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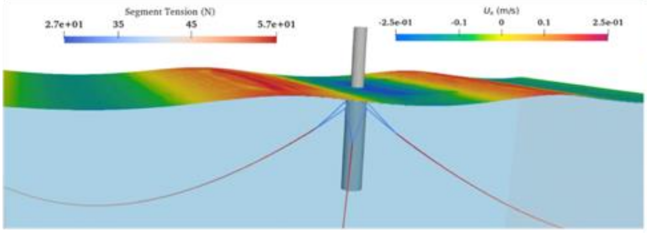

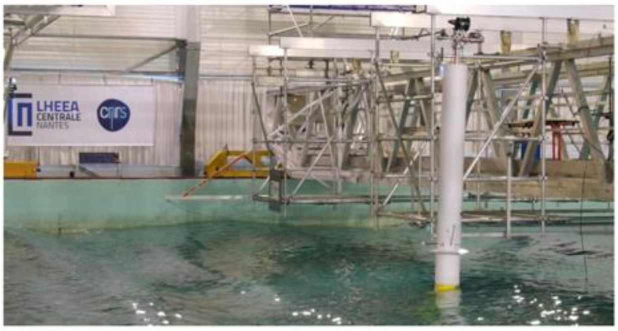

APPROCHE TEMPORELLE DE LA MANŒUVRABILITE ET DE LA TENUE A LA MER : DEVELOPPEMENT ET VALIDATION DE MODULES DEDIES AU SEIN D'UN SIMULATEUR SYSTEME

TIME DOMAIN APPROACH FOR MANOEUVRABILITY AND SEAKEEPING: DEVELOPMENT AND VALIDATION OF DEDICATED MODULES WITHIN A SYSTEM-BASED SIMULATOR

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Résumé

La manœuvrabilité et la tenue à la mer des navires sont habituellement traitées séparément, et la manœuvrabilité sur houle a été relativement peu étudiée. L'arrivée récente ou prochaine de réglementations concernant ce dernier aspect, principalement celles du STANAG ([1] et [2]) et de l'OMI ([3] et [4]), et la nécessité croissante de fournir au concepteur un outil permettant d'obtenir des informations préliminaires sur la manœuvrabilité du navire sur houle dès le début de la phase de conception ont conduit à la nécessité de pouvoir prédire les performances des navires en tenue à la mer et en manœuvrabilité sur un domaine plus large que le domaine classique.

L'objet des travaux présentés dans cet article est d'améliorer la modélisation de la manœuvrabilité sur houle au sein du simulateur temporel xdyn en s'appuyant sur des essais en bassin sur l'ONRT. Des résultats pour des manœuvres de tenue de cap, zig-zag et giration sont présentées.

Summary

Until recently, manoeuvrability and seakeeping have been dealt with separately, and manoeuvring in waves has been little studied and evaluated. Some recent or upcoming regulations concerning manoeuvring in waves, mainly from STANAG ([1] and [2]) and IMO ([3] and [4]), and the growing need to provide the designer with a tool which allows to get preliminary information about the ship manoeuvrability in waves in the early design stage have led to the need to be able to predict seakeeping and manoeuvring performances of ships in a wider domain than the classical one.

The work presented in this paper aims at improving the modelling of manoeuvres in waves within the time domain simulator xdyn based on model tests on the ONRT ship. Results for heading keeping, zigzag and turning circle manoeuvres are shown.

I – **Introduction**

In time domain simulation, two main approaches are usually considered to take into account both manoeuvring forces and wave frequency forces, as described in [10]: the unified method, which consists in solving the ship motions using both low-frequency forces (typically manoeuvring) and high-frequency forces (induced by waves), and the two-time-scale method, which consists in solving only the low-frequency ship motions in the time domain and adding the first order ship motions coming from a preliminary frequency domain calculation if necessary.

From previous experience and as stated in several papers, including [10], the use of a unified method is not fully appropriate in the context of a system-based simulator, basically relying on the superposition of separate models for each physics, and where these models are based on approximations and not on a direct resolution of the flow.

The work carried out and presented in this paper consisted in the development of dedicated force modules to be integrated within the time-domain simulator xdyn [5]; xdyn is already able to deal with manoeuvring in calm water and in waves, at different stages: it is based on good basic models/approaches and is able to capture relevant effects, but the models are not yet complete for manoeuvring in waves. The main objective was to design, implement, test and validate more efficient and accurate models.

For the aforementioned reason, the developments focused only on the two-time-scale method, and the emphasis was on the manoeuvrability model and the second order wave drift forces. Aiming for better accuracy than classical coefficient-based manoeuvrability models, and possibly for better adequacy to each target ship at the cost of an additional pre-processing effort, the manoeuvring model consists in using a previously calculated force table, or alternatively a response surface based on such a table, using drift angle, non-dimensional yaw rate and ship speed as inputs. The mean and slowly varying second order wave drift forces are computed using the Newman approximation, which usually shows to be sufficient and is much less time-consuming than a full-QTF approach.

For validation purposes, a comprehensive set of model tests were carried out on the ONRT ship, namely captive, semi-captive and free-running tests. They were used to test the elementary models described above and to validate the overall manoeuvring behaviour and performance of the ship in calm water and in waves, through heading keeping, zigzag and turning circle manoeuvres.

II – **Ship characteristics**

The ship chosen for the work presented in this paper is the ONRT. The main characteristics used are given in the table below, at full scale; they are intended to be similar to those used for the SIMMAN 2020 workshop [7], except for k_{xx}.

Figure 1: ONRT ship.

Quantity	Symbol	Unit	Value
Length between perpendiculars	L_{PP}	m	154.00
Breadth	B	m	18.78
Draft at aft perpendicular	T_A	m	5.494
Draft at forward perpendicular	T_F	m	5.494
Displacement volume	∇	m^3	8521
Displacement mass in seawater	Δ	t	8743
Longitudinal position of the centre of gravity from / AP	LCG	m	74.41
Vertical position of the centre of gravity	KG	m	7.62
Vertical position of the centre of buoyancy	KB	m	3.21
Transverse metacentric height	GMt	m	2.07
Non dimensional mass radius of gyration around x-axis	k_{xx}/B	-	0.374
Non dimensional mass radius of gyration around y-axis	k_{yy}/L_{PP}	-	0.246
Non dimensional mass radius of gyration around z-axis	k_{zz}/L_{PP}	-	0.246
Natural roll period	T_Φ	s	10.8

Table 1: ONRT characteristics.

III – Modelling

The work focused on system-based simulators, i.e. software tools which solve in time-domain the equations of the ship motions submitted to external forces, among which the hydrodynamic forces are modelled with simplified formulations, without any direct resolution of the fluid flow, but with a sufficient accuracy to provide the requested information in the target domains.

The time-domain solver architecture is not so much a difficulty, and several tools or methods exist for this purpose. One of them is xdyn, developed by SIREHNA.

III – 1 Basic models

The forces solved by xdyn include gravity, propulsion, rudder, non-linear hydrostatics, manoeuvring, viscous damping, radiation, non-linear Froude-Krylov, linear diffraction. Ship control can also be used if needed.

Non-linear hydrostatic and Froude-Krylov forces are computed considering the relative position of the ship in relation to the free surface and the incident waves.

Radiation forces are computed using retardation functions based on Cummins formulation [8]. This formulation as well as the computation of the diffraction forces need a seakeeping database coming from the frequency domain; for xdyn, this database is generated using the linear seakeeping code AQUA+ [6].

III – 2 Manoeuvring forces

Classical manoeuvrability models are coefficient based and derived from a set of well-chosen physical experiments (captive tests, with forced motions); they are usually limited to small drift angles and yaw rates and do not always correctly account for the changes in ship speed when they are large.

Therefore, the proposed method is aiming at more accuracy, and possibly a better adequacy to each target ship at the cost of an additional effort regarding pre-processing. It consists in using, rather than coefficient based models, a previously calculated force table, or alternatively a surface response based on such a table. In practice, the inputs of these tables are:

- ship velocity $U_0 = \sqrt{u^2 + v^2}$,
- drift angle $\beta = \tan^{-1}(v/u)$,
- non-dimensional yaw rate $r' = \frac{rL_{PP}}{\sqrt{u^2+v^2}}$.

with u and v the horizontal velocity components, r the yaw rate and L_{PP} the ship length.

Then, the time-domain calculation remains very fast, and allows a range of scenarios only limited by the range of variation of the table. In this respect, this approach virtually enables to deal not only with high speed/slow drift angle situations, but also with low speed/large drift angles, and even off-design situations such as backward speed/propeller rotation, etc.

This database can come from any source, in particular from a coefficient based model as mentioned above or from direct CFD computations. This latter approach is of course heavier than the previous one, but:

- it is more specific to each target ship, and can consider intrinsically specific geometric configurations or appendages that can affect the manoeuvrability (skeg, bilge keels, shafts and brackets, sonar domes, etc.), and thus a better accuracy can be expected than with semi-empirical methods;
- nowadays, a complete version of the hull shape can be expected quite early in the ship design process, which enables this approach requiring a good definition of the hull; the process can then be repeated all along the design evolutions.

In the case of the work presented here, the CFD computations were performed for ONRT ship using STAR-CCM+. An example of input values for drift angle and non-dimensional yaw rate is shown in the figure below.

Figure 2: Conditions for the CFD computations of the manoeuvring hull forces.

Once these CFD computations have been performed, a meta-model of F_X, F_Y, M_X and M_Z as functions of U_0, β and r' can be derived. An example of the obtained response surfaces for F_X and F_Y are shown in the graphs below in a (β, r') plane (hence for a constant U_0).

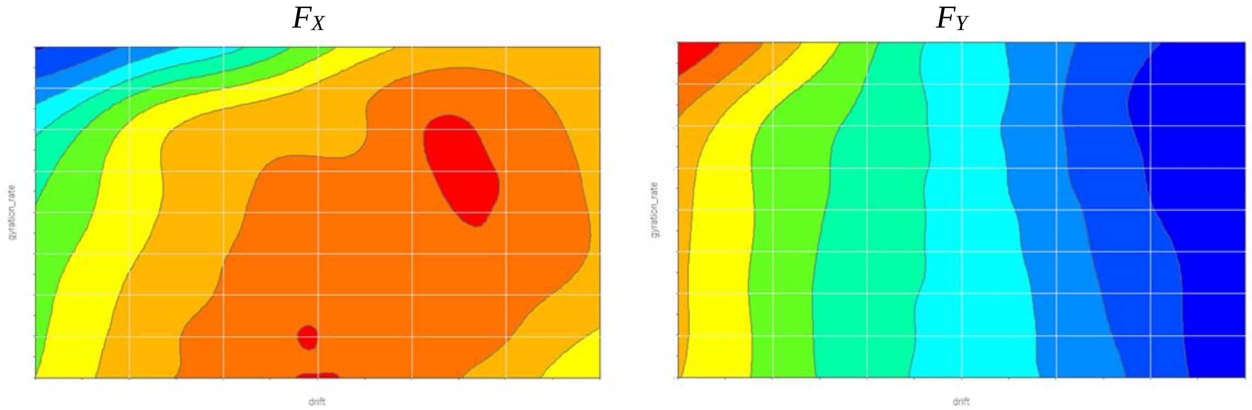


Figure 3: Response surfaces $F_X = f(\beta, r')$ and $F_Y = f(\beta, r')$.

The response surfaces obtained are then used directly within xdyn.

III – 3 Second order wave forces

Considering irregular waves as a sum of *N* linear regular waves, the time-varying wave elevation η at any point of coordinates $\vec{x} = (x, y)$ is given by:

$$\eta(t) = \sum_{i=1}^{N} a_i \cos\left(\overrightarrow{k_i} \cdot \vec{x} - \omega_i \cdot t - \varphi_i\right) \tag{1}$$

with a_i, k_i, ω_i and φ_i respectively the amplitude, the wave number, the angular frequency and the random phase of wave component *i*.

The wave numbers and angular frequencies are given by:

$$\overrightarrow{k_i} = \left(\left|\overrightarrow{k_i}\right| \cdot \cos\theta_i, \left|\overrightarrow{k_i}\right| \cdot \sin\theta_i\right) \tag{2}$$

$$\omega_i^{\,2} = g \cdot \left|\overrightarrow{k_i}\right| \cdot \tanh\left(\left|\overrightarrow{k_i}\right| \cdot h\right) \tag{3}$$

with θ_i, g and h respectively the wave direction of wave component *i*, the gravitational acceleration and the water depth.

The full quadratic transfer function (QTF) is then expressed using frequency pairs, and the time-varying slow drift (or difference frequency) second order forces are given by:

$$\begin{aligned} F^{(2)}(t) = \sum_{i=1}^{N}\sum_{j=1}^{N} a_i a_j \Big[& P_{ij} \cdot \cos\left(\left(\overrightarrow{k_i} - \overrightarrow{k_j}\right) \cdot \vec{x} - \left(\omega_i - \omega_j\right)t + \left(\varphi_i - \varphi_j\right)\right) \\ & + Q_{ij} \cdot \sin\left(\left(\overrightarrow{k_i} - \overrightarrow{k_j}\right) \cdot \vec{x} - \left(\omega_i - \omega_j\right)t + \left(\varphi_i - \varphi_j\right)\right)\Big] \end{aligned} \tag{4}$$

with $P_{ij} = P_{ij}\left(V, \omega_i, \omega_j, \overrightarrow{k_i}, \overrightarrow{k_j}\right)$ and $Q_{ij} = Q_{ij}\left(V, \omega_i, \omega_j, \overrightarrow{k_i}, \overrightarrow{k_j}\right)$ respectively the in-phase and out-of-phase QTFs at the considered ship speed, wave angular frequency pair and wave number pair.

Therefore, the mean wave drift forces are given by:

$$F^{(2)}(t) = \sum_{i=1}^{N} a_i^{\,2} P_{ii} = 2\sum_{i=1}^{N} S(\omega_i) P_{ii} d\omega_i \tag{5}$$

where $S(\omega)$ is the wave power spectral density, with

$$a_i^{\,2} = 2S(\omega_i)d\omega_i \tag{6}$$

Concerning the calculation of the slow-drift forces, Newman's approximation [9] allows to estimate their variations only from the diagonal of the QTF matrix, which reduces complexity and computing time: it assumes that P_{ij} and Q_{ij} can be estimated from P_{ii} and P_{jj} and from Q_{ii} and Q_{jj} respectively.

QTF are also assumed to be instantaneously valid, thus neglecting transient effects due to time-varying ship speed and heading.

Furthermore, as $P_{ij} = P_{ji}$ and $Q_{ij} = -Q_{ji}$, we derive:

$$Q_{ij} = Q_{ji} = 0 \tag{7}$$

$$P_{ij} = P_{ji} = \frac{1}{2}\left(P_{ii} + P_{jj}\right) \tag{8}$$

$$F^{(2)}(t) = \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N} a_i a_j \left(P_{ii} + P_{jj}\right) \cdot \cos\left(\left(\overrightarrow{k_i} - \overrightarrow{k_j}\right) \cdot \vec{x} - \left(\omega_i - \omega_j\right)t + \left(\varphi_i - \varphi_j\right)\right) \tag{9}$$

Another possibility, introduced by Standing et al. [11], is to use the geometric mean of terms instead of the arithmetic mean:

$$P_{ij} = P_{ji} = \sqrt{\left|P_{ii}P_{jj}\right|} \times \mathrm{sign}(P_{ii}) \tag{10}$$

leading to:

$$F^{(2)}(t) = \begin{array}{l} \left[\sum_{i=1}^{N} a_i \left(\sqrt{|P_{ii}|} \times \mathrm{sign}(P_{ii})\right) \cdot \cos\left(\vec{k_i} \cdot \vec{x} - \omega_i t + \varphi_i\right)\right] \times \sum_{i=1}^{N} a_i \sqrt{|P_{ii}|} \cdot \cos\left(\vec{k_i} \cdot \vec{x} - \omega_i t + \varphi_i\right) \\ + \left[\sum_{i=1}^{N} a_i \left(\sqrt{|P_{ii}|} \times \mathrm{sign}(P_{ii})\right) \cdot \sin\left(\vec{k_i} \cdot \vec{x} - \omega_i t + \varphi_i\right)\right] \times \sum_{i=1}^{N} a_i \sqrt{|P_{ii}|} \cdot \sin\left(\vec{k_i} \cdot \vec{x} - \omega_i t + \varphi_i\right) \end{array} \tag{11}$$

This approximation allows to considerably reduce the number of additions (from N^2 to $4N$). Furthermore, to stick with low frequency forces, it is not required to perform the complete double summation: the summation needs to be done up to a maximum encounter difference frequency, to be defined by the user.

The QTF data used as input for this force model come from the aforementioned AQUA+ seakeeping database.

IV – Model tests

The aim of the model tests was to support the developments and validation of the time-domain simulation tool, with two main objectives:

- providing information on the involved phenomena, to support the design and elementary verification of individual models of the simulator;
- providing information and data for the global validation of the simulator.

For this purpose, the model tests included captive tests (forced motions), semi-captive tests (added resistance in waves) and free running tests on a ship model including propellers and rudders, with local forces measurements.

The model tests were performed at MARIN, in the Seakeeping and Manoeuvring Basin (SMB).
A scale ratio of 1 to 24.9 was chosen.

IV – 1 Captive manoeuvring model tests in calm water

The captive model tests were performed using a Computerised Planar Motion Carriage (CPMC), which allows to perform predefined planar motions (like a PMM set-up) as well as unsteady motions. The model was free to heave and pitch.

Both bare and fully appended hull tests were performed (bare hull meaning that the propellers and the movable part of the rudders are removed from the fully appended hull); they included powering and propulsion, drift, rotation, combinations of rotation and drift, rudder angle variations.

IV – 2 Semi-captive seakeeping model tests

The semi-captive model tests were carried out using a configuration that enables to tow the model at a constant speed, while leaving free most degrees of freedom. The model was towed by the carriage by means of a flexible pole attached to a force transducer. During runs in waves, the propeller revolutions were set to the self-propulsion point in calm water. The additional pulling force needed to keep the speed constant was delivered through the pole and measured by the force transducer.

The tests were performed for various wave conditions in regular waves (variation of wave height and wave period) and irregular waves, with several wave headings.

IV – 3 Free-running seakeeping and manoeuvring model tests

All free-running model tests were performed with a self-propelled, free-running model.

Free-running tests comprised heading keeping and manoeuvres (zigzag and turning circle) in calm water and in waves. The tests in waves were performed for various wave conditions in regular waves (variation of wave height and wave period) and irregular waves, and with several wave headings for the heading keeping tests.

V – Validation

V – 1 Manoeuvring database

The manoeuvring meta-model generated from CFD computations was checked against the results of the captive model tests, using pure drift tests, pure yaw tests and several combinations of yaw rate variation with drift.

The following graphs show some of the comparisons between the model tests and the calculations.

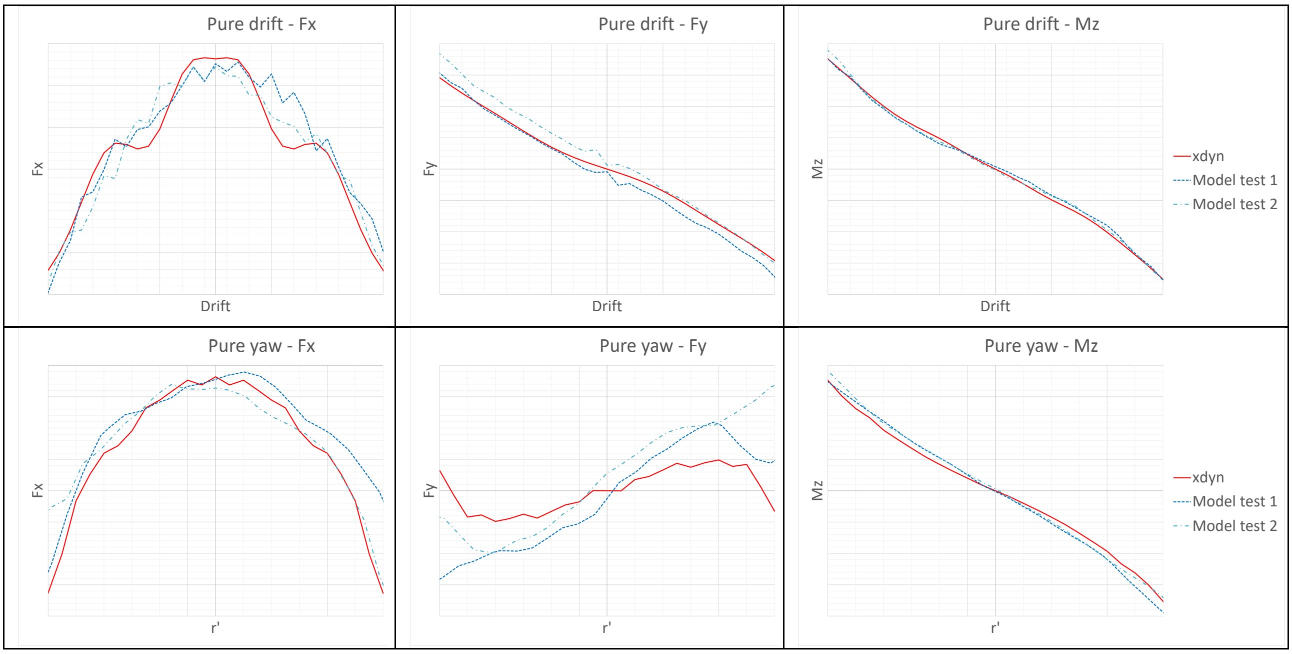


Figure 4: Comparison of model tests and xdyn manoeuvring model: F_X (left), F_Y (middle) and M_Z (right) for pure drift (top) and pure yaw (bottom).

These results show that the manoeuvring database and its usage within xdyn give results very close to the experimental ones. Only F_Y for some yaw tests show discrepancies, but the order of magnitude of the forces for these cases is much lower than for cases with drift.

V – 2 Seakeeping database

The longitudinal wave drift forces were checked against the results of the semi-captive and free running model tests for bow and stern quartering regular waves, for three different ship speeds.

The following graphs show the comparisons between model tests and calculations.

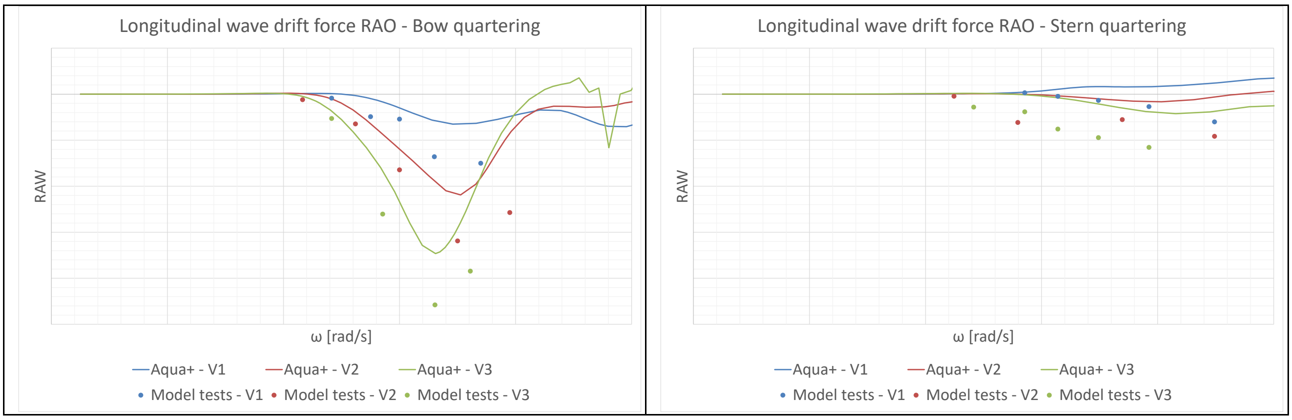


Figure 5: Comparison of model tests and AQUA+ longitudinal drift forces: bow (left) and stern (right) quartering waves; the same scale is used on both graphs.

These results show that the shape of the computed drift forces is similar to the one obtained during model tests for bow quartering waves, but the values are underestimated. On the other hand, the longitudinal drift forces are poorly predicted for stern quartering waves, even showing an opposite sign for the first (lower) speed; these latter forces are however one order of magnitude lower than those for bow quartering waves.

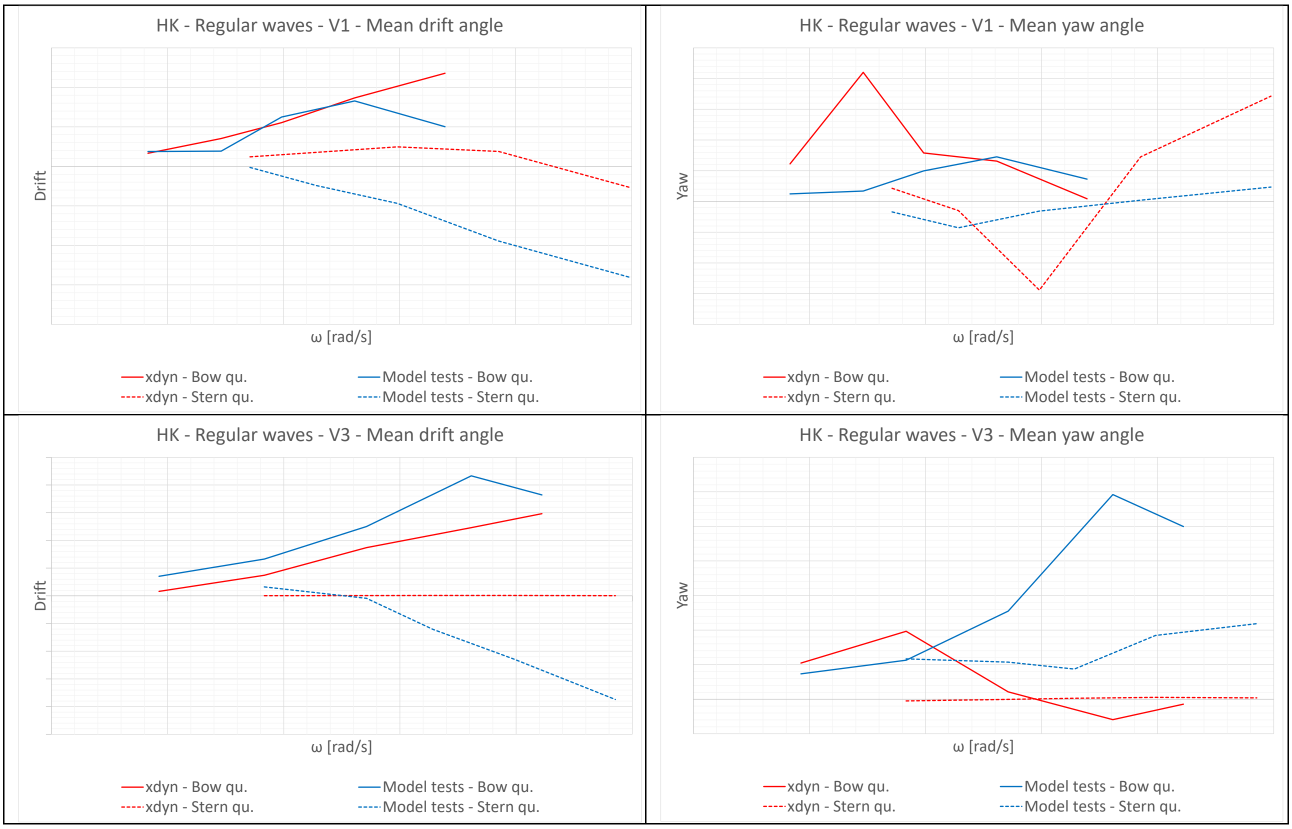
This can partly be explained by the fact that AQUA+ uses a zero-speed Green function approach, which is valid for low Froude numbers, and can start to give unrealistic results above a Froude number of 0.2, or even lower for second order forces. The use of a more precise method for considering the ship speed (for example a Rankine method) should improve the results.

These conclusions therefore lead to consider carefully the results of the xdyn simulations in waves when second order wave drift forces are used.

V – 3 Heading keeping

Some heading keeping simulations were performed for bow and stern quartering waves (at the same wave headings as in the previous section) and at 2 different speeds (V1 and V3), for regular and irregular waves (sea state 6 at V1 and sea state 4 at V3).

The following graphs show the comparisons between free running model tests and calculations.



HK - Regular waves - V1 - Mean drift angle

HK - Regular waves - V1 - Mean yaw angle

HK - Regular waves - V3 - Mean drift angle

HK - Regular waves - V3 - Mean yaw angle

Figure 6: Heading keeping – Regular waves – Comparison of model tests and xdyn results: mean drift (left) and yaw (right) angles at V1 (top) and V3 (bottom).

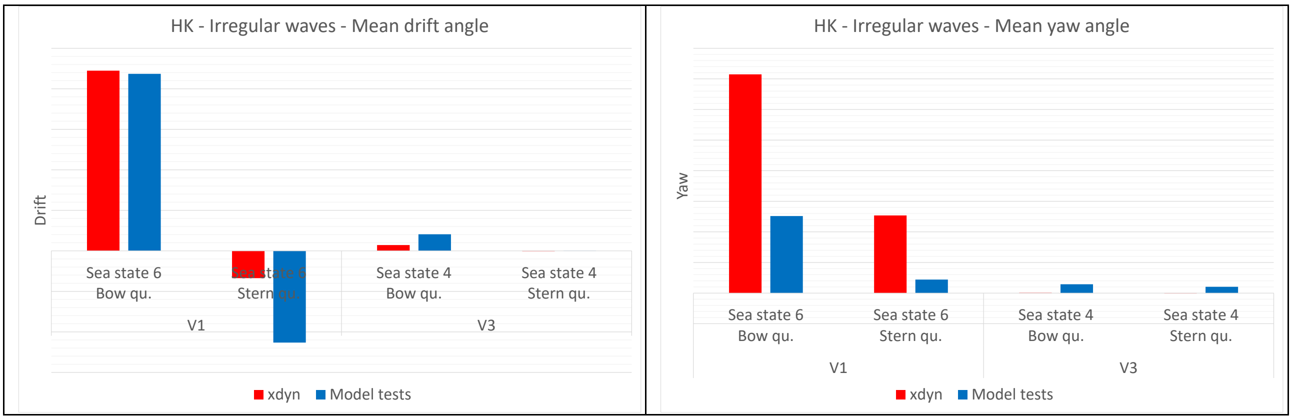


Figure 7: Heading keeping – Irregular waves – Comparison of model tests and xdyn results: mean drift (left) and yaw (right) angles.

The following conclusions can be drawn from the regular wave results:

- the mean drift angle is well predicted for bow quartering waves whatever the ship speed; the prediction is not as good for stern quartering waves;
- regarding the mean yaw angle, the xdyn results show discrepancies for almost all the frequency range, probably due to the discrepancies observed for wave drift forces;
- the mean rudder angle (not shown here) shows very similar trends to those for the mean yaw angle.

Regarding irregular waves, it is harder to draw conclusions since there are not enough simulations to correctly compare the statistical values (in particular, the influence of the seed used to generate the wave component phases could be studied since it has an impact on the generated waves). However, the general trends emerging for regular waves are more or less observed for irregular waves as well with some higher differences, in particular for the mean drift angle.

These conclusions are in line with those drawn from the analysis of the results for the wave drift forces.

V – 4 Zigzag manoeuvres

Some 20/20 zigzag manoeuvre simulations were performed, at 2 different speeds (V1 and V3), on calm water and with regular waves (RW) and irregular waves (IW, sea state 4); the test cases with waves were only performed at V3, with head waves at the start of the manoeuvre.

The following graphs show the comparison between free running model tests and calculations, namely time traces at V3 in calm water and classical derived parameters for all the test cases.

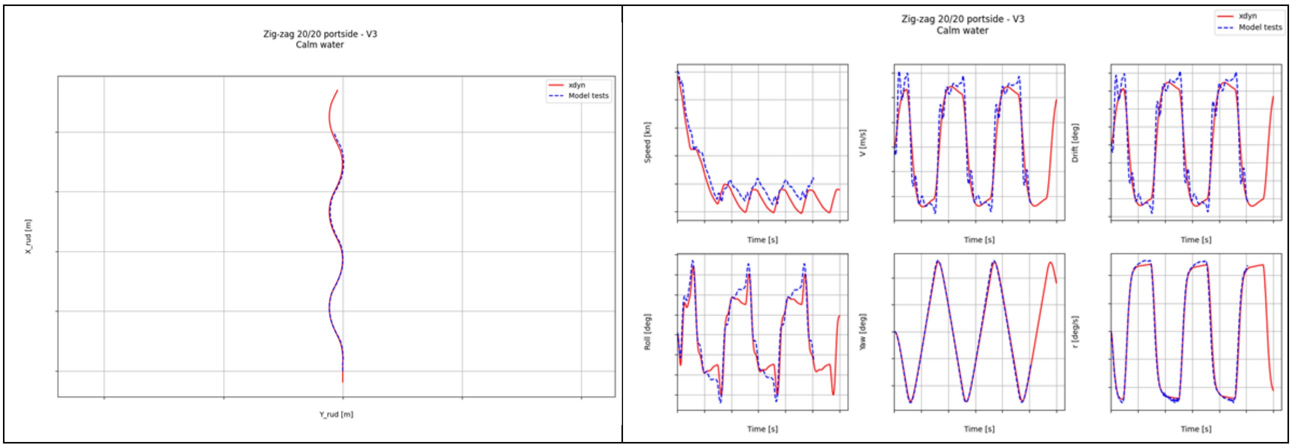


Figure 8: Zigzag 20/20 – Calm water – V3 – Comparison of model tests and xdyn results: trajectory (left) and motions (speed, lateral speed, drift, roll, yaw and yaw rate) (right).

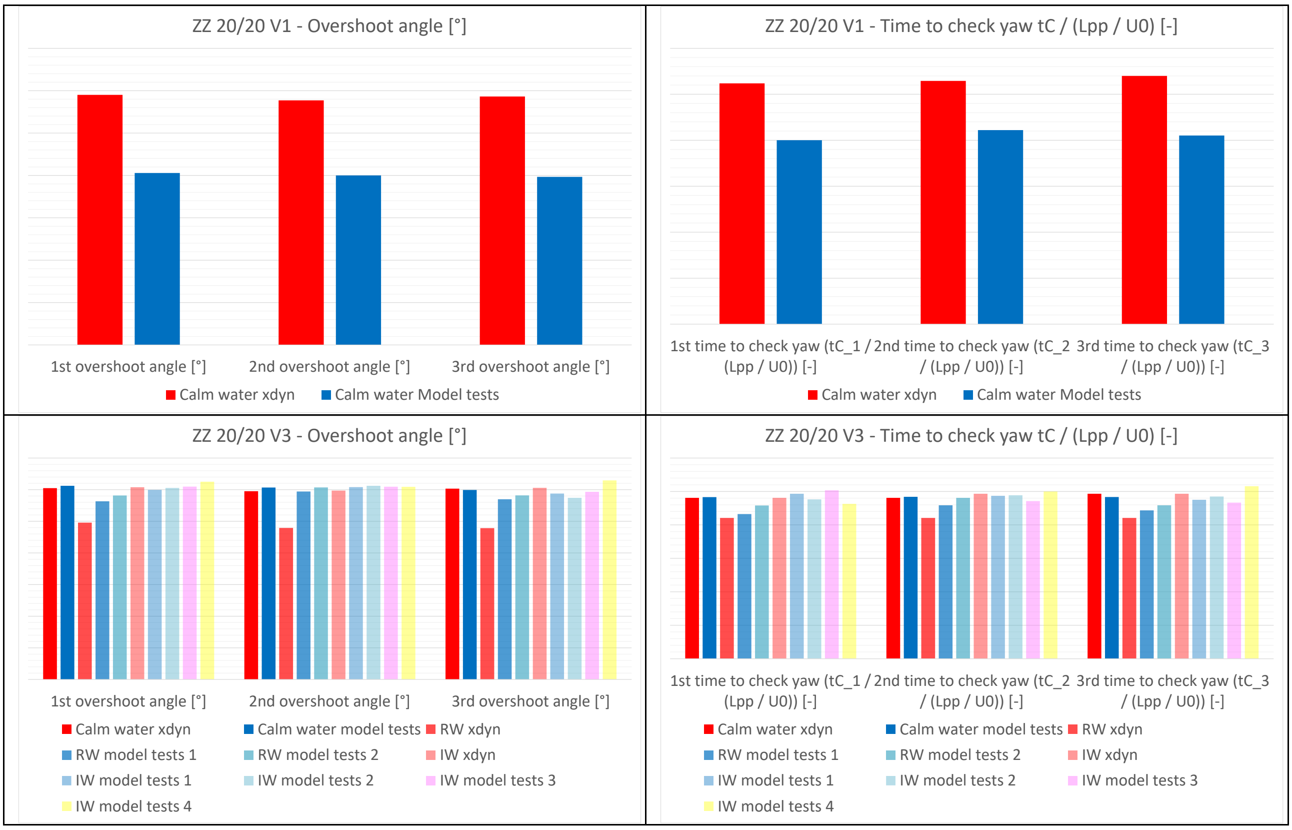


Figure 9: Zigzag 20/20 – Calm water – Comparison of model tests and xdyn results: overshoot angles (left) and times to check yaw (right) at V1 (top) and V3 (bottom).

From these results, it can be seen that xdyn is in quite good agreement with the model tests for the zigzag manoeuvres in calm water, for time traces as well as for derived parameters.

Concerning the test cases with waves, there are slightly more discrepancies between the calculations and the model tests for regular waves; the differences are lower for irregular waves, probably due to the relatively small sea state.

V – 5 Turning circle manoeuvres

Some turning circle manoeuvre simulations were performed with a rudder angle of 35°, at 2 different speeds (V1 and V3), on calm water and with regular waves and irregular waves (sea state 4); the test cases with waves were only performed at V3, with head waves at the start of the manoeuvre.

The following graphs show the comparison between free running model tests and calculations, namely time traces at V3 in calm water and classical derived parameters for all the test cases.

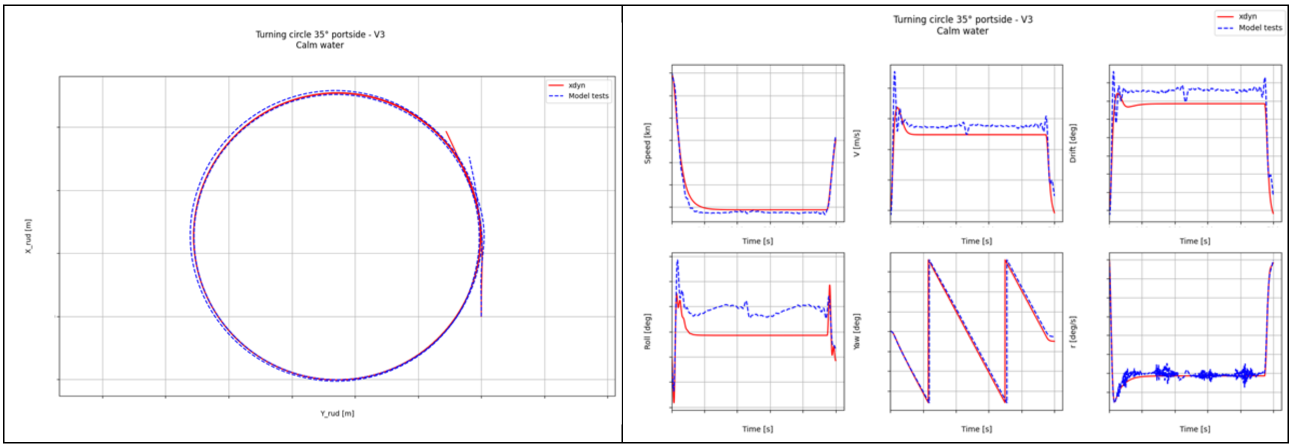


Figure 10: Turning circle 35° – V3 – Comparison of model tests and xdyn results: trajectory (left) and motions (speed, lateral speed, drift, roll, yaw and yaw rate) (right).

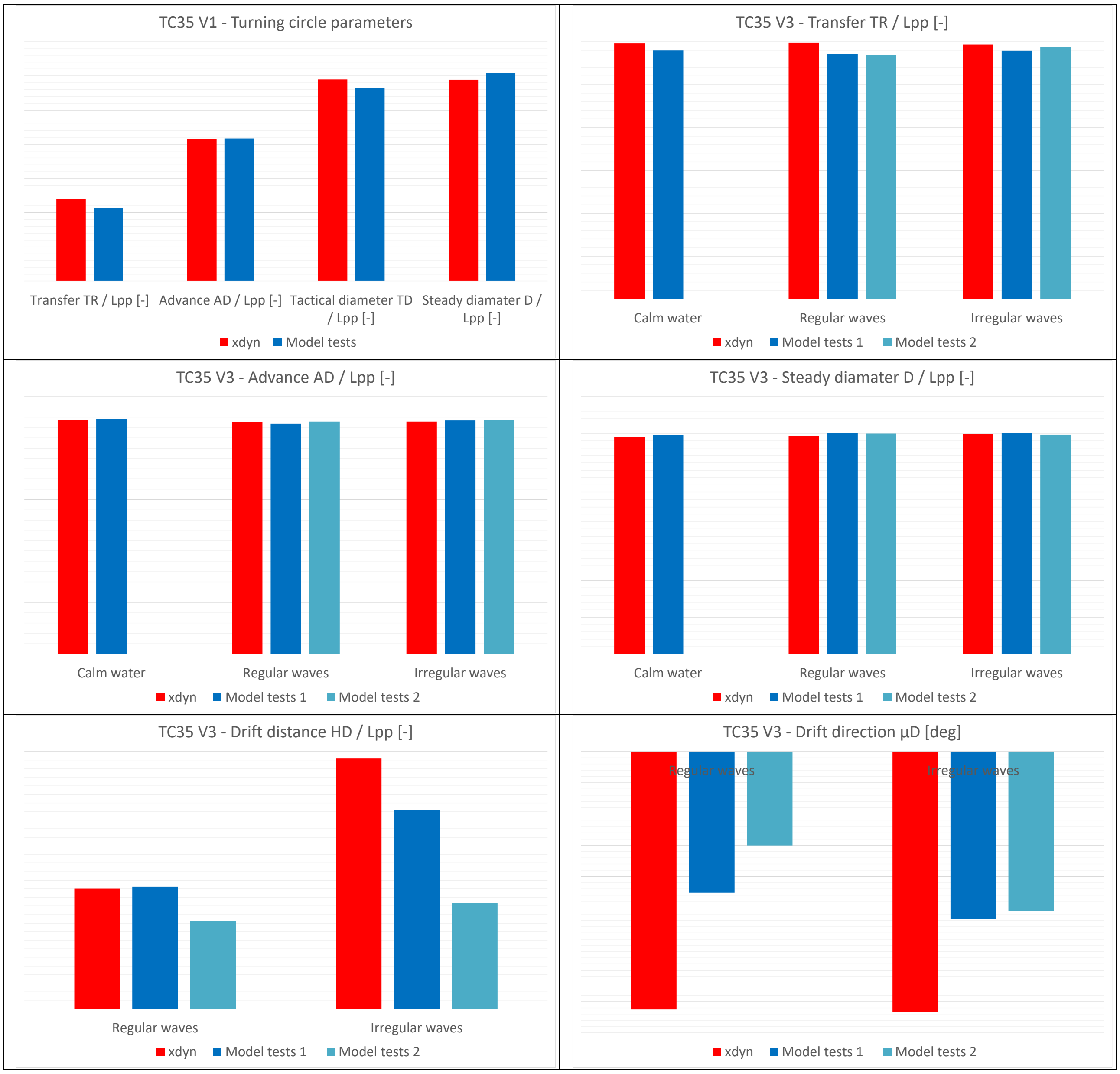


Figure 11: Turning circle 35° – Comparison of model tests and xdyn results: a few classical parameters at V1 (top left) and V3 (top right to middle right), wave drift parameters at V3 (bottom).

From these results, it can be seen that xdyn is in quite good agreement with the model tests for the turning circle manoeuvres in calm water, for time traces as well as for derived parameters.

Concerning the test cases with waves, the classical turning circle parameters change very little compared to the calm water case; they are well captured by xdyn. The drift distance is in the trends of model tests for regular waves but overestimated for irregular waves, and the drift direction is poorly predicted by xdyn; two main reasons can explain these discrepancies: the wave drift forces might not be well calculated as mentioned earlier, and the influence of the waves is very small (even for model tests), hence difficult to capture.

VI – Conclusion and future work

New models and their associated methodology were developed and implemented within xdyn. These elementary models as well as the whole simulation tool were partly validated against model tests. This validation showed that the modelling of the ship during heading keeping in waves gives results of various quality depending on the ship speed and on the wave heading. The validation of the modelling of zigzag and turning circle manoeuvres showed that xdyn can very well predict the motions of the ship during these manoeuvres as well as their derived parameters.

The work presented here therefore helped improving xdyn by the addition of a wave drift force model and the possibility to accurately model the manoeuvring forces.

Future work on the development of xdyn will consist in using the model test results to improve the modelling of the interaction between hull, propellers and rudders as well as their interaction with waves. Another area for progress is the improvement of the quality of the input data, for example the seakeeping database.

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