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Author Toxopeus, Serge
Address Delft University of Technology
Ship Hydromechanics Laboratory
Mekelweg 2, 26282 CD Delft

TUDelft

Delft University of Technology

Validation of Slender-Body Method for Prediction of Linear Manoeuvring Coefficients using Experiments and Viscous-Flowe Calculations

by

Toxopeus, Serge

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PREFACE

This ICHD 2006 is the seventh International Conference on Hydrodynamics. The first one was held in Wuxi, China, in 1994. Since then four Conferences have taken place approximately biannually in Hong Kong, Seoul, Yokohama and Taiwan. After these five successful Symposia, the sixth ICHD 2004 was moved for the first time out of the Asian Region to Perth, Australia. The ICHD 2006 is the first one the Conference takes place in Europe. We would like to remember now our friend, lost to soon, Maurizio Landrini who strongly believed in the possibility to host the conference in Europe.

The main goal of ICHD Conferences is to promote exchange of knowledge and discussions among researchers, designers and engineers in various branches of hydrodynamics. Themes of this Conference include Naval Architecture and Ocean Engineering, Coastal Engineering, Environmental, Hydraulics and Water Resources, Computational Fluid Dynamic and Experimental Techniques, Fundamental Research in Hydrodynamic and Industrial Fluid.
The ICHD provides an opportunity for people, working in these fields, to present and discuss theoretical and experimental researches, and to consider practical applications of research activities.
It is our strong belief that works in the fields discussed in the Conference will be beneficial to solve practical engineering problems, and to promote our understanding both of sea resources protection and conservation and of coastal environments.

The ICHD 2006 is co-hosted by the Department of Naval Architecture and Marine Engineering of the University "Federico II" of Naples and by INSEAN (the Italian Ship Model Basin).
The ICHD 2006 Proceedings contain four keynote lectures, on top of the papers to be presented at the Conference.
Proposal for about 150 works were received from 20 countries and almost 100 were accepted for presentation.
We strongly hope that the high quality of the selected works will guarantee a success comparable to that of the previous editions.
Based on the information available to the Organising Committee, this Conference will be attended by over 110 delegates from around the world.

We, as the ICHD Organising Committee, would like to thank all the members of the International Scientific Committee for their devotion towards the success of the ICHD 2006 Conference.
It is also almost impossible for us to find a proper expression, to express our sincere gratitude to Mr. Pasquale Cioffi of the ICHD Secretariat, for the time and the efforts devoted, during the past two years, in the Conference preparation.
We have done our utmost to create the proper atmosphere for an interesting and enjoyable Symposium.
We wish everyone a nice stay in Ischia!

VAdm.Giano Pisi -
Prof Pasquale Cassella

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	Taketani Tadashi	Akishima Laboratory (Mitsui Zosen) Inc., Tokyo	Japan
	Kimura Koyu	Akishima Laboratory (Mitsui Zosen) Inc., Tokyo	Japan

Validation of slender-body method for prediction of linear manoeuvring coefficients using experiments and viscous-flow calculations

Serge Toxopeus
Maritime Research Institute Netherlands (MARIN), Wageningen, The Netherlands
Delft University of Technology, Delft, The Netherlands

ABSTRACT: This paper presents the validation of the prediction of linear manoeuvring coefficients by a state-of-the-art fast-time simulation model by using the results of viscous flow calculations and experimental values. The simulation model is of the modular type in which forces on the hull, propellers, rudders and other appendages and their interactions are described separately. The linear forces on the hull are modelled using a semi-empirical method often referred to as the slender-body method. According to this method, the linear manoeuvring coefficients are determined by the rate of change of fluid momentum along the length of the ship. Only a few empirical parameters are used and these can be validated and improved using viscous flow calculations. In this paper, details of the slender-body method and comparisons with viscous-flow calculations and experiments will be presented.

1 INTRODUCTION

Although viscous-flow calculations are increasingly used to study the flow around manoeuvring ships, the computational requirements do not yet allow the daily application for manoeuvring predictions during the early design of ships. Furthermore, in multi-objective optimisation studies during which numerous different design options have to be assessed, fast-time simulation models are still the preferred option. Therefore, the need for high-fidelity simulation models with short computation times still exist today.

This paper presents the validation of the linear hull forces predicted by a state-of-the-art fast-time simulation model by using the results of viscous flow calculations and experimental values. The simulation model is of the modular type in which forces on the hull, propellers, rudders and other appendages and their interactions are described separately. The linear force components on the hull are modelled using a semi-empirical method often referred to as the slender-body method. According to this method, the linear manoeuvring coefficients are determined by the rate of change of fluid momentum along the length of the ship. Only a few empirical parameters based on careful validation with experiments are used and these can be validated and improved using viscous flow calculations. Since this method utilises the full description of the hull form, the influence of changes in local details of the hull can be investigated within a short time-frame. This makes the method very suitable to daily application and optimisation studies. Additionally, the method can be used easily for simulation of manoeuvring in waves or shallow water due to the generalised approach of the method. In this paper, details of the slender-body method will be presented.

Viscous flow calculations and tests with segmented models of several different hull forms have been conducted. The forces obtained through these calculations and tests are compared directly to the forces obtained with the slender-body method and good agreement will be demonstrated.

In this paper, only the accuracy of the linear manoeuvring coefficients for the bare hull is studied. For a full validation of a fast-time manoeuvring simulation program, also the other components governing the manoeuvring of the ship (e.g. non-linear hull forces or rudder forces and their mutual interactions) should be examined.

2 FAST-TIME SIMULATION PROGRAMS

Due to developments within several projects and varying applications, several different fast-time simulation programs are available at MARIN for prediction of the manoeuvring characteristics of ships, with each program having its specific area of application. Examples of these programs are MPP (developed by the NSMB CRS group), SurSim (for general merchant ships), FreSim, Fredyn (both for high-speed semi-displacement ships) and CrabSim (for low speed and harbour manoeuvring). The purpose of these programs is to predict the manoeuvrability of a ship, based on limited input and without use of any a-priori information of the ship's manoeuvring derivatives, by simulating a specified set of standard manoeuvres within a short time frame. Generally, the outcome of the program is compared to manoeuvring criteria, either posed by regulatory bodies such as IMO (2002) or criteria posed by the owner or shipyard. Due to its limited computational requirements, such a program is furthermore well suited for mission-based design studies or for multi-objective optimisations in which for example an optimum trade-off is sought between the powering, seakeeping and manoeuvring requirements.

Although details of the implementation may differ between different programs, the calculation of the forces required to predict accelerations and subsequently the trajectory of ships as a function of steering or propeller actions is quite similar. In more advanced cases of generic manoeuvring simulation programs a so-called modular approach is mostly used. This means that the total force (and moment) on the ship is divided into distinct components, such as the force due to the flow around the bare hull, the force including interactions due to the propeller(s), the force due to the rudders, etcetera. The forces and moments can furthermore be considered to consist of linear and non-linear contributions, with the non-linear contributions calculated using e.g. the so-called cross-flow drag theory, presented by e.g. Hooft (1994) or Hooft and Quadvlieg (1996). The linear forces in these models can be considered to be representative of the lift generated on the hull while the non-linear forces represent the drag.

Mathematically, for the transverse force on the bare hull Y_H an expression similar to the following is generally used:

$$
\begin{aligned}
Y_H &= Y_{H,lin} + Y_{H,non\text{-}lin} \\
Y_{H,lin} &= Y_{uv} \cdot u \cdot v \cdot \cos\beta + Y_{ur} \cdot u \cdot r \\
Y_{H,non\text{-}lin} &= -\tfrac{1}{2}\rho \int_{x_{aft}}^{x_{fore}} C_D(x) \cdot T(x) \cdot v(x) \cdot |v(x)| \cdot dx
\end{aligned}
\qquad (1)
$$

In these formulae, u is the longitudinal ship-fixed velocity, v the transverse velocity, r the yaw rate of turn, β the drift angle defined as $\beta=\arctan(v/u)$, ρ the density of the water, x the longitudinal position with respect to the origin and T(x) the local draught.

Traditionally, the linear coefficients are calculated using empirical formulae, for example similar to the well-known method of Inoue (1981). Since these formulae require limited input, this approach is very well suited to the first stage of a design. However, such methods have insufficient resolution to distinguish between changes in hull form details. For example, changing the length of the centreline skeg normally does not lead to different linear manoeuvring coefficients. Furthermore, these methods are relying heavily on previous ships used for the regression analysis. The manoeuvring characteristics of new ships or ship types that deviate strongly from the ships in the database can in general not be predicted reliably.

Therefore, alternative methods such as the so-called slender-body theory are required to arrive at a more generic derivation of the linear contributions, see e.g. Hooft and Quadvlieg (1996) or an application to an unconventional hull form presented in Keuning et al (2001). A detailed discussion of the method can also be found in e.g. Beukelman (1995).

A modified version of the slender-body method has been developed and implemented in the manoeuvring simulation programs available at MARIN. Details of the implementation and modification of the theory, required to arrive at reliable results, are discussed in the present paper. Examples of the application of the method are presented, with the attention focussed on the program SurSim, which was developed to predict the manoeuvrability of merchant surface ships. Details and applications of SurSim have been presented earlier, by e.g. Hooft and Nienhuis (1995) and Hooft and Quadvlieg (1996). Since in all MARIN manoeuvring prediction programs the slender-body method is used to predict the linear hull forces, the differences in the prediction of the forces on the hull follow from the different implementations of the non-linear hull force components.

3 SLENDER-BODY THEORY

The slender-body method is based on the distribution of the added mass along the length of the ship and is used to determine the linear manoeuvring derivatives. The advantage of this method is that hull details are incorporated in the estimation of the linear derivates. A detailed description of an earlier version of the method can be found in Hooft and Quadvlieg (1996). In the following, a rough outline of the modifications leading to the present method is given.

The slender-body strip theory technique according to Jones (1946) states that the force per slice of the ship is the rate of change of fluid momentum per slice of the ship. For a pure drift motion, this simplifies into:

$$Y_{uv} = -\int_{\xi_{fore}}^{\xi_{aft}} \frac{dm_{yy}}{d\xi} d\xi = -\left[m_{yy}(\xi_{aft}) - m_{yy}(\xi_{fore})\right] \tag{2}$$

In this formula, m_{yy} is the (instantaneous) sectional added mass per unit length and ξ is the distance behind the foremost submerged part of the bow. The formula may also be applied to a section of the ship, e.g. using ξ corresponding to $0.4 < x/L_{pp} < \infty$ to arrive at the linear derivative for a bow segment extending from station 18 (for which $x/L_{pp} = 0.4$) forward. The sectional added mass may be derived in different ways, e.g. by using strip-theory, three dimensional diffraction codes or by using empiric formulae, obtained by regression of added mass calculations for ranges of generic two dimensional sections. If required, time-dependent sectional added masses may be derived, using for example the instantaneous immersion of each frame. The instantaneous immersion of a frame may be governed by not only heave or pitch motions of the ship, but also by the passing of waves.

For the other linear derivatives for the transverse force and yaw moment (for the roll moment, a similar approach may be used), the following equations are used (a detailed derivation of the formulae may be found in Beukelman (1995):

$$N_{uv} = -\int_{fore}^{aft} \frac{dm_{yy}}{d\xi} x d\xi = \int_{fore}^{aft} \frac{dY_{uv}}{d\xi} x d\xi \tag{3}$$

$$\begin{aligned} Y_{ur} &= \int_{aft}^{fore} \left(\frac{dm_{yy}}{dx} x + m_{yy} \right) dx = \int_{aft}^{fore} \left(\frac{dm_{yy}}{dx} x \right) dx + \int_{aft}^{fore} m_{yy} dx \\ &= \int_{aft}^{fore} \left(\frac{dm_{yy}}{d\xi} x \right) d\xi - \int_{aft}^{fore} m_{yy} d\xi = -\left(\int_{fore}^{aft} \left(\frac{dm_{yy}}{d\xi} x \right) d\xi - \int_{fore}^{aft} m_{yy} d\xi \right) \\ &= -\left(\left[m_{yy} \cdot x \right]_{fore}^{aft} - \int_{fore}^{aft} \left(m_{yy} \frac{dx}{d\xi} \right) d\xi - \int_{fore}^{aft} m_{yy} d\xi \right) \\ &= -\left(\left[m_{yy} \cdot x \right]_{fore}^{aft} + \int_{fore}^{aft} m_{yy} d\xi - \int_{fore}^{aft} m_{yy} d\xi \right) = -\left[m_{yy} \cdot x \right]_{fore}^{aft} \end{aligned} \tag{4}$$

$$N_{ur} = \int_{aft}^{fore} \left(\frac{dm_{yy}}{dx} x^2 + m_{yy} \cdot x \right) dx$$

$$= \int_{aft}^{fore} \left(\frac{dm_{yy}}{d\xi} x - m_{yy} \right) \cdot x d\xi = - \int_{fore}^{aft} \left(\frac{dm_{yy}}{d\xi} x - m_{yy} \right) \cdot x d\xi \tag{5}$$

$$= \int_{fore}^{aft} \frac{dY_{ur}}{d\xi} \cdot x d\xi$$

As seen in these equations, all linear derivatives are basically a function of the m_{yy} distribution. This means that only an accurate description for m_{yy} has to be found to obtain all four linear manoeuvring derivatives given above.

The problem with the given definition of each derivative is that the added mass at the bow and at the stern in theory both equal zero, therefore reducing Y_{uv} also to zero (paradox of D'Alembert). In previous publications, suggestions were made to solve this problem. For example, Beukelman (1995) suggested integrating from the bow up to the section with maximum cross-sectional area. However, the weakness of this approach is that the actual shape of cross-sections in-between the bow and the section with maximum area does not contribute to the final linear manoeuvring derivatives. Additionally, the influence of aft ship details such as e.g. size of the centreline skeg will be completely ignored and must therefore be incorporated completely in the non-linear terms.

To solve this problem, several test series with segmented ship models have been analysed to obtain a correction for the longitudinal added mass distribution. This leads to a modification due to the growth of the boundary layer thickness (which is a function of the Reynolds number), the incorporation of the influence of trailing edges and an application of three-dimensional effects, limiting the reduction of the added mass along the length of the ship when moving from bow to stern. These corrections can be considered to be analogous to the application of a Kutta condition in potential theory.

4 APPLICATION TO SEVERAL SHIPS

To verify the range of applicability of the prediction method, the calculated forces and moments are compared to existing experimental results and to results of viscous-flow calculations for several different ships.

The hull forms considered are the Esso Osaka (Crane (1979)), the Series 60 hullform (Longo (1996)), the KVLCC2M hullform (Kume et al. (2005)) and the MARIN Ferry. Results of calculations of the flow around these ships sailing at drift angles of 10° were already available from previous studies, see Van Oers and Toxopeus (2006). Additionally, the slender-body method is applied to one of the ships used as a test case within the Virtue EU project: the Hamburg Test Case (HTC) (see e.g. Toxopeus (2006)). The experimental results for the HTC used in this paper were kindly provided by HSVA. The following table shows some main particulars of these ships:

Table 1: Non-dimensional main particulars of ships

	KVLCC2M	Series60	MARIN Ferry*	Osaka	HTC
C_b	0.810	0.599	0.570	0.825	0.650
C_m	0.999	0.978	0.981	0.998	0.983
C_p	0.810	0.613	0.756	0.826	0.662
C_{wp}	0.905	0.708	0.778	0.889	0.822
L_{pp}/B	5.522	7.503	5.53	6.129	5.582
L_{pp}/T	15.386	18.699	28.56	15.633	14.922
B/T	2.786	2.492	5.19	2.551	2.673

* sailing in ballast draught

5 ADDED MASS AND FORCE DISTRIBUTIONS

In SurSim, the sectional added mass is calculated using empiric functions of the sectional area coefficient $C_m(x)$ and the local $B(x)/T(x)$ ratio. The empiric functions were derived by regression of the results of strip theory calculations for a range of two-dimensional cross sections with varying B/T ratios and cross sectional shapes. Alternatively, it is possible to derive the sectional added mass distribution along the length of the ship by more advanced methods, such as three-dimensional seakeeping codes, and feed these results into the SurSim.

In the left graph presented in Figure 1, the distribution of the non-dimensional sectional transverse added mass as calculated by SurSim (designated m_{yy}) for the MARIN Ferry is presented. The sectional added mass has been made non-dimensional using $\frac{1}{2}\rho L_{pp}T$. Additionally, the inverse relation of equation (2) is used to estimate the added mass distribution based on the distribution of the sectional transverse force derivatives for drift motion obtained from viscous flow calculations (cfd) using PARNASSOS (see Hoekstra and Eça (1998) or Hoekstra (1999)) or experiments (exp).

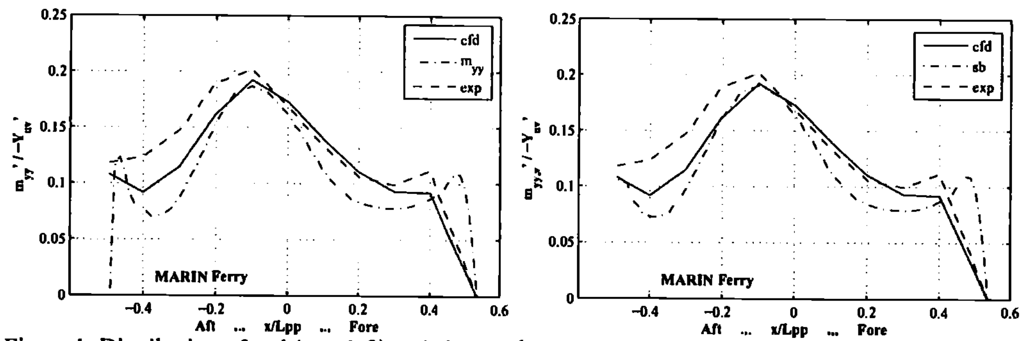

Figure 1: Distribution of real (m_{yy}, left) and virtual (sb, right) sectional transverse added mass

In this distribution, it is clearly seen that at the stern the sectional added mass returns to zero. Based on earlier studies, in which also the growth of the boundary layer along the length of the ship was considered, it was decided to derive a "virtual" added mass $m_{yy,v}$ instead of the original added mass distribution, by using the a virtual increase of the beam, draught and sectional area based on the local boundary layer thickness. Furthermore, analysis of several model test campaigns with segmented models showed discrepancies between the slender body method and model test results when a sharp decrease of the draught is encountered going from bow to stern. When the ship is equipped with e.g. a sonar dome or sharp centreline skeg, it was found that the influence of the sectional added mass of these constructions were still present downstream. To model this effect, analogous to applying a Kutta condition in potential flow calculations, the added mass of upwind stations is used also for downstream stations when the decrease draught T is larger than a given positive angle α_T:

$$m_{yy,v}(\xi) = m_{yy,v}(\xi - d\xi) \quad \text{when} \quad \arctan\frac{T(\xi-d\xi)-T(\xi)}{d\xi} > \alpha_T \tag{6}$$

Using results of various experimental campaigns with several different segmented models, a value of α_T=20° was derived. Based on these considerations, the left graph of Figure 1 changes into the right-hand graph when the virtual added mass is presented. It is now clearly seen that at the aft ship, the sectional added mass (designated sb) does not return to a zero value, resulting in a non-zero Y_{uv}, see equation (2).

The hydrodynamic sway force derivative for pure drift motion on a segment of the ship, designated $Y_{uv,n}'$, can be calculated with equation (2) using the virtual added mass distribution and the appropriate integration ranges, as follows:

$$Y_{uv,n}' = -\left(m_{yy,v}'(\xi_{aft}') - m_{yy,v}'(\xi_{fore}')\right) \tag{7}$$

Using as an example the MARIN Ferry for which extensive tests with a segmented model were conducted, these derivatives are given in the figure below according to respectively the slender-body method, to the viscous flow calculations and to the experiments for two speeds. The cfd results and experimental results have been obtained by extrapolating the results for $Y_n'/(\cos^2\beta\sin\beta)$ for several drift angles to zero drift angle. It is seen that in general the modified slender-body method corresponds well to both the cfd results as the experimental results. Similar results were found for the other ships.

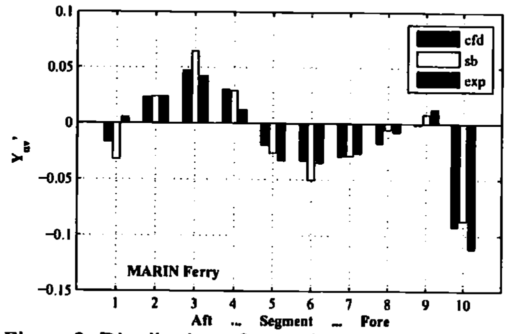

Figure 2: Distribution of sway force derivative for drift along the segments (MARIN Ferry)

For the other ships, similar graphs can be made, see Figure 3. Although some discrepancies between the slender-body method results and the viscous flow calculations appear for individual segments, a distinct relation between the added mass distribution and the transverse force distribution is seen.

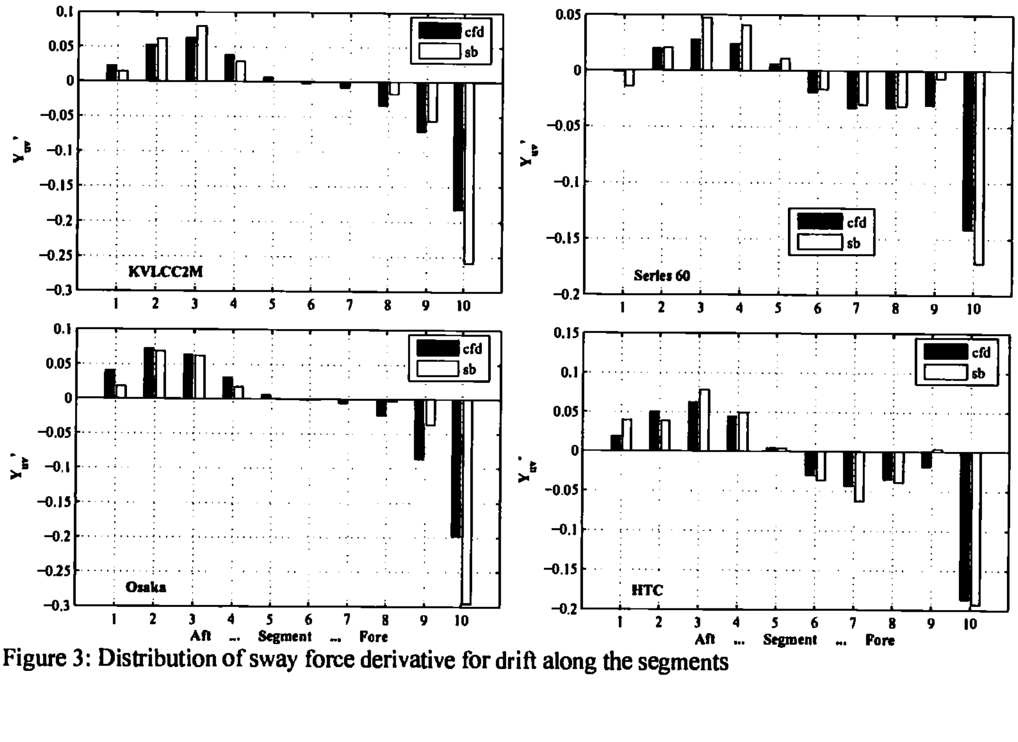

Figure 3: Distribution of sway force derivative for drift along the segments

The linear yaw moment derivative for yaw motion $N_{ur,n}'$ is calculated using equation (5). Unfortunately, experimental results for rotational motion were not available for the subject ships at the time of writing of this paper. For the KVLCC2M and HTC hull forms, however, viscous-flow calculations for several rates of rotation were conducted which can be compared with the results obtained using the slender-body method. More details of these calculations are presented by Toxopeus (2006). In Figure 4, the results for $N_{ur,n}'$ are presented. Once again, agreement between the added mass distributions and the coefficients is found. However, for the KVLCC2M a large discrepancy between the results from the viscous-flow calculation and from the slender-body method for $N_{ur,n}'$ for the bow segment (segment 10) is found. This is caused by the amplification of the over-prediction of the added mass along segment 10 which is also seen in Figure 3. One of the origins of the discrepancy can be explained by the large block coefficient of the KVLCC2M (and Esso Osaka). For such full-block ships the application of the slender-body theory may be less suitable. Further study is required to find the reason for this over-prediction.

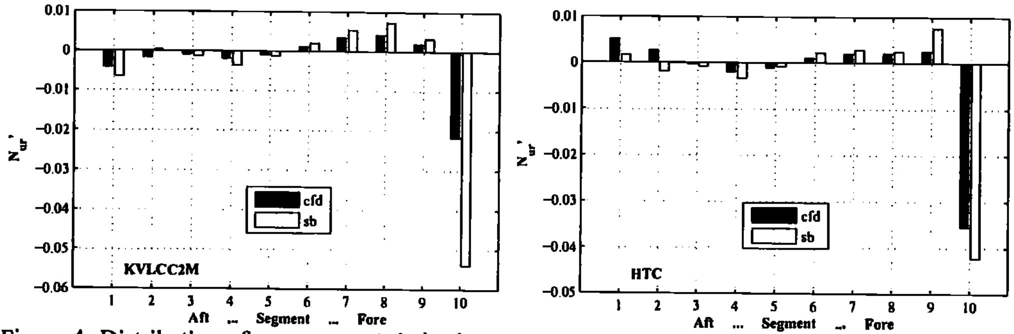

Figure 4: Distribution of yaw moment derivative for rotational motion along the segments (KVLCC2M and HTC hull forms)

6 COMPARISON OF INTEGRAL FORCES WITH EXPERIMENTS AND CFD

The correlation between the trends found based on the slender-body theory and the results obtained from the viscous-flow calculations or experiments shows that the modified slender-body theory produces quite an agreeable representation of the force distribution along the length of the ship. An example of the correlation between the drift angle and predicted or measured forces for some of the subject ships is given in Figure 5. A similar graph is made for the forces and moments as a function of the yaw rate, see Figure 6. The sway forces and yaw moments have been made non-dimensional using $\frac{1}{2}\rho V_s^2 L_{pp} T$ and $\frac{1}{2}\rho V_s^2 L_{pp}^2 T$ respectively. From Figure 5, it is seen that the prediction for the yawing moment using the viscous-flow solver (designated cfd) is very accurate even up to large drift angles. The prediction of the transverse force represents the trends in the experiments well, but is in most cases somewhat smaller in magnitude. The modified slender-body method implemented in SurSim (designated sb) predicts the transverse force relatively well although for large drift angles some deviation from the measurements or viscous-flow predictions may occur. The prediction of the yawing moment, however, needs some improvement. This is mainly caused by over-prediction of the added mass distribution at the bow, but the deviation must also be attributed to an over-prediction of the non-linear bare hull moments. In general it is concluded that the slope of the predictions at the origin, governed by the linear coefficients, is quite well predicted.

Figure 6 shows that the prediction of the transverse force for pure yaw rates is similar for the viscous-flow calculations and the slender-body method. The yaw moment predicted by SurSim for the KVLCC2M is however much larger than the yaw moment obtained by the viscous-flow calculations. Once again, this deviation is caused by the over-prediction of the added mass distribution at the bow.

Based on these comparisons, it is judged that the slender-body method can be used in the early design to predict the change in the manoeuvring performance of ships as a function of changes in the hull form. In case more accurate estimations are required for the final design, accurate viscous-flow calculations or model experiments are required.

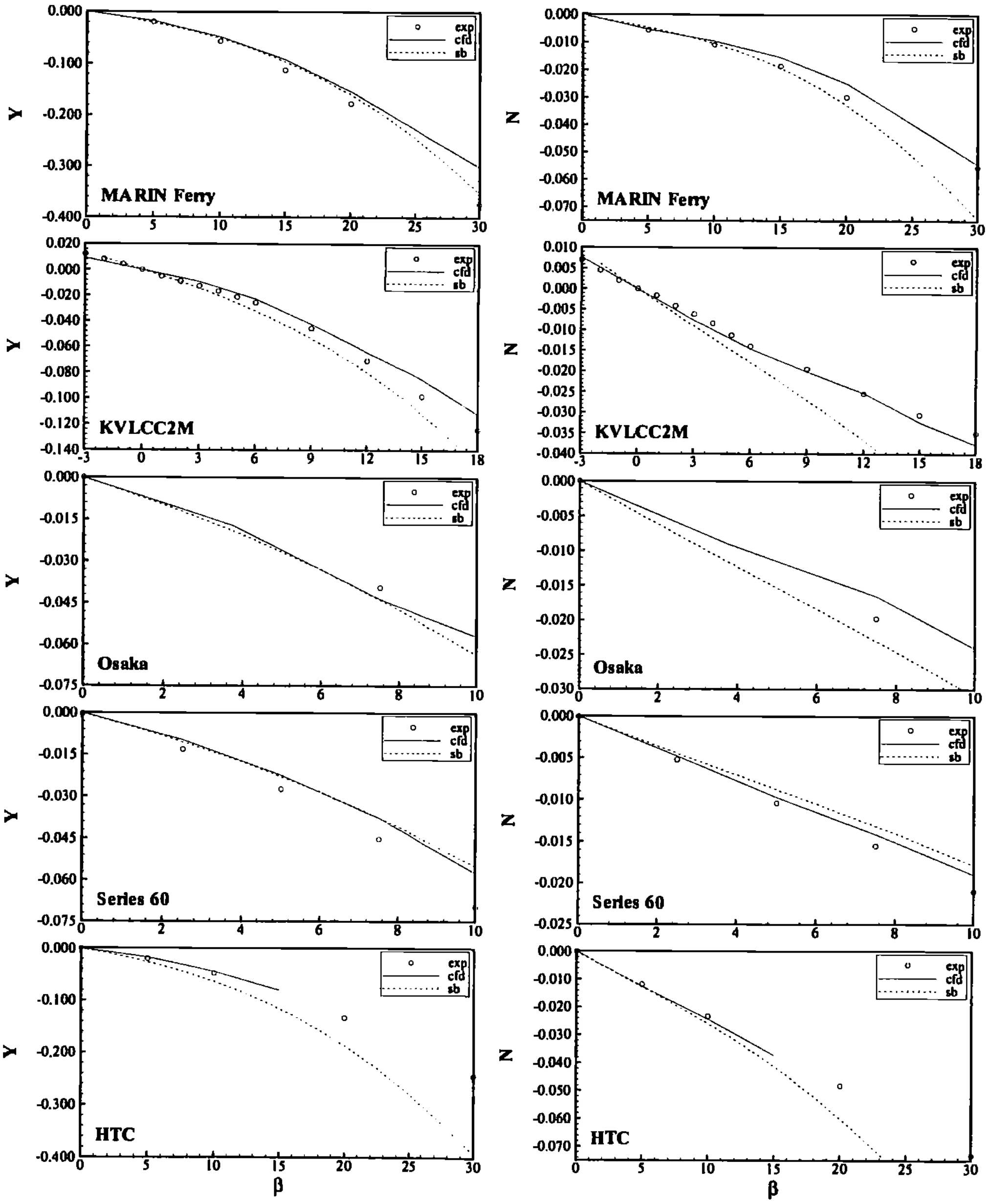

Figure 5: Comparison between predicted forces for drift using viscous flow calculations and using slender-body method

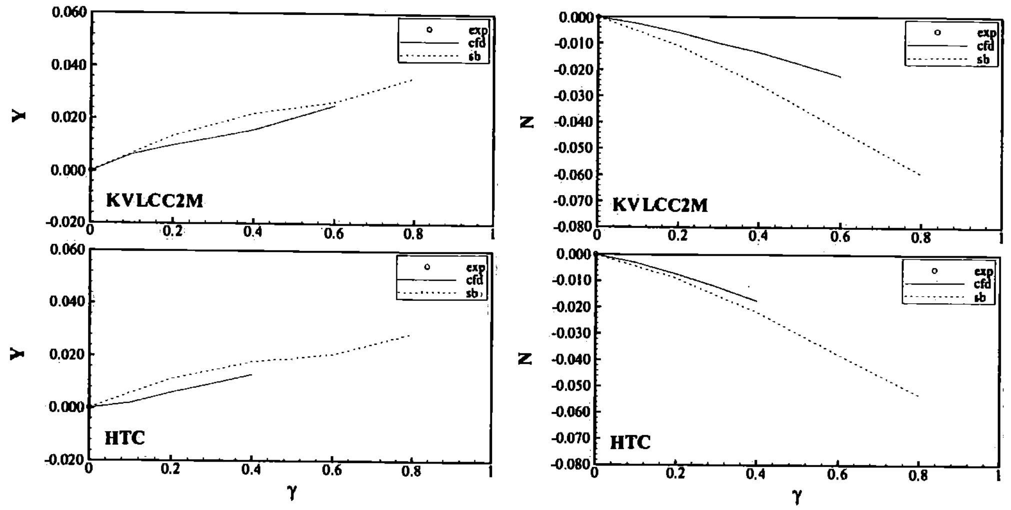

Figure 6: Comparison between predicted forces for yaw rotation using viscous flow calculations and using slender-body method

7 CONCLUSIONS

In this paper, a modified version of the slender-body method to estimate the linear manoeuvring derivatives for the bare hull is presented. One of the major benefits of the method is the incorporation of hull details, such that during the design process the influence of changes in the design on the manoeuvring characteristics of the ship can be examined. Only a limited number of empiric coefficients is used to arrive at the prediction of linear coefficients and therefore the method is suitable for a wide range of ships.

Using experimental results and results of viscous-flow calculations, the accuracy of the method is demonstrated. In general, the slender-body method represents the trends found from experiments or using viscous-flow calculations well. Therefore, it is judged that the slender-body method can be used reliably in the early design to predict the change in the manoeuvring performance of ships as a function of changes in the hull form. For full-block ships, however, the method may slightly over-predict the forces generated at the bow.

Further research is ongoing in order to investigate the applicability of the method for e.g. shallow water conditions, incorporating speed effects such as squat and influence of the generation of the ship's wave system on the linear coefficients.

8 ACKNOWLEDGEMENTS

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