, through dedicated control functions, to maintain the shaft torque or the engine torque within the allowed limits, to reach and maintain the required rotational shaft lines speed, etc.

As it is well known, during manoeuvring of a twin-propeller vessel, like turning circle or zig-zag manoeuvres, significant unbalances on the shaft lines, in terms of torque and thrust loads, are experienced. As regards the propulsion and the control system design, this aspect has to be taken into account together with the general increase of the shaft torque with respect to the steady state value.

Usually the ship manoeuvring characteristics are evaluated by a series of model tests. In some cases, the model tests are performed with a free running model. The model hull geometry is perfectly reproduced by the scale factor, on the contrary, because of economic reasons, or technical problems, an exact scale propulsion plant (engines, propellers, etc.) cannot be installed on the free running model. Moreover, also the installed control system is simplified with respect to the full scale, often its interaction with the propulsion plant is not realistic (or even not existent at all) and consequently it does not affect the model manoeuvring characteristics.

As a consequence, possible unexpected behaviours may be experienced during sea trials, such as shaft lines revolutions drop, alarm activation in the control panel, propulsion system stopping due to the intervention of various protections. The best way to evaluate the different behaviours between the model and the full scale in preliminary design, is adopting simulation techniques. By means of these techniques, it is possible to evaluate the different behaviours of the propulsion plant (even in off design and/or potentially dangerous conditions) and to understand their causes.

On the basis of previous free running model experiments, general ideas about the simulation of the interaction of propulsion control and manoeuvring systems are outlined in this paper. The proposed simulation tools may be helpful to the designers for various tasks, such as the correct shaft line sizing or the propulsion control system tuning.

The considered ship for the present analysis is a fast twin screw / twin rudder ship, similar to those analysed in [1], whose range of main characteristics values is reported in Table 1, where L is the ship length, B is the ship beam, T is the draft and C_B is the block coefficient.

Table 1: Main characteristcs of ships analysed [1]

L/B	5.5 - 8.5
B/T	2.75 - 3.75
C_B	0.5 – 0.65

2 PROPULSION AND MANOEUVRING SIMULATOR

The simulation model has been developed starting from the methodology proposed by the authors in [2]. In particular, the numerical code, developed by Matlab® software, is a simulation platform that allows to study the vessel behaviour during transient conditions (acceleration, deceleration, etc.) as well as during steady state conditions (constant speed navigation). Such type of simulation models have proven their validity in a considerable number of previous works, including validation at sea [3][4].

Three different ship macro systems contribute to the global ship behaviour: the ship manoeuvrability, the propulsion plant and the control system. For each macro system, different elements have been modelled using differential and algebraic equations and tables. In detail, the following propulsion plant elements have been schematized: the main engines, the gearbox, the shaft lines. From the control system point of view, mathematical models, representing the propulsion plant supervisor controller as well as the local machineries controllers, are present. The ship motions have been evaluated by a numerical model characterized by three degrees of freedom; the model includes, as usual, forces due to the hull, the propulsors and the rudders, following the widely used modular approach. All the interactions among the different machineries/elements have been properly modelled, considering the ship like a whole system.

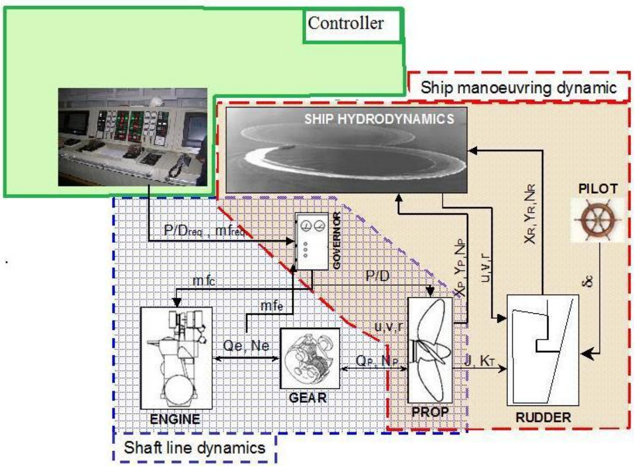

Figure 1: Simulator Architecture

As previously mentioned, a simulator was developed for both free running model and full scale ship. This step has been easily achieved by means of the simulator modular structure. The details of ships configurations are reported in the following sections.

2.1 Propulsion Plants

The main differences between the two developed simulators concern the propulsion plant. The free running model propulsion system is very simple, with two fixed pitch propellers driven by two Electric Propulsion Motors. The propulsion plant layout is shown in Figure 2.

The full scale (ship) propulsion plant is a CODLAG (COmbined Diesel eLectric And Gas turbine) system. As regards the prime movers, one gas turbine is used when a high power is required. One electric motor for each shaft is installed for low speed or silent operation. When the maximum power is needed, the main engines may be used all-together. A particular kind of gearbox is present, characterized by one input and two output shafts. Each shaft drives a controllable pitch propeller. The propulsion plant layout is shown in Figure 3.

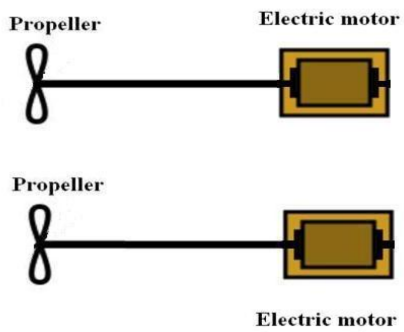

Figure 2: Model propulsion plant

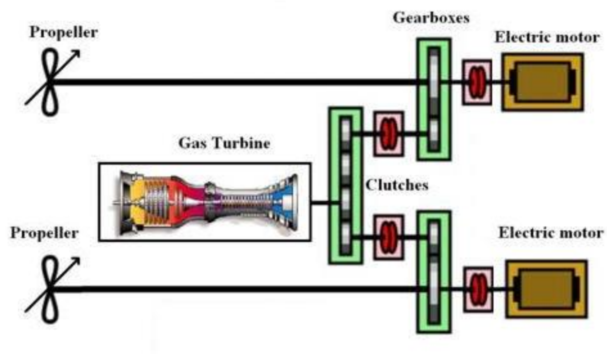

Figure 3: Full scale propulsion plant

The two shaft lines have been studied independently. By solving the differential equations of the shaft lines (1) it is possible to obtain the shaft lines dynamics.

$$2\pi J_p \frac{dn(t)}{dt} = Q_e(t) - Q_p(t) - Q_f(t) \quad (1)$$

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

The aim of this paper is to focus attention on the propulsion controller, therefore a simplified model for the main engines has been used in order to reduce the computational time. Considering the electric motors, the torque has been modelled by a proper transfer function, applied to the shaft revolution error between setpoint and feedback. With regard to the gas turbine, the numerical dependence of power on shaft revolutions and fuel consumption flow rate has been used; the adopted data have been provided directly by the manufacturer. By an interpolation process, it is possible to obtain the gas turbine power (or torque). The fuel flow is evaluated by the gas turbine controller, on the basis of the gas generator rotational speed. Finally, the gearbox model includes the speed reduction ratio and the logics of the clutches activation.

2.2 Propulsion Control Systems

As remarked above, the propulsion control is usually very simple in model tests; in the present case, a series of free running model tests have been carried out preliminarily using various control system approaches, namely keeping constant (and equal to the value of the approach phase) revolution per minute (RPM), torque or power. The simulator in model scale has been calibrated on the basis of experimental results, showing a good correspondence in all the control system configurations, as reported in [5]. The constant RPM approach is more frequently adopted in free running model tests, because of its straightforwardness; this work mainly focuses on it.

In the full scale ship, and then in her simulation model, the use of a CODLAG propulsion system with two controllable pitch propellers led to the need of developing dedicated control functions [4]. First of all, the propulsion system is managed by a typical "combinator" law, where the equilibrium point for pitch and rpm have been implemented. For what concerns the engines, a limiting maximum torque, based on a PID algorithm was introduced.

Moreover, the over torque protection for shaft lines was also introduced, by means, at first, of a control function reducing propeller pitch; when this action is not sufficient, a fuel flow rate reduction acts in order to avoid shaft lines overload. Due to the particular gearbox, that forces the two shaft lines to operate at the same rpm, also a torque balance function has been designed. An overview on the considered control variables is shown in Figure 4.

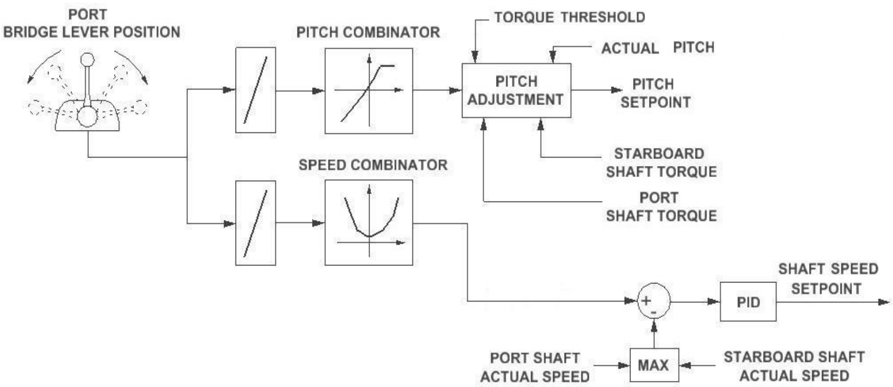

Figure 4: Control system layout

2.3 Manoeuvrability model

The model used in this work is fully described in [6] and [7], to which the reader is referred for a more detailed discussion. The model, characterized by a modular form, has been specifically developed in order to consider the peculiarities of a twin screw ship manoeuvrability, with particular attention to the appendages configuration, which may play a very important role. A further peculiarity of the adopted model is the possibility to consider shaft unbalances. In particular, the asymmetric behaviour of the two shafts is considered using an asymmetric variation of the wake fraction, as already proposed in [8].

In addition to this, the large amount of experimental data, recorded during the free running model tests, allowed to further validate the manoeuvrability model in order to take into account a second asymmetry in propeller thrust, by means of an asymmetric correction factor applied to the propeller thrust during manoeuvres [5].

In particular, the values of the two correction coefficients were evaluated for the internal and external shafts on the basis of experimental data as a function of the ship drift angle (obtained at different rudder angles during manoeuvres) and of the ship speed.

The mathematical model is the same for the two simulators in model and full scale configuration and the hydrodynamic coefficients have been voluntarily considered constant; the total resistance of the hull has been opportunely scaled in accordance to usual practice.

3 SIMULATION RESULTS

In this section, some simulation results concerning both the free running model and the full scale ship are presented, allowing to outline some differences between the two cases. Three manoeuvres, corresponding to different rudder angles δ_R and Froude numbers Fn, have been proposed hereinafter (Table 2).

Table 2: Proposed manoeuvres

Test	δ_R [°]	[F_n]
Turning circle (A)	max	0.26
Turning circle (B)	max	0.39
ZIG-ZAG (C)	δ_0	0.39

For all the simulated manoeuvres, trajectory, heading, velocities and propulsion parameters have been considered. In the following figures, non-dimensional data are reported; propulsion parameters (propeller pitch, shaft revolutions, torque), have been made non dimensional with respect to the values corresponding to the rectilinear motion in the approach phase.

The first simulated manoeuvre (A) is a turning circle at medium speed. In this manoeuvre the influence of the control system is practically not visible, since all machineries operate below their operational limits and no protection actions are required. However, it is possible to see, in Figure 10, the asymmetrical behaviour of the two shafts with torque increasing more on the external shaft (about 60% with respect to 20% on internal shaft in correspondence to the stabilized phase of the manoeuvre) for both model and full scale ship. In Figure 6, 7 and 8 it is possible to appreciate some differences between velocities; these differences could be partly due to the different propeller working regimes in full and model scales (for example resistance scaling), and to the consequent different effect on the rudder. As a consequence, the predicted trajectory is slightly larger in full scale.

The second manoeuvre (B) is a turning circle corresponding to a higher speed, slightly lower than the maximum speed. In this case, it possible to appreciate larger differences between the model and the full scale ship. Figure 18 shows the shaft torque during the proposed manoeuvre, clearly showing the torque limitation for the external shaft in order to avoid over torque. This reduction is achieved acting on the propeller pitch (see Figure 15). In addition to this, in Figure 17 a decrease of shaft revolution for both shafts is visible; this reduction is due to the prime mover not being able to provide the required torque. As a consequence of this propulsion system running, it is possible to see (Figure 13, 14, 16) that the ship velocities drop is slightly larger in full scale than the previous manoeuvre.

Also the effect on the trajectory is slightly larger, even if still resulting in rather small variations.

The last proposed manoeuvre (C) is a Zig-Zag manoeuvre at a high speed. Also in this case, a propeller RPM reduction (Figure 23) is visible in full scale, due to the torque limits of the prime movers; moreover, a further (very limited) torque reduction on the external shaft during each counter-rudder, by means of the propeller pitch (Figure 25), is present. Notwithstanding these differences, it is clear that the effect on the manoeuvre is very limited, since the macroscopic parameters are almost invariant (Figure 26 and 19-22).

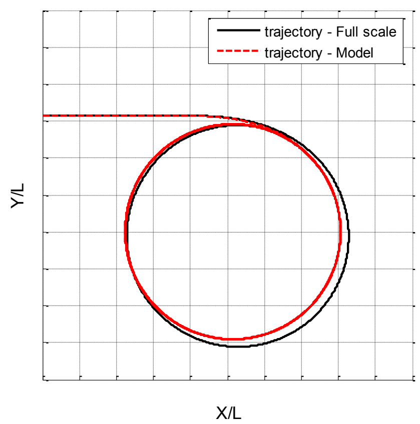

Figure 5: Ship trajectory (man A)

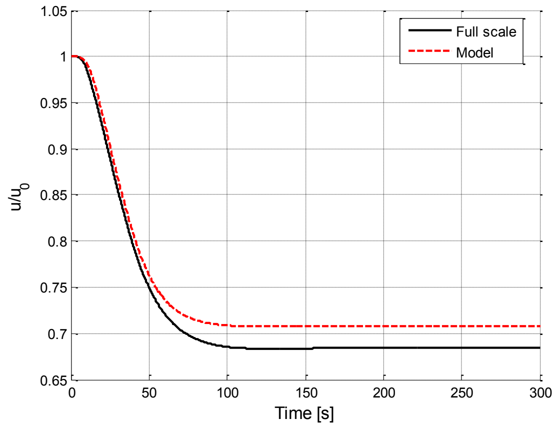

Figure 6: Surge velocity vs. Time (man A)

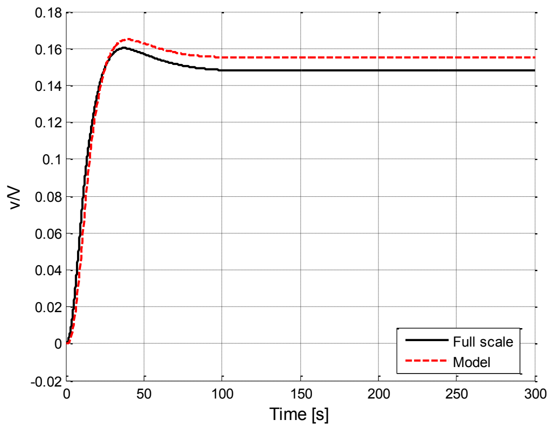

Figure 7: Sway velocity vs. Time (man A)

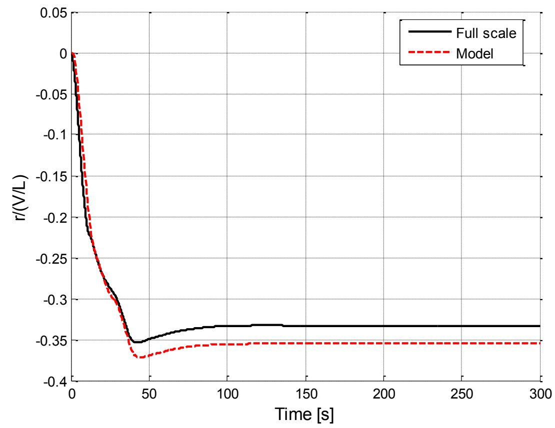

Figure 8: Yaw rate vs. Time (man A)

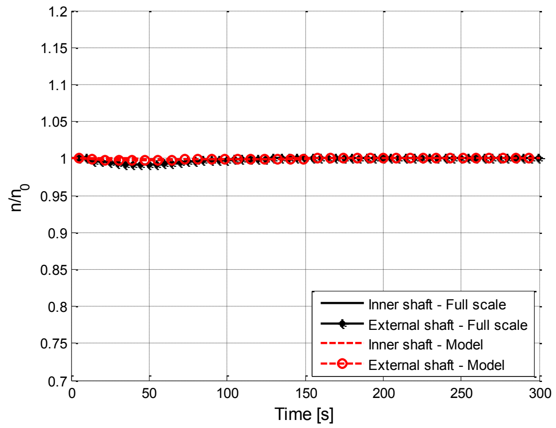

Figure 9: Shaft lines revolution vs. Time (man A)

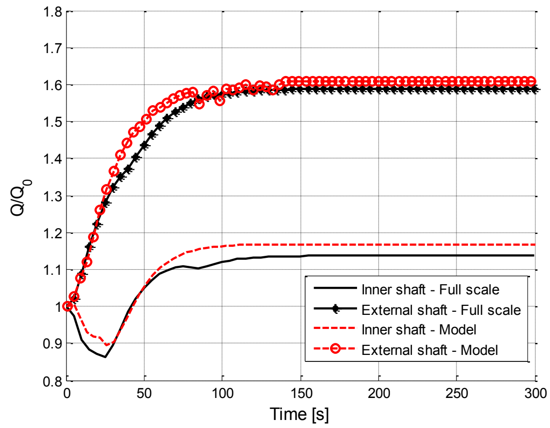

Figure 10: Torque vs. Time (man A)

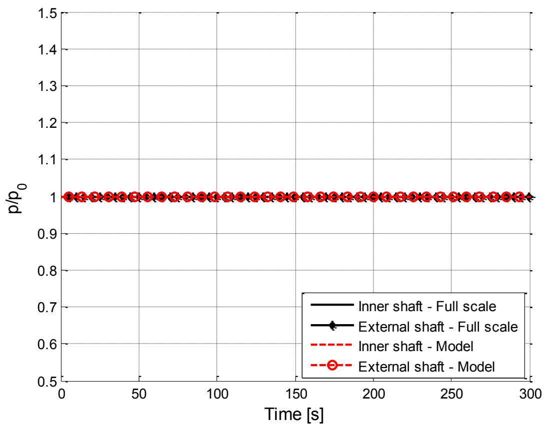

Figure 11: Pich angle vs. Time (man A)

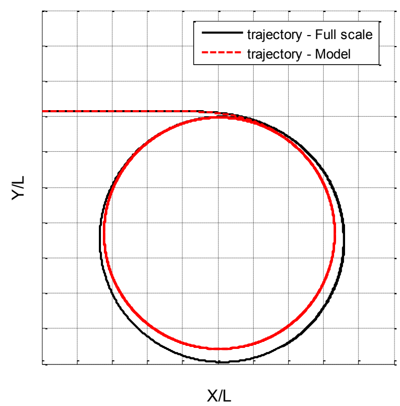

Figure 12: Ship trajectory (man B)

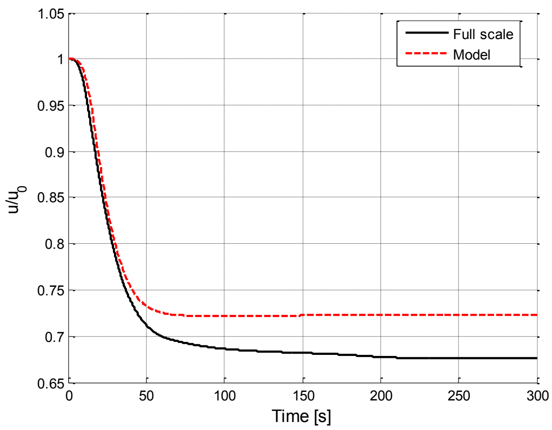

Figure 13: Surge velocity vs. Time (man B)

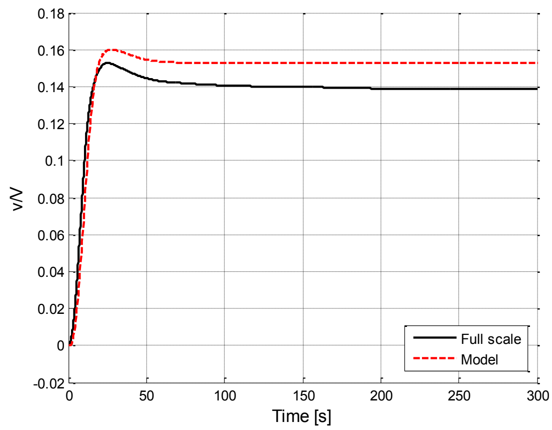

Figure 14: Sway velocity vs. Time (man B)

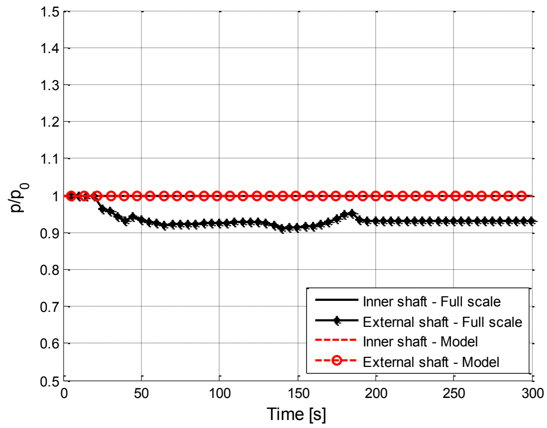

Figure 15: Pich angle vs. Time (man B)

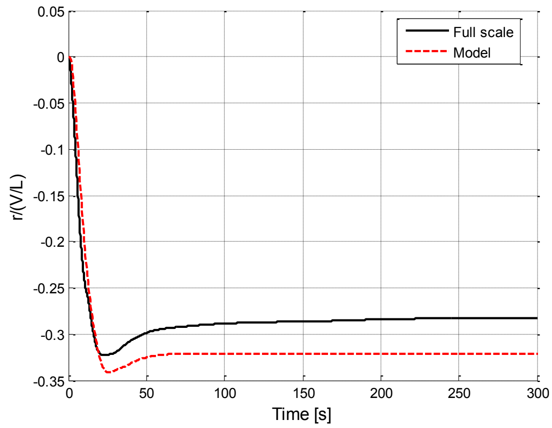

Figure 16: Yaw rate vs. Time (man B)

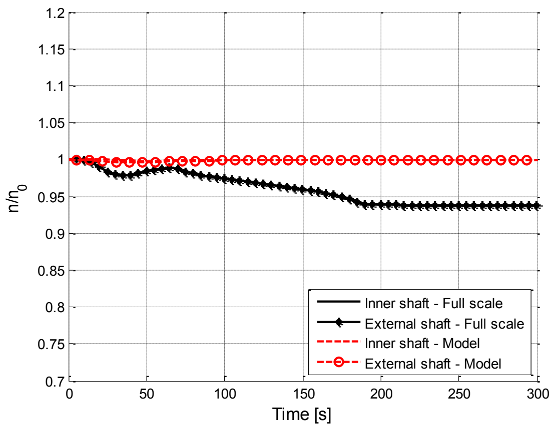

Figure 17: Shaft lines revolution vs. Time (man B)

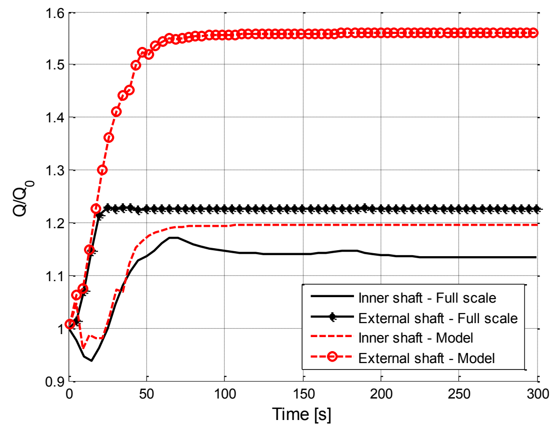

Figure 18: Torque vs. Time (man B)

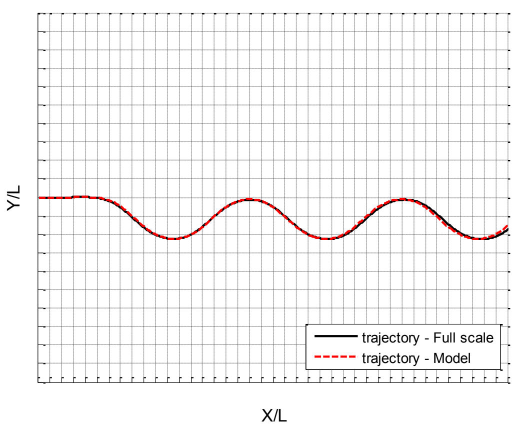

Figure 19: Ship trajectory (man C)

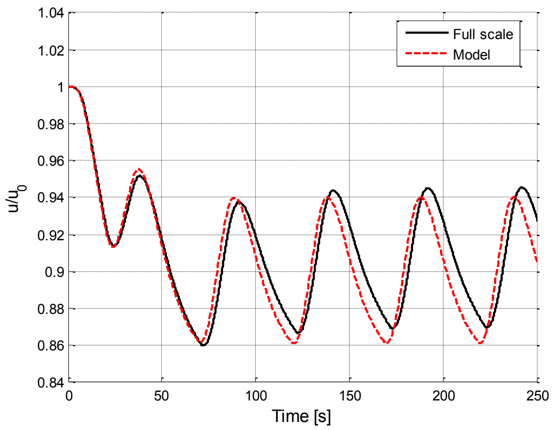

Figure 20: Surge velocity vs. Time (man C)

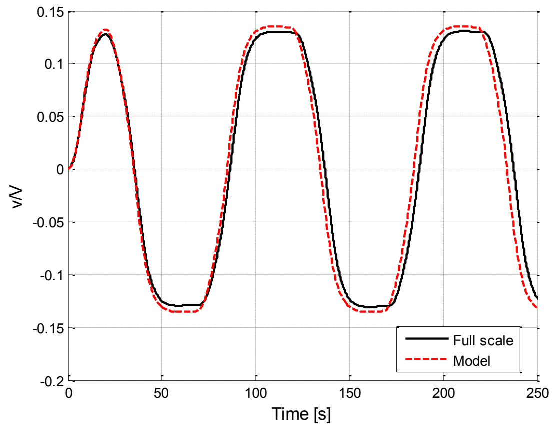

Figure 21: Sway velocity vs. Time (man C)

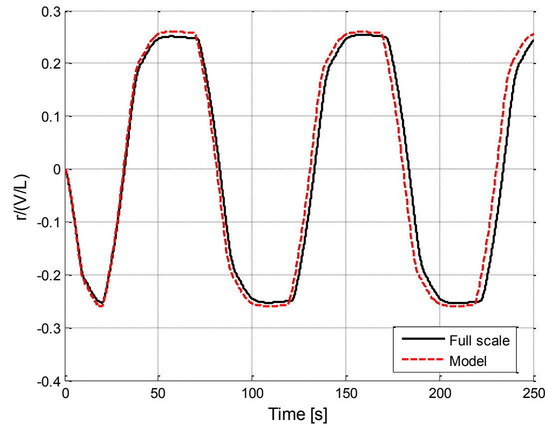

Figure 22: Yaw rate vs. Time (man C)

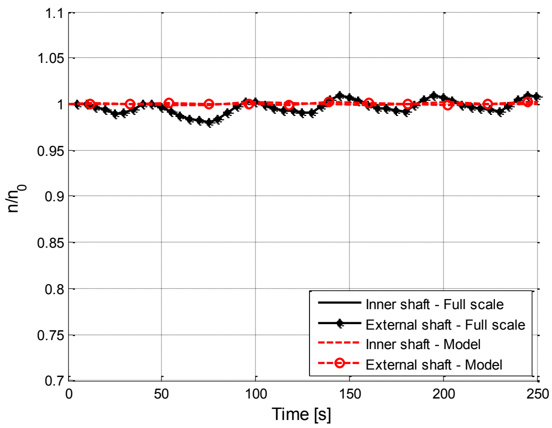

Figure 23: Shaft lines revolution vs. Time (man C)

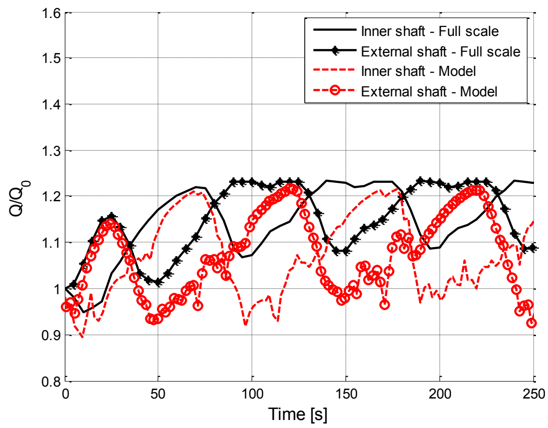

Figure 24: Torque vs. Time (man C)

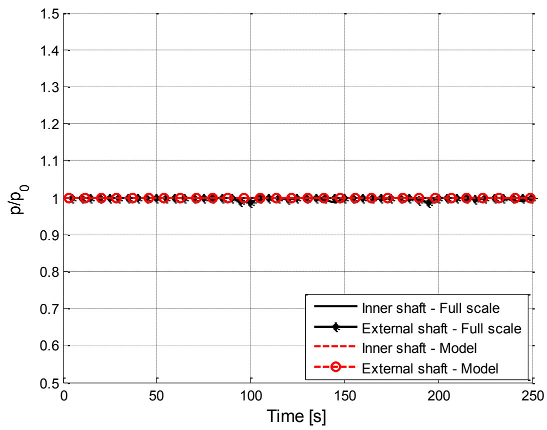

Figure 25: Pich angle vs. Time (man C)

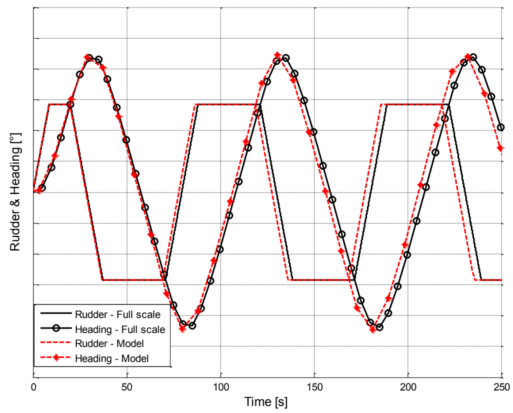

Figure 26: Rudder & Heading vs. Time (man C)

4 CONCLUSIONS

A comprehensive time domain manoeuvrability and propulsion plant simulator representing a twin screw ship both in model scale and in full scale, has been presented. The developed simulation models present the peculiarity of a modular structure that allows to represent the ship in different scales and with different propulsion configurations.

A series of simulations have been performed in order to analyse possible non-linear effects of automation on the propulsion plant behaviour during manoeuvres. For particular marine propulsion plants, these effects could not be analysed with model tests and would require the full scale ship availability.

The propulsion control effects resulted in a very limited influence on macroscopic manoeuvrability characteristics for low Froude numbers, as it could be expected, while differences are more significant when higher Froude numbers are considered.

It is believed that the simulation technique may be an essential tool in order to optimize the ship propulsion system control strategies or more generally the global ship performances. In order to increase the capability and reliability of the simulators, it is deemed of utmost importance to further validate the proposed methodology through full scale sea trials; the parallel analysis of model tests and full scale experimental data could be also useful in order to investigate other scale effects (e.g. variation of hydrodynamic coefficients) which have not been taken into account in the present work.

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