Development of a test program for the prediction of ship manoeuvrability in deep and shallow water.

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Abstract: As in many coastal and estuary areas, navigation to and in the Belgian harbours takes place in environmental and operational conditions which differ from the design conditions of sea-going ships: water depth to draft ratios vary between 2.0 and 1.1 which means that the under keel clearance is often restricted to 10% of the ship's draft. In addition, low ship velocities have to be considered as manoeuvring in harbour areas is characterised by a wide range of speed – propeller rpm combinations. Based on the results of captive model tests executed in the Towing Tank for Manoeuvres in Shallow Water (co-operation Flanders Hydraulics Research – Ghent University, Antwerp, Belgium) with a 6000 TEU containership and the tanker *Esso Osaka*, an optimized test program has been developed for the determination of a mathematical manoeuvring model in laterally unrestricted water. Contrary to deep water and service speed the selected test types and test parameters will influence the measured contributions of the modules hull, propeller and rudder in shallow water: as an example, stationary oblique towing and harmonic sway tests may lead to different results, while the reliability of the test results is much more sensitive to the selected test parameters during PMM tests. Due to the reduced under keel clearance even unusual phenomena may occur.

1. Introduction

Computational Fluid Dynamics techniques are more and more used to predict the flow patterns around and the forces acting on a ship's hull [1]. In spite of the great progress that has been made, difficulties still remain related to for example environmental effects such as shallow water. Because the influence of restricted water depths is very important for the Belgian harbours, Flanders Hydraulics Research (FHR) and Ghent University are constantly optimizing their towing tank facility for the prediction of the manoeuvring characteristics of different ship types.

Thousands of captive model tests have been executed since the installation of the towing tank in 1992. Opportunities and limitations of this Experimental Fluid Dynamics (EFD) technique have been examined and discussed in [2] mainly based on tests with a 6000 TEU containership and the tanker Esso Osaka (model D and E in table 1), the most cited and used benchmark ship for manoeuvring in deep and shallow water. Based on this examination an optimized test program was set up with the objectives to incorporate:

- the four quadrants of operation for speed – propeller rpm combinations;
- low and ordinary speed values;
- the influence of test parameters or test types.

This paper is subdivided in two main parts:
- discussion of the influence of test types and parameters on derived hydrodynamic forces acting on hull, propeller and rudder;
- development of a captive model test program for the prediction of ship manoeuvrability.

2. Observations during captive model tests

2.1 Ship models and test types

The captive model tests were executed with a fully automated PMM-carriage at the *Towing Tank for Manoeuvres in Shallow Water* (*co-operation Flanders Hydraulics Research – Ghent University*), Antwerp (Belgium). The main characteristics of the towing tank are 88 x 7 x 0.5 m³, with a useful length of 68 m. Hull characteristics and the tested loaded condition of the fully appended ship models are summarised in table 1. Two additional models of bulk

carriers (model A and C) and a model of an 8000 TEU containership (model U) are added.

Table 1 Geometrical characteristics

Model		E	D	A	C	U
L_{OA}	m	343.0	301.5	265.0	230.0	352.0
L_{PP}	m	325.0	289.8	259.2	220.0	331.8
B	m	53.0	40.3	43.0	32.2	42.8
T	m	21.8	15.0	14.6	12.3	12.0
C_B	-	0.83	0.61	0.84	0.81	0.63
Scale	-	85	75	75	64	81

The test program consisted of following test types:

Stationary model tests:
❑ straight-line tests with positive and negative forward speed;
❑ oblique towing tests with positive and negative forward speed.

Non-stationary model tests:
❑ oscillatory tests in x- and y-direction and around ψ-axis;
❑ harmonic sway tests: pure sway;
❑ alternative sway tests: pure sway;
❑ harmonic yaw tests: pure yaw, yaw with drift with positive and negative forward speed;
❑ multi-modal (MM) tests, executed with varying rudder angle, propeller rate or forward speed, while the other parameters are kept at constant values. Two special types are widely used in [2]: type A is stationary in all kinematical parameters and the propeller rpm but gives a harmonically varying rudder angle; type B is stationary in all kinematical parameters while the control parameters, propeller rate and rudder angle, are varied harmonically. MM tests have been introduced to increase the number of parameter combinations covered in one test, and therefore reduce the total test program.

2.2 Deep and shallow water

The influence of the under keel clearance (UKC) on forces and moment can be observed for all modules of a manoeuvring ship: hull, propeller and rudder. An example is given for the added mass due to sway and the lateral force and yawing moment induced by propeller action.

Hull forces. In Figure 1 a comparison is made of the frequency dependence of added mass for full ships at three different UKCs: 150% (deep water), 50% (medium to shallow water) and 20% (shallow to very shallow water). The added mass, defined in (1), is shown as a function of the non-dimensional frequency ω'.

$$m'_y = -Y'_{\dot{v}} = \frac{-Y_{\dot{v}}}{\frac{1}{2}\rho L_{pp}^2 T} \qquad (1)$$

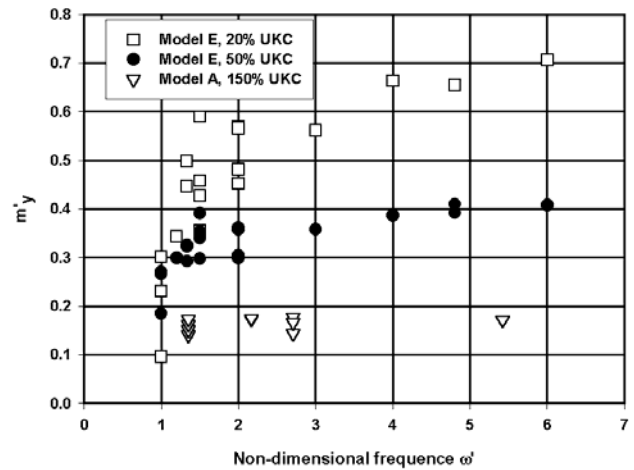$$\omega' = \frac{\omega L_{PP}}{u} \qquad (2)$$

Fig. 1. Frequency dependence of added mass due to sway with decreasing under keel clearance (full form)

As the water depth decreases, the influence of the non-dimensional frequency ω' on the acceleration derivative increases considerably so that at lower frequency the scatter becomes very important. The accuracy can be increased by executing small amplitude and/or high frequency PMM sway tests. In conclusion, although the frequency is often considered as a non-affecting parameter in deep water, this common procedure needs to be revised or to be executed with caution in shallow water.

Propeller forces. For the prediction of all kind of manoeuvres, i.e. low speed harbour manoeuvres and standard manoeuvres at service speed, speed – propeller loading combinations must be available in four quadrants (table 2).

Lateral force and yawing moment induced by the propeller represent generally a minor part in the total force equation. However, in shallow water the following phenomena occur:
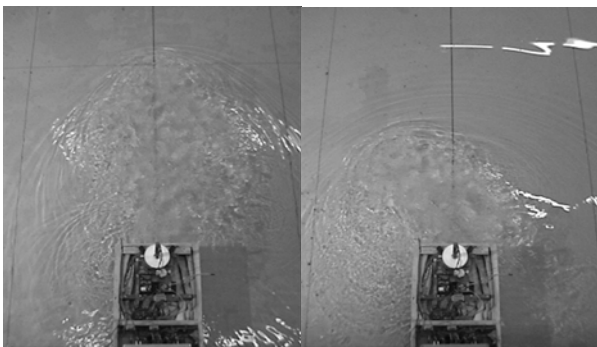❑ For quadrant 1 and 3, characterized by identical flow directions of wake and propeller

slipstream, lateral force and yawing moment increase with increasing propeller rate. The importance of this effect can be illustrated as follows: at ±8 deg drift angle an increase with 30% to 60% (depending on the speed) for the total lateral force at a propeller rate of 100% of the reference propeller rate (100 rpm at full scale) is observed for tanker E at 20% UKC.
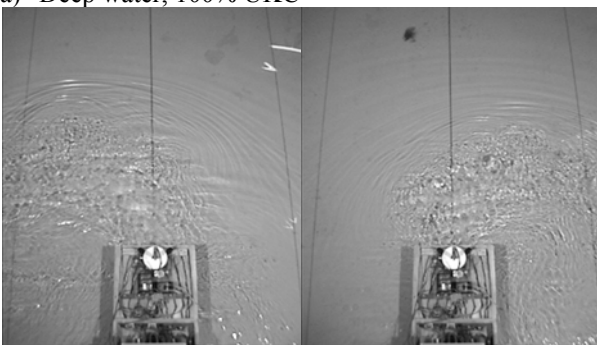
❑ For quadrant 2 and 4, characterized by two opposite flows for the ship motion and the propeller race, oscillating lateral forces and yawing moment are measured. In quadrant 4 (Figure 2) a wave train originates from the propeller and moves in the sailing direction, disappears at a certain distance ahead of the ship and another one is produced at the propeller. Due to the restricted water depth in Figure 2(b) the unstable flow is alternating at starboard and port side of the aft body. Figure 3 shows that the amplitude of the oscillatory component of the lateral force can take several times the propeller thrust in quadrant 2.

Fig. 3. Model D, *quadrant 2*, oscillating lateral force measured at three combinations of reversed propeller rate during one test run (F_n=0.016)

2.3 Low and ordinary speed

The influence of ship speed and test type is illustrated in Figure 4. Two different test types have been selected to determine the longitudinal hull force $X'^{(\beta)}$ depending on the drift angle β:

❑ type 1: conventional oblique towing without propeller or rudder action; the complete range of drift angles has been examined for F_n=0.016 (low speed) while tests at higher F_n were only performed at β=0 and ±8 deg.

❑ type 2: non-conventional multi-modal (MM) tests type B with slow harmonically varying propeller action and with zero rudder deflection; tests have been executed with Froude numbers from 0.016 to 0.065.

In medium deep water (Figure 4, top) the difference between both test types for F_n=0.016 is important, probably due to the magnitude of measured longitudinal forces when the propeller is not working (type 1) and the difference in generated flow patterns around the ship's hull. At drift angles ±8 deg the values for type 1 are based on higher ship velocities and correspond to the surrounding values of test type 2. The values for low speed manoeuvring and conventional oblique towing tests without propeller action can therefore be considered to be divergent. For decreased UKC (20%) the difference between both test types is smaller, even for low speed manoeuvring. It can be concluded that the more time efficient MM type B tests are preferable for determining the longitudinal hull force at low speed.

Table 2. Four quadrants of operation

u > 0	n > 0	quadrant 1	running ahead
u > 0	n < 0	quadrant 2	stopping from headway
u < 0	n < 0	quadrant 3	running astern
u < 0	n > 0	quadrant 4	stopping from sternway

(a) Deep water, 100% UKC

(b) Shallow water, 10% UKC

Fig. 2. Model U, quadrant 4, development of an unstable flow at the aft body in deep and shallow water
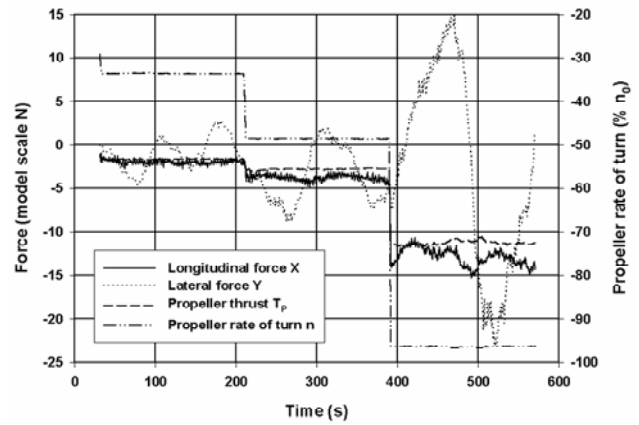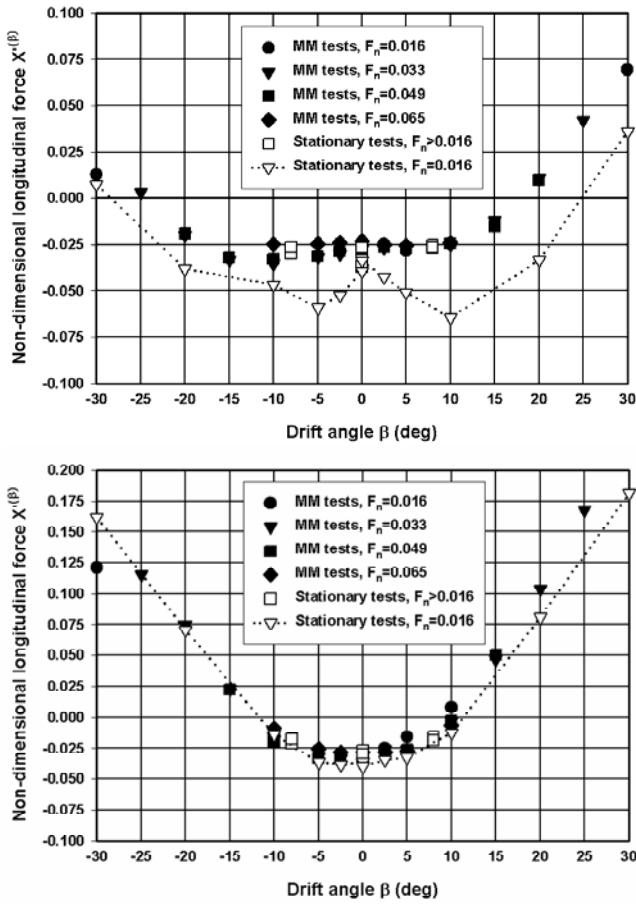
Fig. 4. Model E, comparison of non-dimensional longitudinal force $X'^{(\beta)}=X^{(\beta)}\div(\frac{1}{2}\rho U^2 L_{PP}T)$ for different F_n based on test types 1 and 2. UKC: 50% (top), 20% (bottom).

2.4 Test type and test parameters

Hydrodynamic forces and moments acting on a manoeuvring ship can be determined by executing captive model tests of different type with varying test parameters. As an example, a comparison between damping moments $N'^{(\beta)}$ derived from oblique towing tests and from PMM sway tests carried out with constant sway amplitude ($y_A/B=1$) with $1.35<\omega'<3.6$ leads to following conclusions (Figure 5):

❑ For $\omega'<2.7$, $N'(\beta)$ does not change significantly with increasing frequency. Compared to the stationary oblique towing tests, N' is underestimated for all drift angles.
❑ A significant difference is found between the $N'(\beta)$ curves obtained from PMM sway tests at relatively high frequency ($\omega'>2.7$) compared to tests performed in the lower frequency range.
❑ Even at low frequency it seems impossible to reproduce steady drift forces by one single PMM sway test.

There are indications that damping forces are affected by memory effects in the frequency range $\omega'>2.7$, which can be ascribed to wake interference.
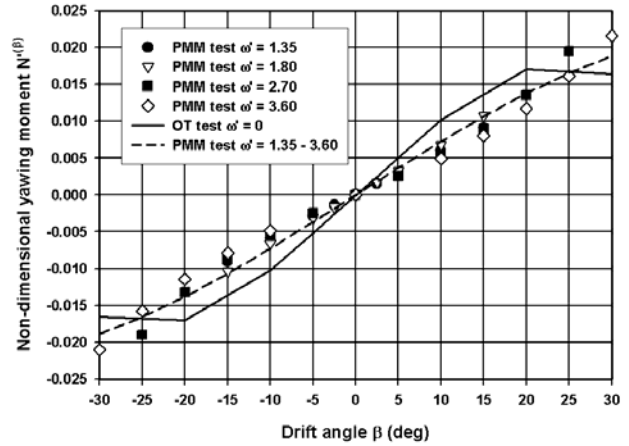

Fig. 5. Model C, comparison of non-dimensional yawing moment $N'^{(\beta)}=N^{(\beta)}\div(\frac{1}{2}\rho U^2 L_{PP}^3)$ for stationary oblique towing (OT) tests and harmonic PMM tests (10% UKC)

3. Development of a standard test program

Based on the observations described in the previous chapter, the selected test program will definitely determine the derived mathematical model, especially in shallow water conditions. The development of an optimized captive test program for a particular simulation model gives a total number of 20 combined sway/yaw tests according to Sutulo & Kim [3] and 97 runs according to Blok et al [4], the latter comprising both bare and appended hull tests. Contrary to the program executed at FHR, these programs are especially designed for the deep water case and the (ship) self propulsion point. The increase of the number of runs from 20 to 97 is caused by e.g. the choice of model type (regression or modular model) and the number of speed values tested.

The test programs for container carrier D and tanker E, extensively discussed in [2], were composed of rather arbitrarily chosen test types and parameters. Some conclusions, summarized below, have nevertheless led to the development of a balanced and optimized test program:

❑ PMM sway and yaw tests, characterized by a test frequency and a sway or yaw amplitude, induce non-stationary effects in the towing tank which can be determined introducing a run-out phase with a straight ahead

or oblique motion. Generally accepted guidelines, summarized in [2], must be kept in mind while selecting the test parameters. Non-stationary effects can indeed be diminished if the non-dimensional test frequency is restricted to values below 4 and if the sway amplitude is limited to e.g. 0.4B. In addition, while executing tests at, at least, two frequencies the influence of this parameter can be examined.

❑ As no rotating arm facility is available at FHR, PMM yaw tests will be necessary to obtain the dependence of the hydrodynamic models on yaw velocity. A comparison of these two test types is recommended and could give some insight into the variation of forces and moment using stationary and non-stationary test runs, a comparison that has been made for drift angle dependence.

❑ Non-stationary phenomena are also generated during multi-modal rudder angle tests of type A (constant propeller rate) and type B (harmonically varying propeller rate). Test type B has been widely used in the test programs for the container carrier and the tanker. Test programs that have been executed after 2000, have been modified so that tests of type B are no more used for the determination of hull-propeller-rudder interaction. The harmonic variation of more than one parameter at once (exclusively for tests of type B) during the determination of a model must indeed be avoided and can be replaced by multi-modal tests of type A.

❑ Improvements could probably also be obtained for the multi-modal tests if the harmonically varying function should be replaced by a function with a linear variation in time of e.g. rudder angle between a minimum and a maximum value. In this way, the uneven division, typical for a harmonic function, can be avoided.

❑ The examination of non-stationary phenomena occurring in shallow water due to the opposite flows in quadrant 2 and 4, can only be executed with enough accuracy if the number of test runs is adapted to the expected frequency of oscillation taking into account the velocity and the useful tank length. The execution of test runs with three sub-runs must be avoided.

❑ All captive model tests at FHR have been executed with the fully appended hull forms. As a consequence, the three modules hull, propeller and rudder are interacting during each test run, although e.g. only hull-propeller interaction is expected to be determined and modelled. Models for the hull forces will therefore incorporate a small part of rudder induced forces which makes it difficult to exchange the individual modules and compose the same hull e.g. with another propeller and/or rudder.

In 2004-2005 a shallow water and a deep water test program have been executed with model U [5]. These test programs could be used as reference programs for the development of any test program that will be set up in the future, applicable for a four-quadrant determination of a mathematical manoeuvring model:

❑ The deep water and shallow water test programs differ only slightly in the applied maximum model speed, maximum propeller rate and the occurrence of oscillating flow phenomena in the even quadrants.

❑ The maximum speed is restricted to 10 (or 12) knots for the shallow water condition (<35%UKC) and 16 knots for the deep water condition. The maximum speed astern is -4 knots.

❑ Sway acceleration derivatives are determined based on PMM sway tests, although these tests could be replaced by non-conventional sway tests. The influence of test frequency is examined with more test runs in shallow than in deep water and the sway amplitude is restricted to a small value of 0.4B.

❑ The influence of yaw rate angle and yaw acceleration on all modules is examined based on PMM yaw tests. The maximum yaw rate angle is limited and depends on the applied yaw amplitude, test frequency and model speed (ahead or astern). For pure

yawing with zero speed, one oscillatory test has been added.

❑ Multi-modal tests of type B have been executed for the determination of hull-propeller interaction at different drift angles within a range of [-180 deg; 180 deg].

❑ For the examination of the hull-propeller-rudder combination multi-modal tests of type A with constant drift angle have been chosen. The rudder angle is harmonically varied between -40 deg (starboard) and 40 deg (port). Based on the stationary tests that have been executed at zero and maximum rudder angle, the influence of the non-stationary character of multi-modal tests can be examined.

❑ Validation runs are added to be able to validate the derived mathematical model at model scale.

The deep water program is composed of 294 basic test runs and 58 optional runs; the shallow water program has 312 basic and 56 optional runs. Taking account of the fully automated operation of the facility, 24 hours a day and 7 days a week, such a program can be executed in 10 to 12 days.

4. Concluding remarks

Improvements and modifications have always to be considered as, generally, each test program must be adapted to the scope of the simulation model. Speed ranges, ranges of drift angle and yaw rate angle, rudder angle and propeller loading must be determined not only to give test results in a broad spectrum of operation but at least to give results which correspond to the expected manoeuvres during the simulations.

The modular form of the mathematical model, chosen at FHR, should e.g. be extended to the experimental setup. If a so-called modular or flexible mounting of the rudder can be realized with low costs in both time and human action, the determination of the hydrodynamic forces and moment can consequently be phased in hull-propeller interaction on the one hand and hull-propeller-rudder interaction on the other.

This recommendation is hoped to improve the accuracy and the applicability of the EFD technique for the prediction of ship manoeuvres in a wide range of operational conditions.

An uncertainty analysis (UA) on model tests, as was proposed and performed by the 24th ITTC Manoeuvring Committee [1] for the results of one institute, does not accompany each test program until now although the initial impetus is given with a detailed quality control at FHR. In addition, uncertainty is not only caused by the execution of tests but even by the design of the test program. Shallow water manoeuvring will meet other requirements than deep water manoeuvring and as low speed manoeuvres induce smaller forces compared to high speed manoeuvres, these forces will more suffer from measurement inaccuracies.

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