AN INVESTIGATION OF HYDRODYNAMIC FORCING ON A SEMI-PLANING MONOHULL IN FOLLOWING AND STERN QUARTERING SEAS

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SUMMARY

Navigating a ship in following and stern quartering seas is well known to seafarers for the possible troublesome situations that may arise. The issue has also been addressed by many researchers during the last 50 years. In 1964 Du Cane and Goodrich presented one of the first systematic studies on ships in following seas together with a compilation of accounts on real occurrences of dangerous situations for ships in following and stern quartering seas. Later research has confirmed the possibility for occurrence of several types of allegedly capricious behaviour for a ship travelling at a course within one third of the compass card, i.e. between -60° and 60° relative to the waves. The research included in the references is covering many different types of ships from fishing boats to fast naval vessels and merchant ships.

Despite the 51 years of research in the tradition pointed out by Du Cane and Goodrich's work, there is still a lack of effective methodology within many of the areas connected to following and stern quartering seas. The present paper is mainly focusing on manoeuvring in following seas. Nevertheless, results included in the current paper, among others, show that a ships motion in the horizontal plane has a major impact on the magnitude and timing of wave excitation in all degrees of freedom. Therefore the presented results are of importance for most of the seakeeping and safety issues related to navigation in following and stern quartering seas.

The most significant results presented in the current paper come from semi-captive tests with a semi-planing ship model. At these tests the surge force, sway force, roll moment and yaw moment were measured, while the ship model was free to heave and pitch. The test data are compared to computational data obtained by a strongly simplified hydrodynamic modelling. This comparison shows very encouraging results.

The paper does also address criteria for safe manoeuvring in following and stern quartering seas, methodologies for full-scale tests and experiments with a free-running scale model.

1. INTRODUCTION

Navigating a ship in following and stern quartering seas is well known to seafarers for the possible troublesome situations that may arise. The issue has also been addressed by many researchers during the last 50 years. In 1964 Du Cane and Goodrich presented one of the first systematic studies on ships in following seas together with a compilation of accounts on real occurrences of dangerous situations. Later research covering many different types of ships has confirmed there exist several types of allegedly capricious behaviour for a ship in a seaway where the waves are travelling in approximately the same direction as the ship. It has further been found that similar phenomena can also occur when a ship is steered at a courses between $-60°$ and $60°$ relative to the waves. This large sector covering one third of the compass card is often referred to as following and stern quartering seas.

The seemingly unpredictable nature of ship behaviour in following and stern quartering seas is unsatisfying to the shipping business in many ways. E.g. the uncertainty about weather conditions limiting the operability may cause economical loss for a ship owner. Further it is stressful for a ship crew having doubts about the safety onboard. It is of course also very troublesome for a ship designer to have neither tools nor any specific regulations concerning some important aspects of ship safety.

The present work is aimed to provide data helping the understanding of the current topic; to encourage further development of analysis methods and stimulate to discussions on these matters. From previous research by Rutgersson and Ottosson among others, it is acknowledged that physical modelling, combined with experiments when necessary, is an effective way to approach issues concerning safety and behaviour of a ship in following and stern quartering seas.

The current research includes a large series of semi-captive models tests where the most important forces were measured. In addition computations of hydrodynamic forcing were performed and they compared to the experiments. Further full-scale tests were performed and a method to evaluate full-scale trials was developed. Table 1 show an overview of the elements employed in the present work.
In Table 1 computational methods are represented by method a; semi captive model tests are denoted as method b and full-scale tests are shown as method c.

Previous research performed by different groups of researchers has been studied and compared to results of the present work. The major challenges, from a physical point of view, found during this work may be summarised by the four points below.

- Ordinary methods used within manoeuvring and seakeeping are insufficient to describe hydrodynamic forcing in following and stern quartering seas
- Strong coupling between different degrees of freedom may cause a seemingly non-linear behaviour even for a dynamic system that can be described by linear differential equations.
- In following and stern quartering seas there is a significant probability that the ship moves in a way such that non-linear terms are needed to properly describe hydrodynamic or hydrostatic forcing on the ship.
- The manner in which the ship is manoeuvred has a great influence on the wave-induced motions.

Within the current research programme Lundbäck (2005) has presented a lot of data supporting the points above. Other valuable information supporting these points was found in publications by Hua, de Kat, Renilson, Spirou and Umeda

Table 1 Overview of the research

m e t h o d	**Wave model** Described by: Wave length Wave amplitude + Physical model of sea water if appliable	Link describing exchange of energy or forces between ship and sea water	**Ship as a system of dynamics** Described by: A system of ODE:s, a ship model or a full-size ship
a	Standard model of sinusoidal waves in an ideal fluid	An analogy to manoeuvring thy+analogy to strip thy	Newtons 2^{nd} law of motion
b	Wave laboratorium	Scale model of a ship	(Scale model of a ship)
c	Real sea	Manoeuvring theory	Full-scale ship

2. METHODS FOR FULL-SCALE TESTING

The current research programme begun with a series of full-scale tests with different high-speed craft operated by the Swedish and Finnish Navy respectively. The ships were instrumented with sensors measuring motions in all six degrees of freedom plus the rudder angle. Different test procedures and evaluation methods were tried out. The tests were combined with interviews with the ship crew. Results from these full-scale tests were presented by Lundbäck (2002), where the full-scale methodology was also carried over to laboratory experiments.
During the work with tests in full scale a procedure using manoeuvring tests in calm water and course keeping tests in waves was put forward. This procedure is illustrated by Figure 1

The data were evaluated with a novel procedure for estimation of wave excitation using recorded ship motions and rudder angle as input.
The analysis was completed by comparing estimated wave forcing with a new criterion for allowable wave excitation. Equation (1) and (2) describe the equation for wave induced yaw forcing and the criterion for allowed wave forcing.

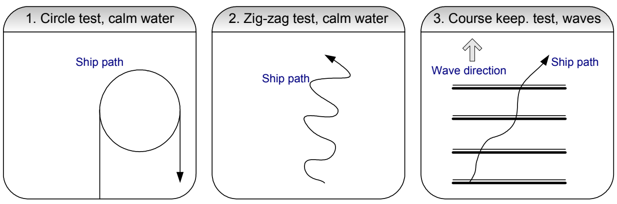

Figure 1. Test procedure.

$$K \cdot \delta = r + T_1 \cdot \dot{r} + T_2 \cdot \ddot{r} + N_w(t)\,, \qquad (1)$$

$$N_w < K \cdot \delta_{\max} + \psi_{\max} \cdot \omega_e \cdot \sqrt{(T_1{}^2 \omega_e{}^2 + 1)}\,, \qquad (2)$$

where N_w is wave induced yaw forcing, r is yaw rate, δ is rudder angle, ψ_{max} is the maximum allowed yaw amplitude for safe manoeuvring and ω_e is encounter frequency. K, T_1 and T_2 are constants.

3. SEMI-CAPTIVE TEST SETUP

A model of one of Swedish Navy's patrol crafts (HMS Kaparen) was fitted with a six-component force transducer. However the model was free to move in heave and pitch at the tests. Table 1. Shows main particulars of the full-scale ship. The model is in scale 1:18

Table 2. Main Particulars for HMS Kaparen

Lpp	34 m
B	6 m
T_m	1.96 m
Displacement	190 m^3
C_b	0.46
LCG	-2.1 m
KG	2.9 m

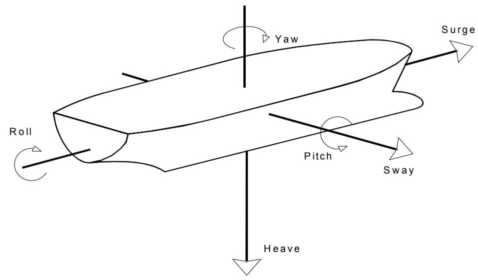

Figure 2. Coordinate system for the measured forces

The directions for the measured forces and moments are described by Fig. 1. At SSPA Sweden's Marine Dynamics Laboratory, there is a wave basin that is 88mx39m with wave makers at two sides. Over the basin spans a carriage to which the model was attached.

4. EVALUATING SEMI-CAPTIVE TESTS

The main idea was to extract sinusoidal forces and moments of the first order to find the amplitudes and phases of the motions. Further to adjust for the slight drift in wave frequency that may occur when waves are travelling, the encounter frequency was determined from the measurements whereof the actual wave frequency was derived. Hence the forces, moments and wave elevation were described by the following equation:

$$\begin{aligned} F_i(t) &= a_i + b_i \cdot \sin(\omega_e \cdot t + \alpha_i) \\ \eta(t) &= a_\eta + b_\eta \cdot \sin(\omega_e \cdot t + \alpha_\eta) \end{aligned}\,, \qquad (3)$$

where F_i are generalised forces, i=1,2..,6; η is wave elevation; ω_e is the encounter frequency and $\alpha_{i,\eta}$ is the phase. a_i, a_η, ω_e, b_i, b_n, $\alpha_{i,\eta}$ were determined using Gauss-Newtons method for optimisation of non-linear problems.

5. COMPUTATIONAL METHODS

A systematic series of computations of forces acting on a ship in following and stern quartering seas has been carried out during the present work. The computations of forces correspond to the semi-captive tests. Further a few examples of time simulations of ship motions have been performed.

The computations were carried out in order to improve the interpretation of semi-captive tests and to demonstrate the possibilities for using strongly simplified modelling of the hydrodynamics.

The hydrodynamic modelling could be described as a combination of linear strip theory and an extension of manoeuvring theory to account also for low frequency wave excitation. In this context it is important to notice that the two different theories are overlapping each other to some extent. Therefore some of the diffraction terms normally used in strip theory were excluded. Table 3 contains information on this matter and an overview of the modelling used at the computations. Lundbäck (2005) has published a more detailed description of the computational methods used in the current work.

Table 3 Hull forces

DOF	Froude-Krylov (lin)	Diffraction (linear)	Manoeuvring (linear)	Manoeuvring (non-linear)
x, term	Included	Not included	Not included	$\frac{1}{2} X_{vv}(v^* + v)^2$
y, term	Included	Included[1]	$Y_v(v^* + v) + Y_r(r^* + r)$	$\frac{1}{6} Y_{vvv}(v^* + v)^3$
z, term	Included	Included[1]	$N_v(v^* + v) + N_r(r^* + r)$	$\frac{1}{6} N_{vvv}(v^* + v)^3$

In Table 3 v and r represents the sway and yaw velocity of the ship, while v^* and r^* is a description of wave induced velocity of water particles.
Reasoning about the physics and mathematics related to these quantities is found in publications by Hua (2004) and Lundbäck (2005).

[1] Ordinary velocity dependent diffraction not included due to overlap of manoeuvring and seakeeping theory. Hence, only acceleration dependent diffraction included.

6. RESULTS OF FULL-SCALE TESTS

One of the most important results of full-scale testing was the criterion described by equation (2). When test data were combined with results of interviews with ship crew it was found that the maximum allowed yaw amplitude for safe manoeuvring, ψ_{max}=7°.

It was also found that the method for assessing wave excitation combined with the novel criterion gave reasonable results.
Figure 3 displays data from a full-scale trial with HMS Sandhamn. The upper graph includes the estimated yaw excitation compared to the constant term of the criterion shown in equation (2). The curves shown in the lower graph clearly demonstrates the manoeuvring difficulties that occur when the estimated yaw excitation approach the low frequency limit of the criterion for safe manoeuvring.

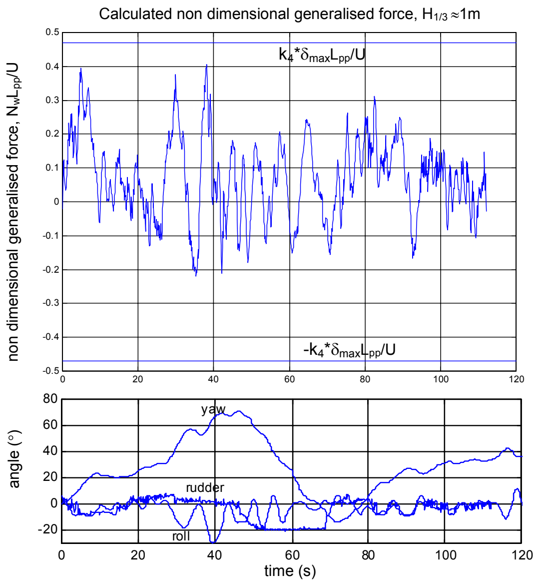

Figure 3. Test data from a patrol craft encountering manoeuvring difficulties. $H_{1/3} \approx 1.0$m, modal wavelength ≈ $0.9 * L_{pp}$

In a work presented by Lundbäck (2005) further results from full-scale tests are presented. In addition that publication includes a study of free running model tests evaluated by the same methodology as described in the present paper.

7. COMPARISON OF SEMI-CAPTIVE TESTS AND COMPUTATIONS

Figure 4-Figure 6 show amplitudes and offsets of surge force, sway force and yaw moment for HMS Kaparen in following and stern quartering regular waves. Curves marked as ‘exp’ show experimental data and data labelled with ‘calc’ are calculated results. The data is obtained from experiments and computations where the wavelength was $2*L_{pp}$, wave height was 5% of the wave length and F_n=0.5.

Figure 7 and Figure 8 show the phase angles of the forcing associated to Figure 4-Figure 6.

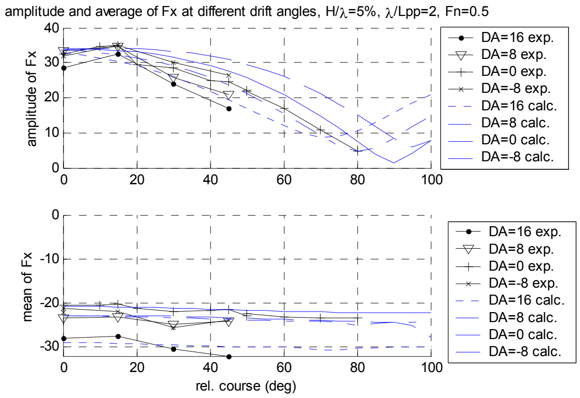

Figure 4. Amplitudes and mean values of F_x.

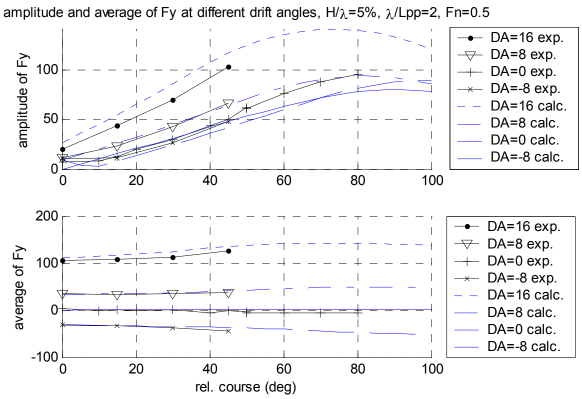

Figure 5. Amplitudes and mean values of F_y.

The data included in Figure 4-Figure 8 is associated to different courses relative to the waves, which is displayed by the abscissa within the graphs.

These data are also associated to different drift angles of the ship, ranging from -8° to 16°. The drift angle is indicated by the quantity “DA” in the legends to the figures.

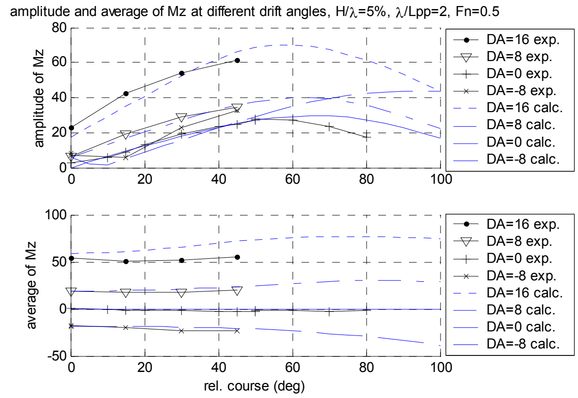

Figure 6. Amplitudes and mean values of M_z.

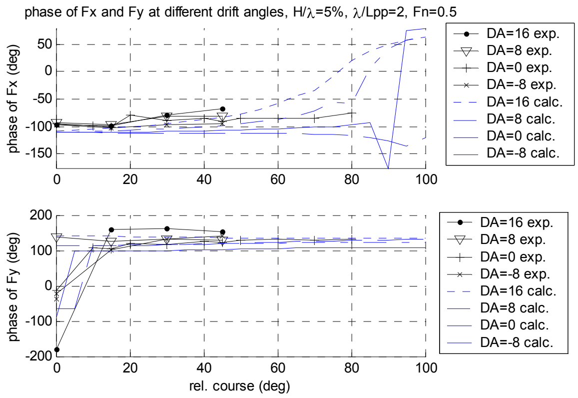

Figure 7. Phases of F_x and F_y.

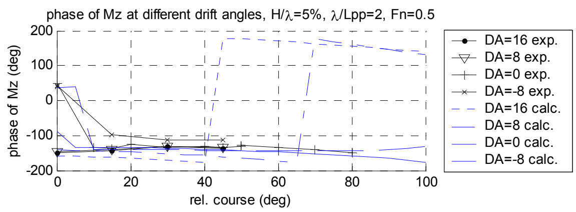

Figure 8. Phases of M_z.

8. SHIP MOTIONS

During the current research the hydrodynamic models, presented in section 5, were implemented also in a computational code for calculation of ship motions in time domain. The code is intended for educational purpose and to demonstrate the capabilities of the hydrodynamic modelling used.

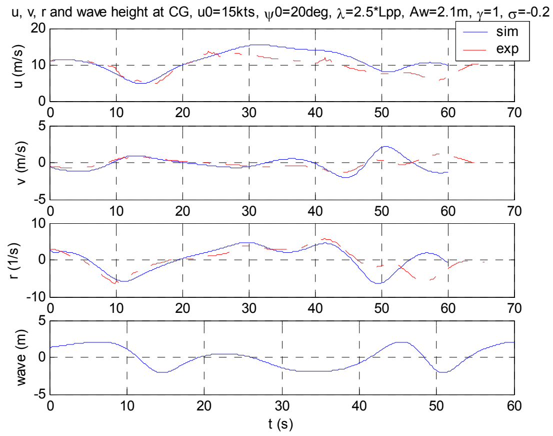

Figure 9. Simulated surge, sway and yaw velocity along with a results of an experiment including simulated wave height. The desired course was 20° relative to the waves, $\lambda=2.5*L_{pp}$, wave amplitude was set to 2.1m, desired speed was 15kts.

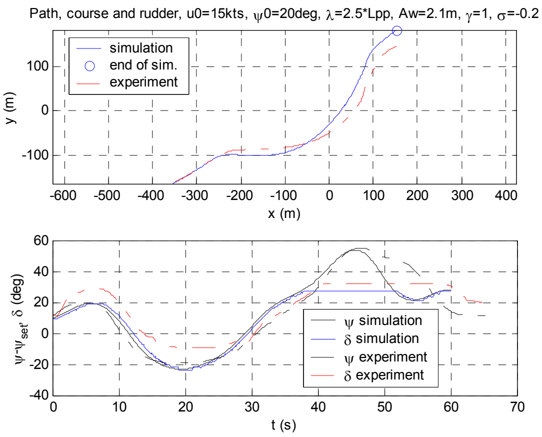

Figure 10. Simulated and experimental data of path and course deviation at the same test as shown by Figure 9.

Figure 9 and Figure 10 demonstrates a comparison between a time simulation and an experiment with a free running scale model of HMS Kaparen. At the free running test the ship model was manually steered, while the simulation was performed using an autopilot. At the simulation the auto pilot constants were chosen to imitate the steering action at the free running test.

6. DISCUSSION

The method for analysing measurement data works well for the test setup that was used. The forces has shown to be approximately sinusoidal with respect to time as the forward speed was kept constant by keeping the ship model fixed in surge. The waves were also, as expected, approximately sinusoidal with respect to time and space. Figure 11 shows a time series of a measurement of a wave and surge force and their sinus approximations. The wave corresponds to a wave with a height of 1.35m and period of 5.68s in full scale, with a ship speed of 21kts and 0° relative course.

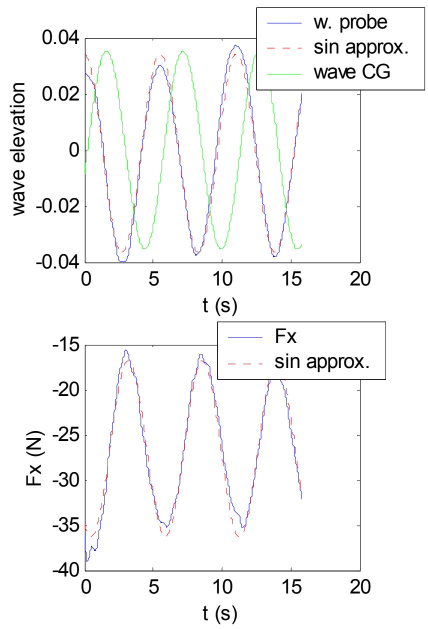

Figure 11. Comparison between wave and sinus approximation (upper graph). Lower graph shows the surge force and its sinus approximation.

The results of systematic experiments and computations show that the hydrodynamic forcing can be faithfully represented by a strongly simplified modelling. This conclusion is supported by Figure 4-Figure 8 and further data published by Lundbäck (2005). Nevertheless the latter publication also points out the need for further research on computations for short waves, typically when the wave length is shorter than 1.5-2.0*L_{pp}.

Irregular seas and wave excitation are also very well described by the current computational methodology, which is shown in the last-mentioned publication.

The methodology associated with full-scale tests and experiments with a free running scale model gives results that are in good agreement with the judgements of ship crew and with the behaviour of the ship. This topic is also further treated in the references by Lundbäck.

One point that unifies all of the references is the rather obvious importance of the rolling of a ship for most of the safety related issues in following and stern quartering seas. Therefore a natural step further is to study hydrodynamic modelling of roll moment, which can be done relatively easy since the current research includes experimental data on roll moment.

7. FUTURE WORK

There are three immediate points for future work pointed out by the current research:

1. Study hydrodynamic modelling of wave induced roll moment.
2. Investigate modelling of wave excitation in short waves
3. Apply computations and experimental data to a wide variety of tasks.

Accurate description of the dynamics for a ship in following seas is a complex task and it is difficult to get overview of dependence of different parameters on a ships performance. Therefore, work on appropriate simplifications and partitions of the ship dynamics would be beneficial for the shipping community. A more rigorous theoretical study of the hydrodynamic modelling could help development within strongly simplified hydrodynamics.

8. ACKNOWLEDGEMENTS

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