

REVIEW OF PRACTICAL METHODS FOR ASSESSING SHALLOW AND RESTRICTED WATER EFFECTS

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Abstract: A brief summary of practical methods for calculating the hydrodynamic horizontal forces and yaw moments acting on a manoeuvring ship in shallow and restricted water is given, with the emphasis on the very shallow water range (water depth to draft ratio less than 1.2), including ship-bank and ship-ship interaction effects. The main purpose is to provide background information for a discussion on the necessity of additional data for the development of reliable simulation models that are able to describe a ship's manoeuvring behaviour in (very) shallow and restricted navigation areas in a realistic way.

1. INTRODUCTION

A ship's behaviour in general, and her manoeuvrability in particular, depends on the depth h of the navigation area. According to the ratio of the water depth to the ship's draft, a rather arbitrary distinction can be made between (see PIANC [1]):

- deep water $h/T > 3.0$
- medium deep water $1.5 < h/T < 3.0$
- shallow water $1.2 < h/T < 1.5$
- very shallow water $h/T < 1.2$

Roughly spoken, the effect of depth restrictions can be noticed in medium deep water, is very significant in shallow water, and dominates the ship's behaviour in very shallow water.

The very shallow water range is quite important for manoeuvring in access channels, harbours and canals. The International Commission on the Reception of Large Ships (ICORELS) suggests following values for the under keel clearance in different kinds of navigation areas (PIANC [2]; see also Bruun [3]):

- Open sea areas: for those exposed to strong and long stern or quarter swell, where speed may be high, gross under keel clearance should be about 20% of the maximum draft of ships.
- Waiting areas: for those exposed to strong and long swell, gross under keel clearance should be about 15% of the draft.
- Channel: for sections exposed to strong and long swell; gross under keel clearance should be about 15% of the draft.
- Channel: less exposed to swell, gross under keel clearance should be about 10% of the draft.

- Manoeuvring and berthing areas: for those exposed to swell, gross under keel clearance should be about 10 to 15% of the draft.
- Manoeuvring and berthing areas: protected, gross under keel clearance to be about 7% of draft.

These values are only indicative, and are only meant as a helpful rule of thumb for port or channel designers at the stage of a preliminary plan; as is stated in the commission report, "*it is not possible to establish accurate rules concerning the minimum depth of port approaches because of the major importance of local conditions*". Nevertheless, in many navigation areas local regulations concerning maximum allowable draft are based on the suggested values mentioned above, which often are even referred to as "PIANC rules". As an example, the required gross under keel clearance in the access channels to the Belgian harbours exposed to the sea is 15% of draft. In more sheltered areas, this value is reduced to 10%; this is the case in the docks of the Antwerp harbour (water depth: 16.5 m; maximum draft: 15.0 m) and the sea canal connecting Ghent with the river Scheldt (water depth: 13.5 m; maximum draft: 12.25 m). Obviously, the ICORELS suggestions are rather strictly followed.

In some areas, even lower values are common practice: the North Sea Canal at IJmuiden (the Netherlands) gives access to ships with a draft up to 13.9 m, whereas the water depth is 15.0 m, so that the gross under keel clearance is only 7.9% of draft. Figures for the port of Rotterdam are given by Deelen et al [4]: on the river Nieuwe Maas, a clearance of at least 1.0 m must be available to guarantee full manoeuvrability; in harbour basins, where speed is lower and tugboats are assisting, the minimum clearance can be reduced to 0.5 m, without

affecting a safe passage. With a typical draft of 12.0 m, the gross under keel clearance is reduced to 8.3 and 4.2% of draft, respectively.

For characterising ship manoeuvrability and controllability, reference is often made to the results of standard manoeuvres. For considerations concerning ship behaviour in deep water, such an approach can be justified by the fact that each ship carries out these manoeuvres at least once in her lifetime in order to check whether the IMO Standards for Ship Manoeuvrability are fulfilled. Trials in shallow water, on the other hand, are so extraordinary that the ships involved have become legendary (e.g. *Esso Osaka*). A comparison of standard manoeuvres carried out at different values of water depth, which is a very common way of demonstrating the effect of under keel clearance on ship manoeuvrability, is therefore mostly based on simulations, and only seldom on full scale observations. The reliability of the available information on manoeuvring behaviour in shallow water, as a consequence, highly depends on the realism and accuracy of the mathematical models used for these simulations. Taking account of the present state-of-the-art, these mathematical models are mainly based on model test results, as CFD techniques applied to manoeuvring aspects, particularly in shallow water conditions, still need to be validated.

Water depth restrictions not only affect ship hydrodynamics. In most cases, people are interested in ship behaviour in either deep water or shallow water only, as other applications are involved. Deep water manoeuvring is mainly investigated for assessing course stability, optimising ship control, predicting standard manoeuvres, being fields of interest of ship designers, shipyards, ship owners, certifying authorities, masters and officers, control experts, Studies of ship behaviour in shallow water, on the other hand, are often related to conditions for which a ship is not particularly designed: course keeping in access channels and canals, swinging, berthing and unberthing in harbours, tug assisted manoeuvres, actions at slow and reversed speed and/or propeller rate, applications belonging to the action range of channel and harbour designers, pilots, tug masters, waterways authorities, shipping traffic experts. This polarisation is even more explicit if manoeuvring in horizontally restricted navigation areas is considered.

A description of a ship's manoeuvring behaviour in (horizontally and vertically) restricted water is therefore not only more complex due to the occurrence of additional parameters such as depth to draft ratio and bank clearance, but also due to the fact that several parameters determining a ship's kinematics (forward speed, drift angle, rate of turn) and control (rudder angle, propeller rate) belong to a more extended range.

Mathematical models used for simulating manoeuvres in shallow and restricted waterways cannot be validated in a straightforward way. Deep water models can be assessed – and tuned – making use of trial data; the final validation of shallow water models, on the other hand, is in many cases based on the opinion of experienced pilots judging the realism of the simulated ship's reactions. Although such a judgement represents a very valuable contribution to the validation process, it is never free of subjectivity, and can only be carried out if the examined situation belongs to the experience of the nautical expert involved – which is not always the case in waterways design studies.

As mentioned before, mathematical manoeuvring models in shallow and restricted waters should be based on model test results. If such data are not available or cannot be obtained due to lack of time and/or financial means, however, (semi-)empirical methods for predicting the effect of geometrical restrictions of the navigational areas on ship manoeuvrability can offer an alternative. A rather detailed overview of such methods, with emphasis on practical formulations, can be found in the Appendix of the Report of the 23rd ITTC Manoeuvring Committee [5]. It is not the purpose of this paper to merely repeat this inventory of empirical formulae, but to give a brief summary, more specifically on following aspects:

- effect of depth restrictions;
- effects of horizontal restrictions (bank effects);
- forces excited by other ships (ship-ship interaction);

in order to give some background information which can be useful in a discussion.

2. EFFECT OF DEPTH RESTRICTIONS ON HULL FORCES

2.1 Semi-empirical estimation methods

The effect of depth restrictions on the hydrodynamic horizontal force components and yawing moment acting on a ship's hull due to its kinematics in the horizontal plane is expressed by several formulae giving estimations for the ratio of the value of manoeuvring derivatives and coefficients valid in shallow water to their deep water value. In literature, following methods are available.

A first set of formulations is based on expressions by Sheng [6] for the added mass of two-dimensional elliptical sections. Clarke et al [7], [8] derived expressions for the most important linear derivatives ($Y_{\dot{v}}, N_{\dot{r}}, Y_v, N_v, Y_r, N_r$), applicable in the range $1.25 < h/T < \infty$. The water depth corrections by Ankudinov et al [9] cover a greater range of water depths ($1.085 < h/T < 5$), manoeuvring coefficients (non-linear sway and yaw coefficients, surge coefficients) and ship parameters ($C_B \leq 0.85$).

A second type of methods provide expressions for the coefficients occurring in the Japanese MMG mathematical manoeuvring model: Hirano et al [10], Kijima et al [11], Kobayashi [12].

Finally, other authors proposed formulae for a limited number of coefficients, e.g. for added inertia coefficients by Li & Wu [13] and Sadakane et al [14].

2.2 Experimental validation

The 23rd ITTC Manoeuvring Committee Report [5] contains a series of figures comparing experimental data for the Esso Osaka with the results of a selection of these formulae, resulting from a study carried out by Petersen [15], see Fig. 1. In general, the Ankudinov formulae appear to result into a fair approximation; for N_{ur} and $N_{\dot{\psi}}$, Kobayashi's expressions perform very well for slender ships. However, the experiments are carried out at a water depth to draft ratio not less than 1.2.

Fig. 2 is based on captive model tests carried out in the *Towing tank for manoeuvres in shallow water* at Flanders Hydraulics Research, Antwerp, with a post-panamax container carrier; as the experimental facilities do not allow carrying out manoeuvring tests in deep water, the experimental data are insufficient for direct evaluation of the empiric formulae. For this reason, the test condition with the largest water depth ($h/T = 1.32$) was selected as reference condition. Such a representation implies that it is not possible to evaluate the prediction methods in a quantitative way, but the results allow assessing qualitatively whether the formulae take account of the effect of water depth on the manoeuvring coefficients in a realistic way in shallow and very shallow water conditions.

The interpretation of these results requires some caution. For instance, only two authors, Kijima and Ankudinov have published semi-empirical formulae for the water depth effect on non-linear velocity coefficients. In almost all cases, the effect of decreasing under keel clearance is overestimated by the predictions; exception can be made for Kijima's approximation for $N_{r|r|}$, which leads to fair results. However, it should also be noticed that Kijima's formulae generally tend to underestimate the linear velocity coefficients, while the nonlinear terms are overestimated. The discrepancies could partly be caused by the different ways of determining linear and non-linear coefficients based on results of captive model tests.

2.3 Validity in the very shallow water range

Some of the formulations yield undetermined values for h/T tending to 1, and therefore cannot be applied to very low under keel clearance conditions. This is especially the case for Clarke's formulae: Fig. 2 clearly shows that the results are meaningless for

$h/T < 1.2$, as the values obtained have an opposite sign. The Ankudinov formulae, which can be considered as an extension of the Clarke expressions, appear to produce values that qualitatively lead to acceptable tendencies, although for some derivatives the values increase extremely with decreasing water depth. Other formulae do not result into extreme values for decreasing h/T ; exception should be made for Hirano's expression for N_{ur} at very low $h/T (< 1.1)$.

Experimental data for the very shallow water range are very scarce. Due to many practical difficulties, model tests with under keel clearances less than 10% of the draft are only carried out exceptionally, as contact between the ship model and the bottom is likely to occur due to squat effects and inaccuracies of the bottom and the water level, so that damage may occur to the ship model, its rudder and propeller.

At present, a comprehensive test program is being carried out at Flanders Hydraulics Research, which to some extent allows extrapolation to h/T values lower than 1.1. During these tests, the bottom of the towing tank is covered with a fluid layer in order to investigate the manoeuvring behaviour of a ship navigating above and in fluid mud layers. Although the mud-water interface will be subject to deformations due to the passage of the ship, especially in the range of positive under keel clearances and in case of layers with relatively high viscosity, the test results give an idea about the evolution of the manoeuvring characteristics at extremely low under keel clearance.

A selection of preliminary results will be reported by Vantorre et al [16]; Fig. 3 gives a first indication.

The effect of water depth on derivatives Y_{uv} and N_{uv} appears to be approximated satisfactorily by several formulae if h/T is not less than 1.1; for smaller values, however, none can be recommended. For the yaw damping derivative N_{ur} , Kobayashi's formula yields very good results, even at very low under keel clearance. The effect of water depth on the value of Y_{ur} appears to be estimated in a realistic way by Kijima's approximation for $Y_{ur} - m$. It appears to be important to consider the hydrodynamic force Y_{ur} and the centrifugal inertia force $-m_{ur}$ as together; the value of Y_{ur} is usually very small in deep water and may change signs, so that the deep water value is not suitable as a reference value. In very shallow water, the centripetal force Y_{ur} may be even become more important than the centrifugal force $-m_{ur}$, which will affect the ship's force balance in a turning circle.

Figs 3 show that the Li & Wu formulae represent very well the effect of water depth restrictions on the added mass for sway and the added moment of inertia for yaw, except for very small under keel clearances. For h/T values not lower than 1.1, also Kobayashi's formulae give satisfying results.

3. SHIP-BANK INTERACTION EFFECTS

3.1 Overview

Shallow navigation areas are mostly limited in lateral sense as well. These lateral limits, such as banks and quay walls, affect the hydrodynamic forces and moments acting on the ship hull and, hence, the ship's behaviour as well. According to the origin of these effects, a distinction is made between *bank effects* (due to a ship's motion parallel to the bank and/or propeller action), *cushion effects* (lateral force acting on a ship hull moving laterally towards a solid boundary) and hydrodynamic *memory effects*, occurring in case of large accelerations or decelerations, which are also influenced by lateral restrictions. In this workshop, only bank effects will be focused.

Several theoretical and experimental investigations on ship-bank interaction have been reported in literature; for a more detailed review, reference is made to the 23rd ITTC Manoeuvring Committee Report [5] and to Vantorre et al [17]. In some cases, the published information allows to develop a bank suction module for simulation purposes which is valid for the ship model(s) involved, although a ready-to-use mathematical formulation is not available.

A very limited number of semi-empirical methods allow direct calculation of ship-bank interaction forces as a function of relevant parameters, and are therefore frequently used for simulation purposes. It is clear why only a small number of generally applicable methods are available: the ship-bank interaction phenomenon is determined by a relatively large number of parameters, so that a comprehensive model test program is required for developing a mathematical model covering the complete action range. Following parameters are relevant:

- Ship geometry characteristics
- Ship's draft
- Water depth to draft ratio
- Bank characteristics (vertical, sloping, flooded bank, ...)
- Lateral ship-bank distance
- Ship's forward speed
- Propeller loading
- Drift angle
- Rudder angle

Also for ship-bank interaction effects, the water depth to draft ratio appears to be a very important parameter. This is illustrated in Fig. 4, based on captive tests with a panamax bulk carrier model. For two lateral ship-bank distances and three water depths, lateral force and yawing moment are displayed as a function of the net forward force; a zero value for the latter coincides with the (model) self-propulsion point, while the symbols denote

situations with propeller stopped. While the yawing moment continuously increases with decreasing under keel clearance, the sign of the lateral force depends very much on the propeller loading and the water depth, especially in the very shallow water range. Again, an extrapolation to even lower under keel clearances is not straightforward.

3.2 Generic models

The formulation published by Norrbin [18], [19] is used very often for simulation purposes. For vertical banks, the lateral forces and yawing moment at self-propulsion point is expressed as a function of the ship's main geometric characteristics, the lateral ship-bank distance, ship speed and water depth to draft ratio. For sloping and flooded banks, formulae are available as well.

It should be borne in mind that the Norrbin model is subject to a number of limitations: the formulation was developed for a specific tanker model ($L = 5.024$ m, $B = 0.852$ m, $T = 0.339$ m, $C_B = 0.821$), the equations are valid for self-propulsion conditions only, and the under keel clearance range is limited to $h/T > 1.20$.

Ch'ng et al [20] proposed a formulation for bank-induced sway force and yaw moment as a function of ship characteristics, lateral ship-bank distance (taking account of the bank slope as well), ship speed, water depth to draft ratio and propeller loading. The equations can easily be introduced into a mathematical simulation model. However, as the method is based on tests with a limited number of ship models (two MarAd Series hull forms, $L = 1.698$ m, $B = 0.340$ m, $T = 0.077$ m, $C_B = 0.85$, bulbous and cylindrical bow; container ship model, $L = 1.750$ m, $B = 0.254$ m, $T = 0.095$ m, $C_B = 0.57$), the overall validity is not guaranteed. As an example, Fig. 5 compares experimental results with a panamax bulkcarrier model with the output of the formulae.

During the present MARSIM Conference, two more papers will be presented on the subject of ship-bank interaction forces: Li et al [21], Vantorre et al [22]. The latter contains a new set of 'generic' formulae; however, it is not expected that the final solution for all bank effect problems will be presented. The abstract of the first mentioned paper reveals that special attention will be paid to the very shallow water range, and in particular to an under keel clearance less than 10%.

4. SHIP-SHIP INTERACTION EFFECTS

As ship-ship interaction tests require an auxiliary carriage, published experimental data are even more scarce. Following authors can be mentioned: Newton [23], Müller [24], Remery [25], Dand [26], Vantorre et al [27]. Other authors have developed numerical methods to calculate interaction forces theoretically,

e.g. Tuck and Newman [28], Kijima [29], Kaplan and Sankaranarayanan [30].

There are very few semi-empirical approaches, resulting in an estimation of the time histories of forces and moments in the horizontal plane due to interaction with another ship as a function of geometry, speeds and environment parameters. Brix [31] presents a method to estimate the forces and moments acting on a ship during overtaking. The influence of water depth not taken into account, and the ratio of ships' lengths is limited. Varyani et al [32] present empirical formulae for predicting the peaks of the lateral force and the yaw moment during encounter manoeuvres. The cases in which one of the ships has zero speed are not covered, and the length ratio is limited.

However, in more recent papers Varyani reports on efforts made for establishing a guide to predict the ship-ship interaction forces and moments by generating new generic models for ship manoeuvring simulators. The theoretical computation involves the use of a singularity distribution technique and slender body theory to obtain coefficients for surge force, sway force and yaw moment. For a number of benchmark examples the computed interaction forces and moments are compared with experimental results. Ratios between experimental and theoretical values for peak forces and moments can easily be used in combination with the generic model to arrive at a more accurate modelling of interaction forces and moments. During the present MARSIM Conference, this topic will be addressed as well.

5. DISCUSSION

The purpose of this paper is to provide background for a discussion on following topics:

- Are the available methods sufficient for providing a reliable background on which mathematical models can be based? More specifically, is there enough information available about the manoeuvring and control behaviour of ships in "very shallow water" ($h/T < 1.20$)?
- The last ITTC Manoeuvring Committee formulated a first version of a *Validation procedure for manoeuvring simulation models*. Does the marine simulation society and the IMSF agree that there is a need for such a standardised validation procedure for mathematical models in general, and shallow/restricted water models in particular? If this is the case, which information should be included?
- Shallow/restricted water models are typically applied for pilot training and harbour/waterways design, studies for assessing the access of

existing ports for new ship types, etc. It could be stated that it is not necessary to have a completely realistic model, as in most cases these studies are intended to assess the behaviour of a typical ship of its type.

- The investigation of manoeuvring behaviour in shallow water, ship-bank interaction and ship-ship interaction require comprehensive experimental studies during which a large number of parameters needs to be varied. Co-operation between research institutions needs to be stimulated in order to reduce the amount of work to a reasonable level.

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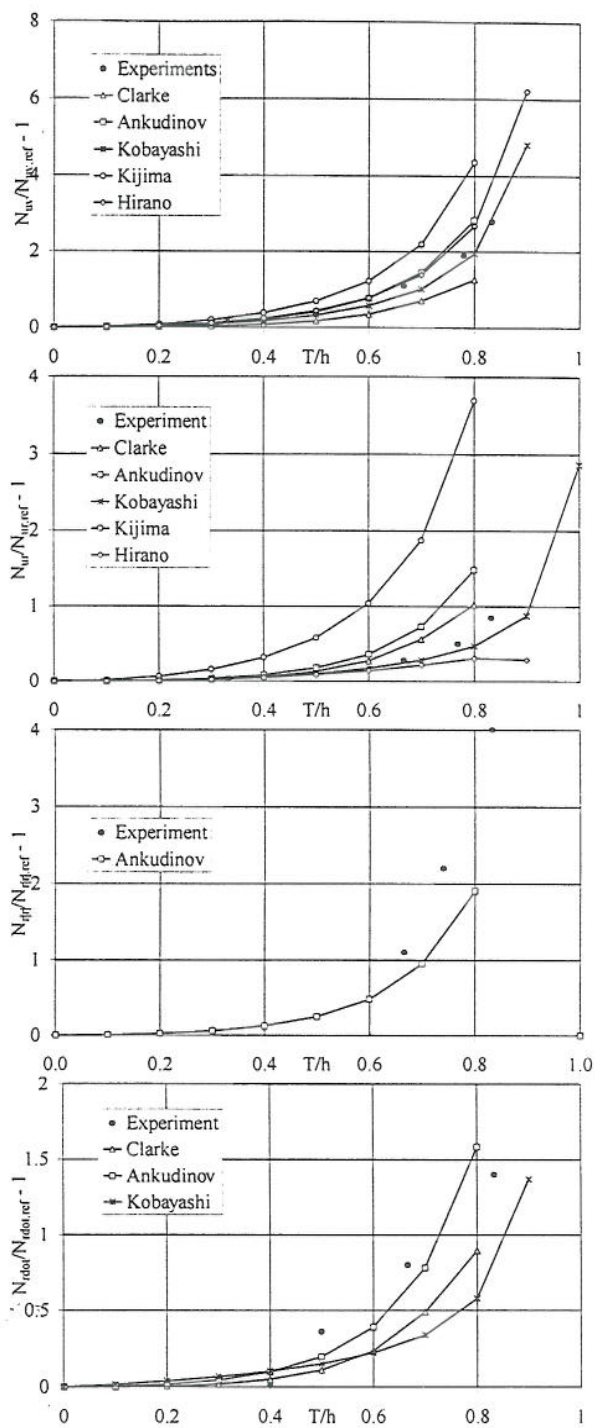
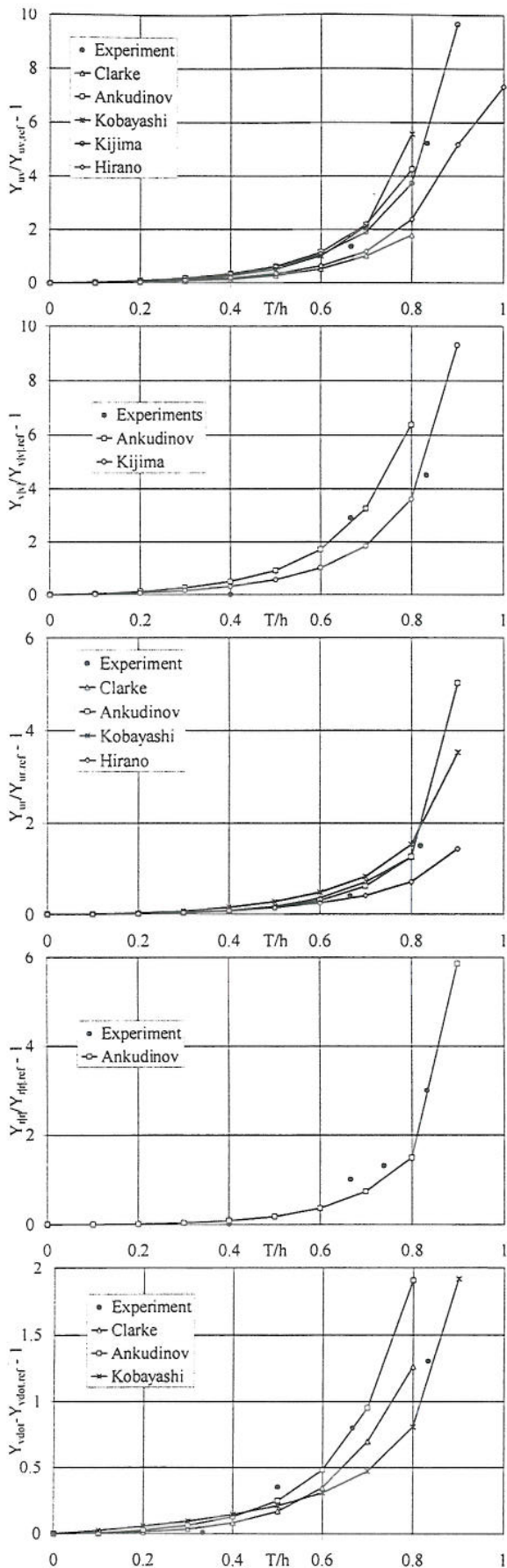
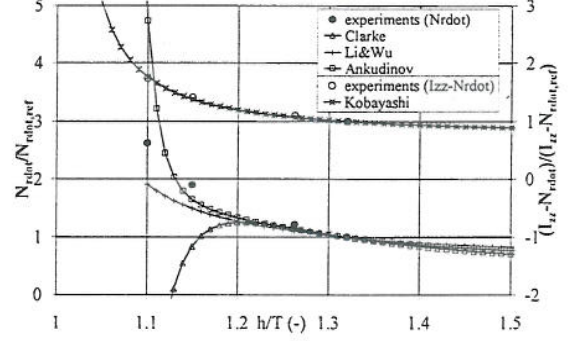
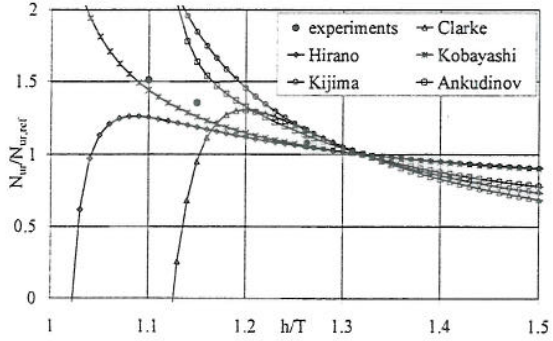
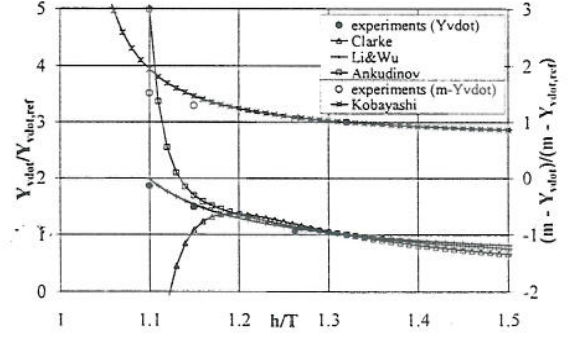
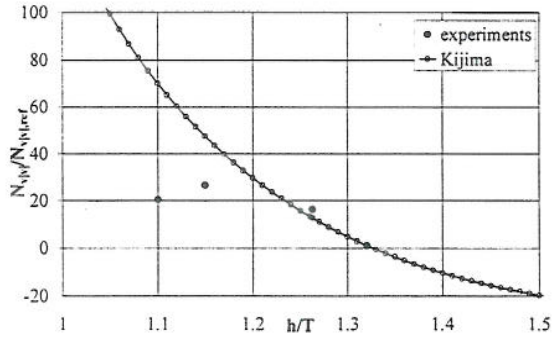
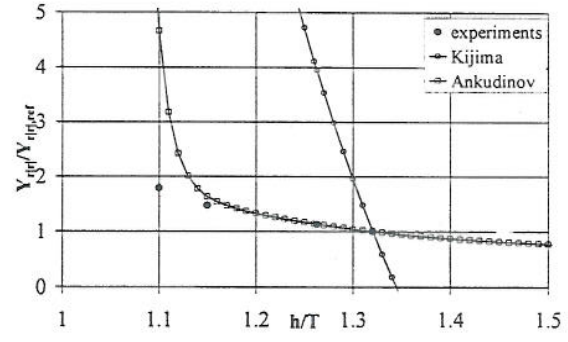
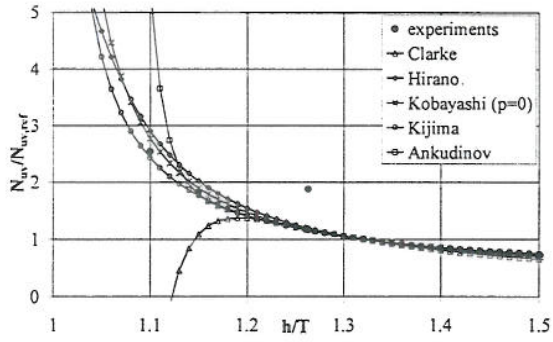
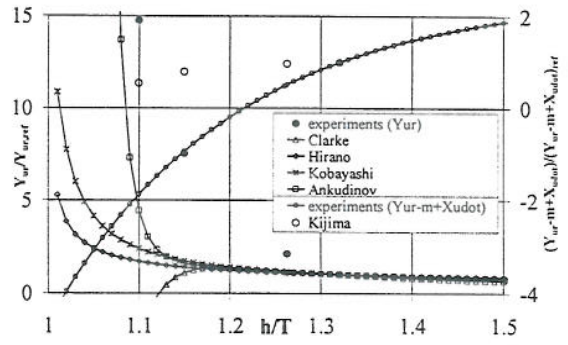
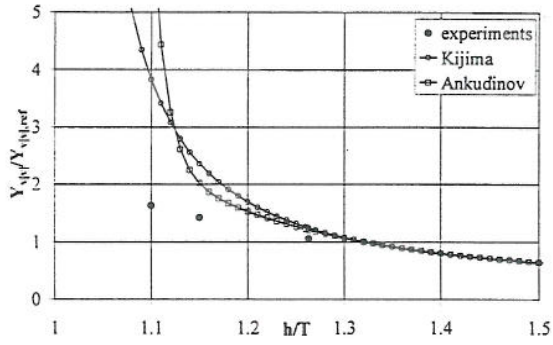
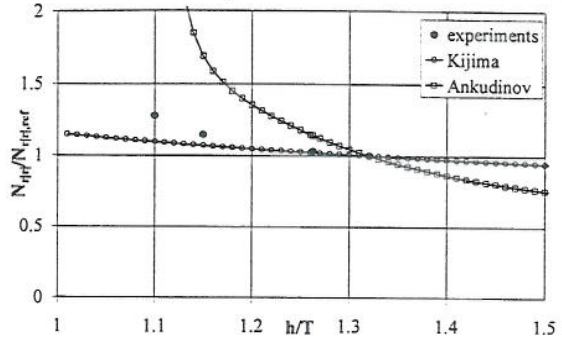
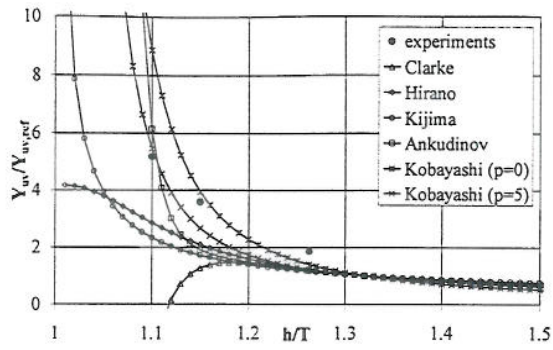


Fig.1 Effect of water depth on manoeuvring coefficients for Esso Osaka, $(h/T)_{ref} = \infty$: experiments vs. empirical formulae (Petersen [15], 23rd ITTC Manoeuvring Committee [5])

Fig.2 (next pages) Effect of water depth on manoeuvring coefficients for container carrier model ($L_{pp} = 3.88$ m, $B = 0.54$ m, $T = 0.18$ m, $C_B = 0.60$, $(h/T)_{ref} = 1.32$): PMM tests results vs. empirical formulae (Vantorre [33]; 23rd ITTC Manoeuvring Committee [5])



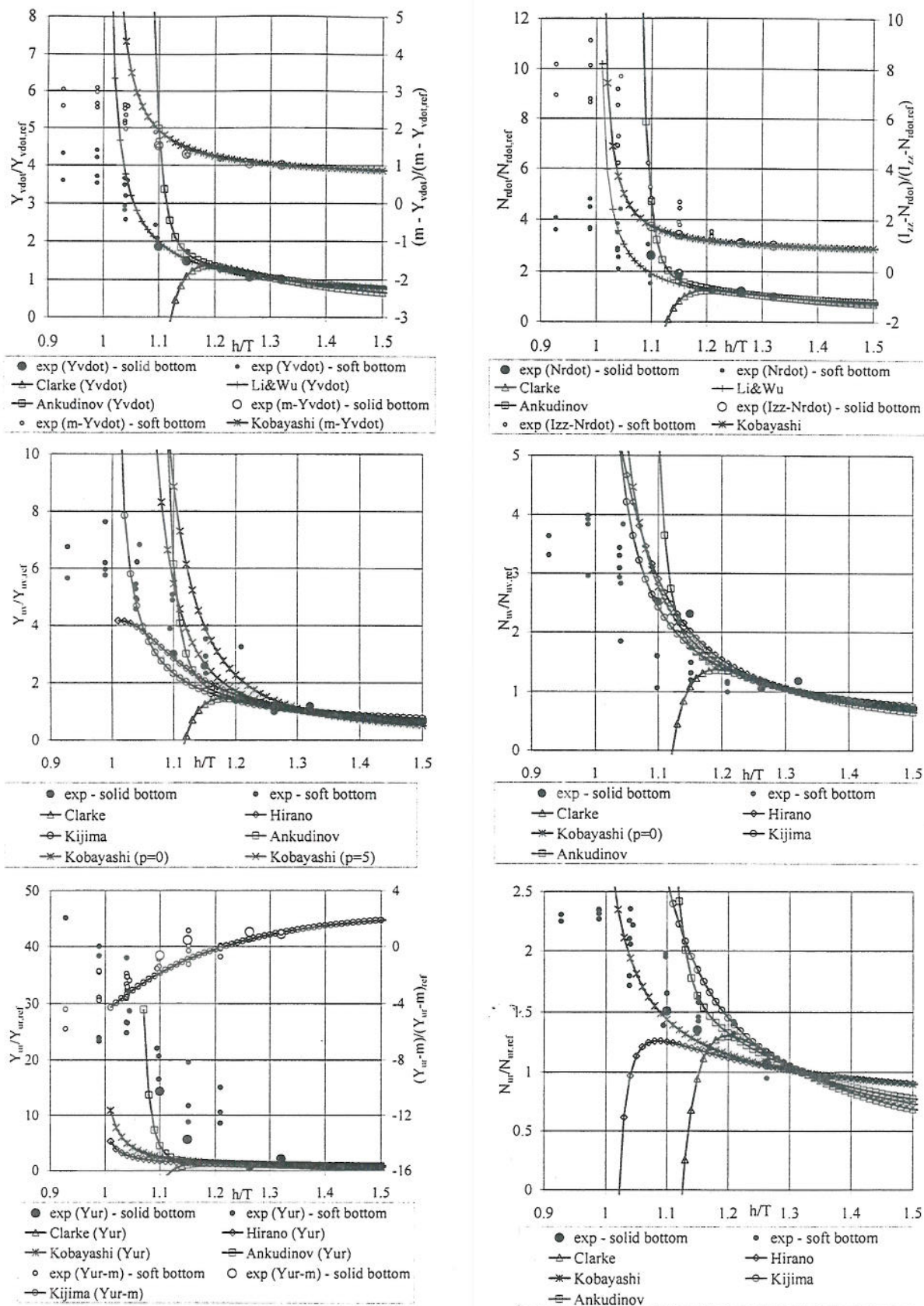


Fig.3 Effect of water depth on manoeuvring coefficients for container carrier model ($L_{pp} = 3.88$ m, $B = 0.54$ m, $T = 0.18$ m, $C_B = 0.60$, $(h/T)_{ref} = 1.32$): experiments above solid and soft bottom vs. empirical formulae (Vantorre [33], 23rd ITTC Manoeuvring Committee [5], Vantorre [16]).

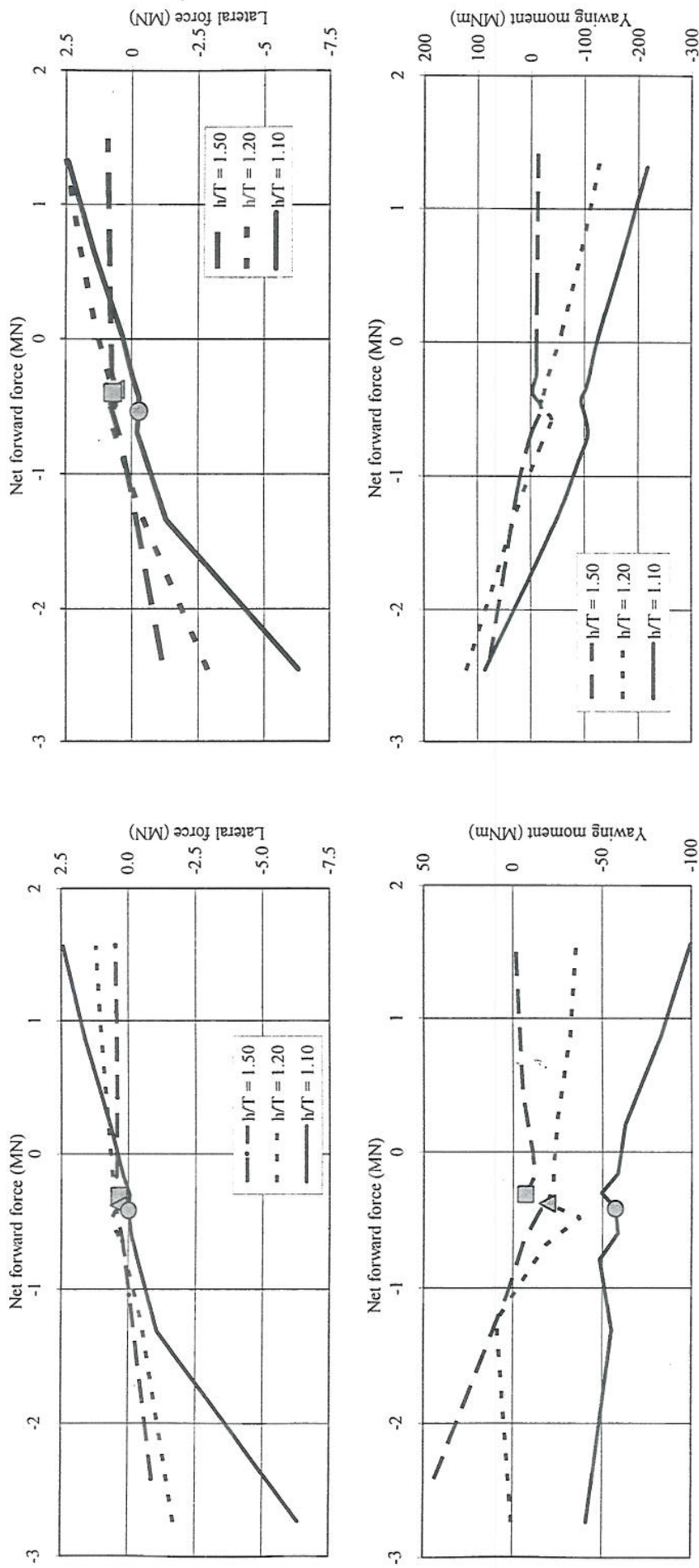


Fig.4 Ship-bank interaction effects on a panamax bulk carrier model ($L = 235.0$ m, $B = 32.2$ m, $T = 12.25$ m, $C_B = 0.828$, scale 1/64): lateral force and yaw moment as a function of net forward force at a forward speed of 2.4 m/s for a ship-bank clearance of 0.5 B (left) and 0.1 B (right). The symbols denote situations with zero propeller rate; self-propulsion is reached when the net forward force equals zero. Towing tank for manoeuvres in shallow water, co-operation Flanders Hydraulics Research – Ghent University, Antwerp, Belgium.

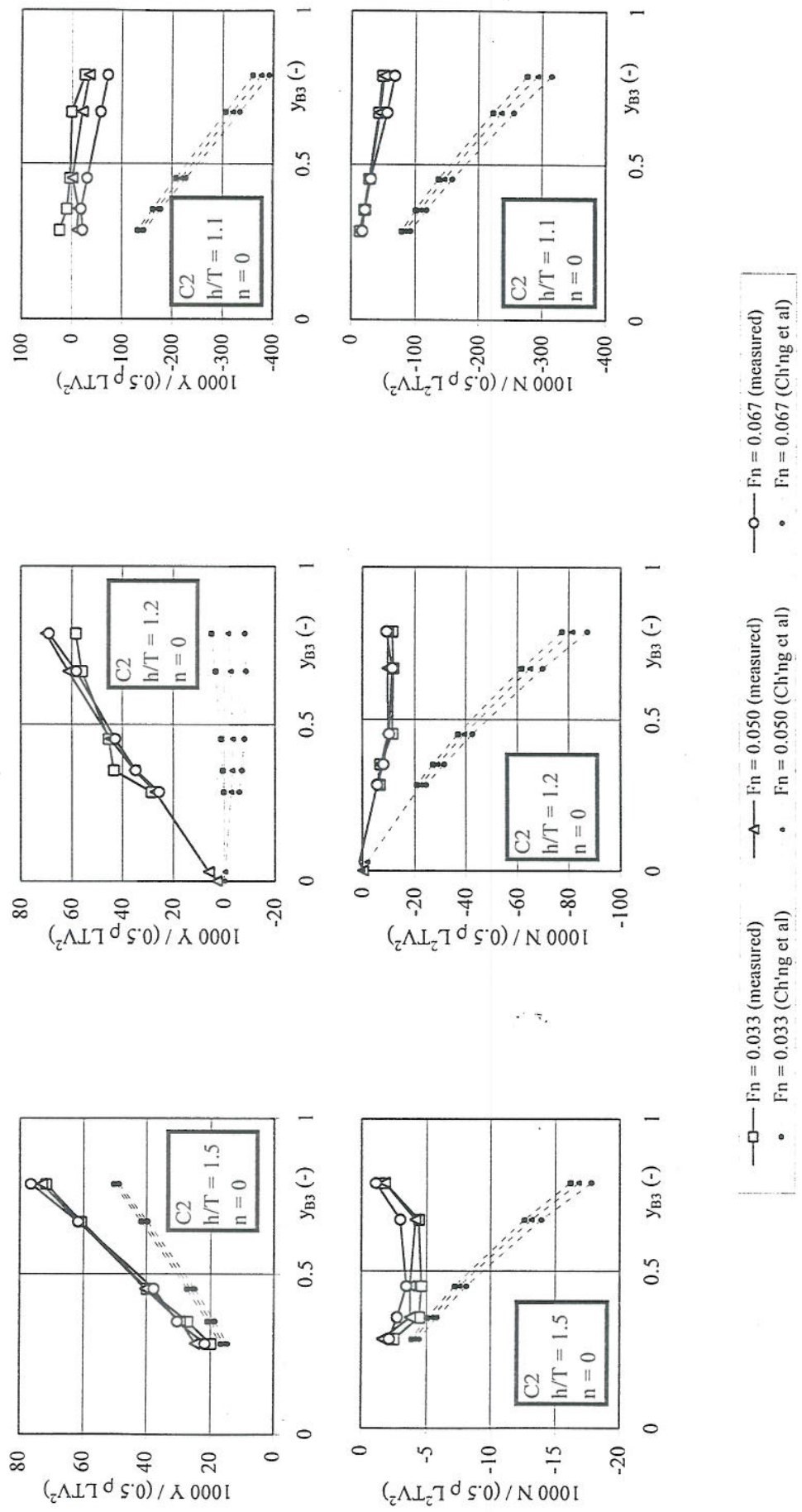


Fig.5 Panamax bulk carrier model: lateral force and yawing moment due to ship-bank interaction in absence of propeller action as a function of ship-bank distance for several water depth to draft ratios (Vantorre [17])