INVESTIGATION OF THE HYDRODYNAMIC FORCES GENERATED ON SUBMERGED PART OF A DECK DURING SHIP LARGE MOTIONS IN WAVES

Stefan Grochowalski, Polish Register of Shipping, S.Grochowalski@prs.pl

ABSTRACT

Physical nature of hydrodynamic forces generated on submerged part of a deck during large motions in waves is explained and a mathematical model of the forces is proposed. Dedicated experiments with a cylindrical model have been performed and the results are presented.

The analysis confirms that the additional force on the immersed deck is composed of a dynamic part dependent on relative velocities of water flowing onto the deck, and of static load caused by additional mass of water entering the deck space.

Keywords: *deck immersion, large ship motions, hydrodynamic forces on submerged deck, ship capsizing*

1. INTRODUCTION

Detailed analysis of capsizing model tests carried out by the author in the past, (Grochowalski, 1989) revealed a dangerous physical phenomenon which may occur when part of the deck becomes submerged during dynamic, large motions of a ship in extreme waves.

A ship navigating in extreme conditions is exposed to impacts of large and steep waves and performs very dynamic, large amplitude motions. In particular, operations in quartering seas create conditions in which the characteristic sequence of large motions together with the corresponding position of the wave crest may lead to deep submergence of a part of the deck. If this happens, and the submerged part of the deck is moving with a significant velocity in relation to the surrounding water, a hydrodynamic reaction is generated which constitutes water resistance to the movement of the submerged surface. This reaction introduces a restraint to ship motions and causes radical alterations in the roll. An additional heeling moment is generated, which either significantly reduces the ship restoring capability or further increases the heel angle and causes a capsize (Grochowalski, 1993). These effects should be included in the ship dynamics simulation models.

Special dedicated model tests with a cylindrical model were carried out in the past at the Institute for Marine Dynamics (IMD) in Canada (Grochowalski 1997). The purpose was to investigate further the nature of the deck-in-water phenomenon, and to provide a basis for validation of the numerical model.

This paper presents the mathematical model of the hydrodynamic forces generated on the submerged part of a deck in large waves, the experimental results of the tests carried out, and the comparison of the theoretical calculations with the experimental results.

2. THEORETICAL MODEL OF THE HYDRODYNAMIC FORCES ON THE SUBMERGED PART OF A DECK.

When part of the deck is submerged during ship motions in large waves, hydrodynamic forces are generated on the submerged surface.

In all theoretical approaches, these forces are considered as the superposition of the hydrostatic force (due to static pressure) and the Froude-Krylov force (due to dynamic pressure caused by the wave motion). Thus, the forces on the immersed deck are calculated the same way as for the rest of the immersed part of the hull. However, if the submerged part of the deck moves significantly in relation to the surrounding water, an additional hydro-dynamic reaction (R) is generated (Fig. 1). This reaction may critically change the whole composition of the hydrodynamic forces acting on the ship

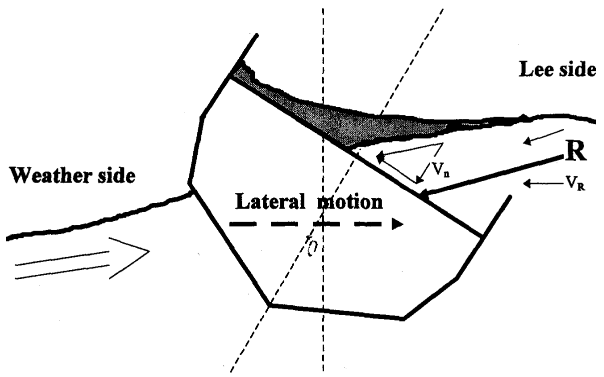

Figure 1. Additional hydrodynamic reaction R generated on the submerged deck in waves.

The total hydrodynamic force on deck $F_{z\ tot}$ in O-Z direction can be expressed as follows:

$$\mathbf{F}_{z\ tot} = \mathbf{F}_{stat} + \mathbf{F}_{F\text{-}K} + \mathbf{R}_n \qquad (1)$$

where: $\mathbf{F}_{stat}$ is the hydrostatic force, $\mathbf{F}_{F\text{-}K}$ - Froude-Krylov force, and $\mathbf{R}_n$ is the normal component of the additional hydrodynamic reaction **R**. The bold print indicates a vector notation.

Detailed analysis of the phenomenon indicated that the reaction $\mathbf{R}_n$ is of a dynamic nature, and it occurs only if there is a forceful motion of the submerged part of the deck in relation to the contiguous water. The larger relative velocity, the larger is the hydrodynamic reaction $\mathbf{R}_n$. Furthermore, the direction of the relative movement of water particles must be towards the element of deck surface. If there is no significant relative movement of the submerged surface, or its direction is such that the water would move outwards the deck surface, the hydrodynamic reaction disappears. This confirms that the considered force has a nature of a resistance to the movement of the submerged part, and it is an additional force to conventionally calculated hydrostatic and Froude-Krylov forces.

The physical nature of the phenomenon generating the reaction R_n is very complex. The flow is discontinuous and deformed by the deck surface and the bulwark. Large relative motion introduces more deformation. There are viscous effects and vortices are generated. In the semi-empirical mathematical model for the additional hydrodynamic force (Grochowalski 1993), it has been assumed that the bulwark is deeply submerged and the forces generated are mainly of the inertial and gravitational nature (i.e. dynamic pressure and additional load). Viscous effects are neglected at this stage.

Calculation of the additional dynamic pressure on the submerged elements of the deck and bulwark is based on a relative velocities concept. This includes all the components of ship motion and the orbital velocities of wave motion. The deformation of the wave profile and of the wave velocities, caused by the presence of the hull in the wave, is not considered in the first version. The additional dynamic pressure is assumed to be proportional to second power of the relative velocities.

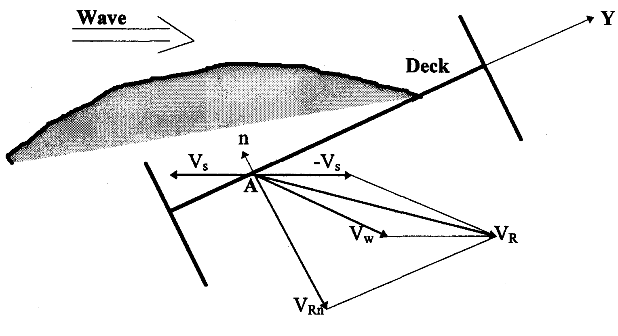

Figure 2. Relative velocity of water elements at the deck surface.

The calculation of the relative velocities is explained in Fig.2, where $\mathbf{V_w}$ - velocity in the wave, $\mathbf{V_S}$ - velocity of a point on the moving deck.

$$\mathbf{V_W} - \mathbf{V_S} = \mathbf{V_R} \qquad (2)$$

$$V_{Rn} = \mathbf{V_R} \cdot \mathbf{n} \qquad (3)$$

where : $\mathbf{V}_R$ - relative velocity of water particle with respect to the deck at the selected point on deck surface, V_{Rn} - relative velocity projected on the normal to the deck surface, $\mathbf{n}$ - unit vector normal to the deck surface, positive outwards.

Total pressure at point A:

$$p^{dk} = -\rho g(\zeta_w - z) - \rho \frac{\partial \Phi}{\partial t} - (\rho/2)|\nabla \Phi|^2 + k_d f(v_{Rn}) (\rho/2) V_{Rn}^2 \qquad (4)$$

where : Φ - is the incident wave potential, ζ_w - is the wave elevation, k_d - the correction coefficient for all deformations of the flow in the deck area, and f (V_{Rn}) - is the relative velocity sign function :

$$f(V_{Rn}) = \begin{cases} 1 & \text{if } V_{Rn} < 0 \\ 0 & \text{- otherwise} \end{cases} \qquad (5)$$

$V_R < 0$ indicates that the water particle velocity is towards the deck.

The total hydrodynamic force acting on the submerged deck at a time **t** can be then calculated by integrating the pressure over the immersed part of the deck.

$$F_{ztot}(t) = -\rho g \iint(\zeta_w - z)\, dS - \rho \iint \frac{\partial}{dt}\Phi\, dS - \rho/2 \iint |\nabla\Phi|^2\, dS + k_d\, \rho/2 \iint f(v_{Rn})\, V_{Rn}^2\, dS \qquad (6)$$

where the integration is made for the area of the submerged part of the deck - S.

The first term in expression (6) represents the static force, while the second and third - the linear and non-linear Froude-Krylov forces. The static and F-K forces are calculated for the instantaneous part of the hull immersed in a wave, including part of the deck. The fourth term represents the additional dynamic pressure generated by the relative motion of the immersed part of the deck with respect to the surrounding water. The influence of the tangential component of the relative velocity, which creates a reaction of viscous nature, is rather small in comparison with the normal force, and is neglected here. The moments corresponding to the forces on the submerged deck can be calculated taking into account the position of the elements of the immersed surface.

According to this, the additional hydrodynamic force and moment generated on the submerged deck, which are the subjects of this study, are formulated as follows :

$$F_{V2} = R_n(t) = k_d\, \rho/2 \iint f(v_{Rn})\, V_{Rn}^2(t)\, dS \qquad (7)$$

$$M_{V2} = k_d\, \rho/2 \iint y\, f(v_{Rn})\, V_{Rn}^2(t)\, dS \qquad (8)$$

The mathematical model has been validated by systematic calculations of the hydrodynamic forces on the submerged part of the deck and comparison with results of specially designed model experiments.

3. EXPERIMENTS WITH A CYLINDRICAL MODEL

The objective of the model tests was to gain more insight into the deck-in-water effects and to provide some data for the validation of the theoretical model developed.

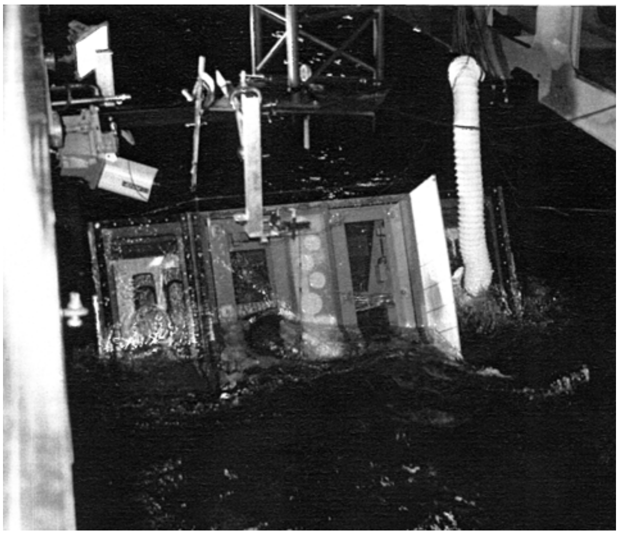

Figure 3. Experiment setup for deck-in-water testing.

The tests were performed in the towing tank of the Institute for Marine Dynamics (IMD) in St.John's, Canada (Fig.3). A specific cylindrical model with a half-circular cross-section was used. The main dimensions were: L=1.800m, B=0.850m, r=0.425m. The rigid deck was mounted to the hull through a dynamometer frame specially designed for this purpose. With such arrangement, the total forces acting on the separated part of the deck can be continuously measured and recorded. The model was rigidly mounted to the carriage in a beam position to the waves. The carriage movement provided the required lateral motion of the model. The details of the model and the experimental technique can be found in (Grochowalski, 1997).

The program of the tests was split into two different parts: tests on calm water, and experiments in waves. The variable parameters were selected in such a way that they should provide an essential information on the deck-in-water effects in case of ship free motions in waves. They were the following :

- depth of the deck submergence (d),
- heel angle (φ),
- drift velocity (V_{dr}),
- wave parameters - wave period (T) and wave height (h_w).

The measured values were :

- wave elevation,
- total force $F_{ztot.}$, normal to the deck surface,
- total moment $M_{xtot.}$ relative to the longitudinal 0-X axis,
- pressure at 8 points in one cross-section of the deck,
- instantaneous water level at the deck edge.

It is essential to realise, that the measured forces or pressure were the total values. It was impossible to measure separately the three components i.e. static, Froude-Krylov and additional dynamic component, as it was presented in the theoretical considerations. The additional dynamic force attributed to relative velocity can be found indirectly by comparisons of the total forces for various V_{dr}. If all other components of the total hydrodynamic forces remain the same in the experiments, then the difference ΔF_Z can be considered as the value of the additional force due to relative movement of the deck (F_{V2} in the calculations).

$$F_{V2}(V_{dr}) = \Delta F_Z = F_{Ztot}(V_{dr}) - F_{ztot}(V_{dr}=0) \qquad (9)$$

The same procedure was applied to the calculation of the additional moment MV2.

The results of the model experiments were analysed in detail and compared with relevant computation results.

4. ANALYSIS OF THE THEORETICAL AND EXPERIMENTAL RESULTS

Since the main objective of the calculation was to examine the theoretical model developed and to define the coefficient $\mathbf{k_d}$, the main time-domain simulation program presented in (Grochowalski, et al 1998) was modified on the basis of the formulae (4)-(8) to include calculations of the hydrodynamic forces on the deck. Systematic computations were carried out for the model used in the experiments, for the same parameters and conditions as they were in the tests. Accordingly, the calculations were done separately for the model moving on calm water and in waves.

4.1. Calm Water

A comparison of the computed and experimental results for the model moving laterally on calm water provides the best data for the examination of the fundamental assumptions of the theoretical model. Detail results of all computations and model tests can be found in (Grochowalski, 1998). This paper presents just a few examples.

Fig.4 shows the influence of drift velocity on the additional force F_{V2} generated on the immersed part of the deck. The lines represent computations while the points are the experiment results. The black points represent the results of the tests without the bulwark while the white ones correspond to the tests with the bulwark.

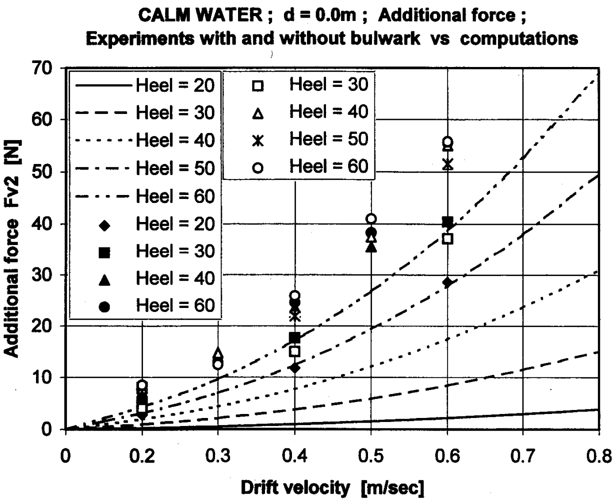

Figure 4. Comparison of the measured and computed additional force on immersed deck.

It can be seen that the experimental results display the same dependence on drift velocity as the theoretical values. This confirms that the assumption on the quadratic dependence of the additional forces on the relative velocity was justified. However, the test results provide much higher values than the corresponding computed ones. In particular at smaller heel angles, the measured forces are more than twice as large as the computations. There is no significant difference between the forces measured when testing with or without the bulwark.

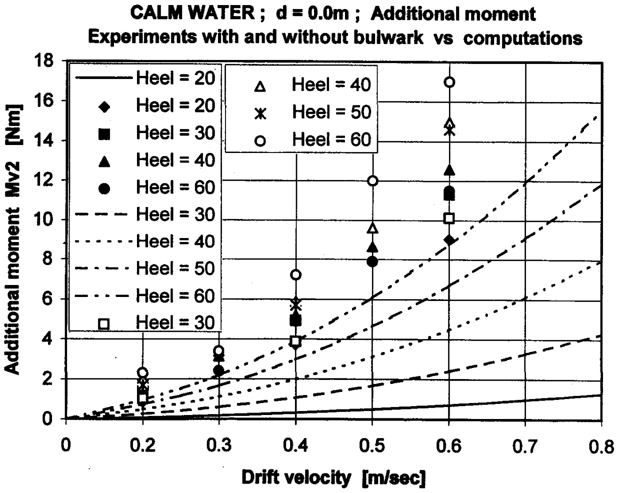

Figure 5. Measured and computed additional moment on immersed deck.

The comparison of the measured and computed additional moment MV2 indicates the same similarities and differences as for the force (Fig.5.). The only difference is that the moment on the deck with the bulwark is significantly larger than in the tests without the bulwark. As the forces are in both cases about the same, it means that the centre of pressure shifts towards the bulwark if the bulwark exists.

A better illustration of the difference between the measured and computed values can be found in Fig.6 which presents the influence of the heel angle on the additional force FV2 on the deck. The experimental points exhibit generally the same trend as the computed results, and seem to form patterns parallel to the theoretical lines but are shifted upwards upon certain values. The same is valid in the case of the moments M_{V2} .

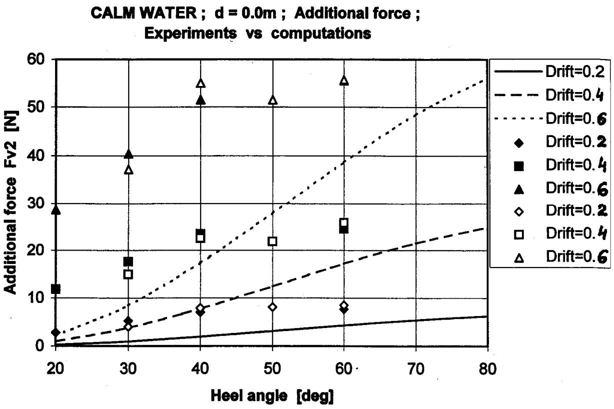

Figure 6. Measured and computed additional force on immersed deck as a function of heel angle.

This situation prompted a re-examination of the records from the model tests, both the measurement data and the video records. It has been found that during the drifting of the model the water level above the deck rises and additional mass of water enters the deck space. This apparently increases the static load on the deck, adding to the dynamic force additional static force which is not considered in the theoretical model. The evidence of this additional static load was found by analysis of the water level above the bulwark, measured by a dedicated wave probe mounted at the model side. The video records show that shortly after the model started moving, the mean level of water on the deck gets established during the drift with a constant velocity. So, it was possible to find from the record of the wave probe at the model side the new "saturated" water level at the immersed deck edge.

If it is assumed that the new water level is equally extended over the immersed area of the deck, then the additional static load dF_{stat} can be estimated for the experiments in calm water. Calculations of the total "new" static force corresponding to the real, i.e. measured water level at the deck edge were performed. The difference between the new values and the static forces calculated for the theoretical water level (without drift) represent the additional static force induced by the drift motion of the deck.

$$dF_{stat}(V_{dr}) = F_{stat}(V_{dr}) - F_0(V=0) \quad (10)$$

$$F_{V2\ exp}(V_{dr}) = dF_{exp}(V_{dr}) - dF_{stat}(V_{dr}) \quad (11)$$

where: $F_0(V=0)$ - static theoretical force at $V_{dr}=0$; $F_{stat}(V_{dr})$ - static theoretical force at the new water level; $dF_{stat}(V_{dr})$ - additional static load on the deck induced by the deck movement; $dF_{exp}(V_{dr})$ - total increase of the force on deck due to drift, calculated by (9); $F_{V2exp}(V_{dr})$ - dynamic component of the measured additional force on deck, corresponding to that theoretically modelled in Chapter 2.

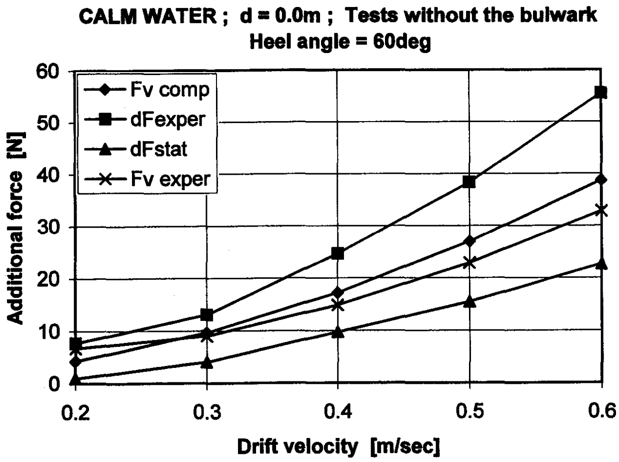

Figure 7. The static and dynamic components of the additional force on the deck.

Similar equations were used for the moment M. An example of the results in a graphical form is given in Fig.7, where all the components of the additional force on the deck are presented. It can be seen that if the additional static component dFstat is deducted from the total additional force dFexp than the remaining component FV2exp is in a good agreement with the theoretical one FV2 comp . This confirms that the dynamic portion of the additional force on the submerged part of the deck is represented quite well by the mathematical model developed.

The dynamic portion of the measured additional forces should be compared with the theoretical F_{V2} in order to develop the correction coefficient k_d .

4.2. Deck Submerged in Waves

Systematic calculations of the additional forces and moments on the immersed part of the deck in waves were performed in order to investigate the influence of the main parameters of waves, deck immersion, and drift on the generated forces on the deck. The bulwark was neglected in the computations at this stage.

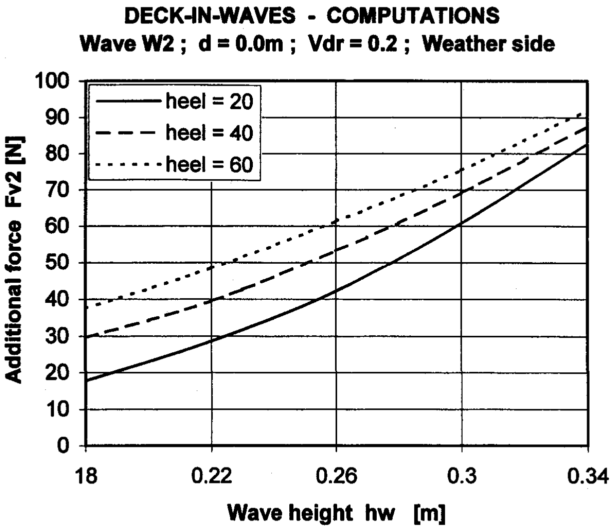

Figure 8. Influence of wave height on the additional force on deck

The additional hydrodynamic force F_{V2} induced by the movement of the submerged portion of the deck depends strongly on the wave height. As it can be seen from Fig.8, this dependence is nonlinear, and the force increases with the increase of the wave height.

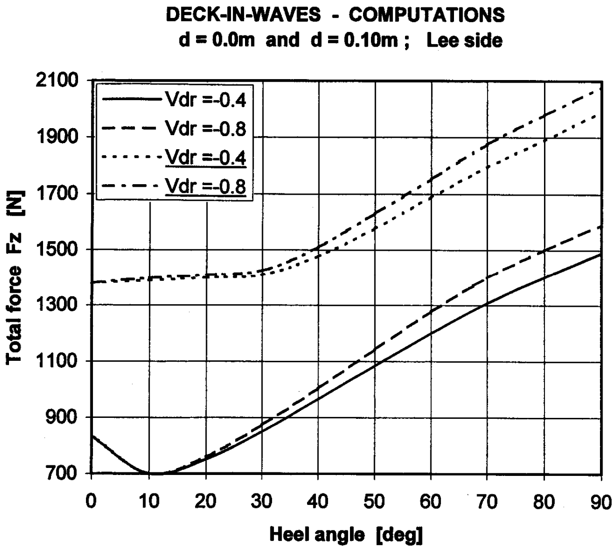

Figure 9. Influence of heel angle on the total force on deck.

The influence of the heel angle on the total force on deck is presented in Fig.9 for the lee side. Both assumed drafts are presented for the comparison. The draft d=0.10m is underscored. It can be seen that a dramatic increase of the force occurs above a certain heel angle and then the increase is linear until the angle about 70 deg. In the most interesting range of heel angles i.e. 30 - 70 deg. the change of the total force can be considered as linear.

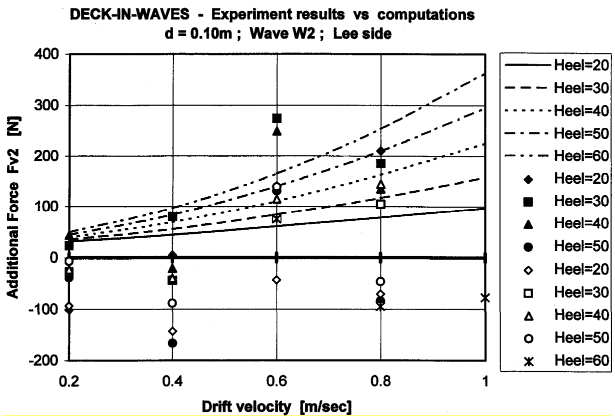

Figure 10. Comparison of the measured and computed additional force on deck in waves.

The influence of the drift velocity on the theoretical FV2 force is similar to that in calm water (Fig. 10.).

A comparison between the computed and the measured values shows that the discrepancy is much bigger in waves than it was in calm water. The measurement results are scattered very much and do not form patterns similar to the computed results. They are not consistent. In many cases the values are negative which means that the total forces during drifting are smaller than the corresponding ones at $V_{dr}=0$. It has been found in the recorded data that the wave heights recorded are very different from those required in the program, and they are spread around the nominal values with significant differences. Detailed analysis of the video record showed that the fully restrained model constituted a huge disturbance to the propagation of the waves, causing a large deformation of the wave profile and thus the velocity and pressure distribution is totally different from those in the undisturbed waves. The deformation was bigger when the model was forced to drift and was particularly visible for the lee side. The theoretical model does not include such deformations.

It is interesting to note that the total additional force in waves is larger in tests without the bulwark (black points) than with the bulwark (unshaded points). It is particularly detectable for the weather side and for smaller heel angles. Apparently, the bulwark acts in those situations as a shield against water inflow, forming a sort of shadow on the part of the deck right behind the bulwark. This decreases the dynamic portion of the additional force and thus the whole additional force on the deck. The "shadow" area decreases with the increase of the heel angle. This phenomenon and the influence of bulwark presence need to be further investigated.

5. CORRECTION COEFFICIENT K_D .

The correction coefficient $\mathbf{k_d}$ for the additional dynamic force has been defined as

$$k_d = F_{V2\ exper} / F_{V2\ comp} \qquad (12)$$

Originally, it was considered that the whole additional force is of the dynamic nature caused by the dynamic pressure due to the relative velocity of water at the deck surface. This study, however, revealed that the additional force contain also the static component caused by additional mass of water entering the deck space when the deck moves relative to the surrounding water. This part of the force requires computation of the mass of water shipping on deck and is different from the dynamic model presented here.

It is possible to assume that the coefficient k_d will represent the whole additional force, then its definition would be:

$$k_{d\ tot} = dF_{exper} / F_{V2\ comp} \qquad (13)$$

The coefficient was calculated in accordance with both formulae for the calm water results. For the waves, formula (13) could only be applied, as it was impossible to distinguish the additional mass of water from the purely dynamic force.

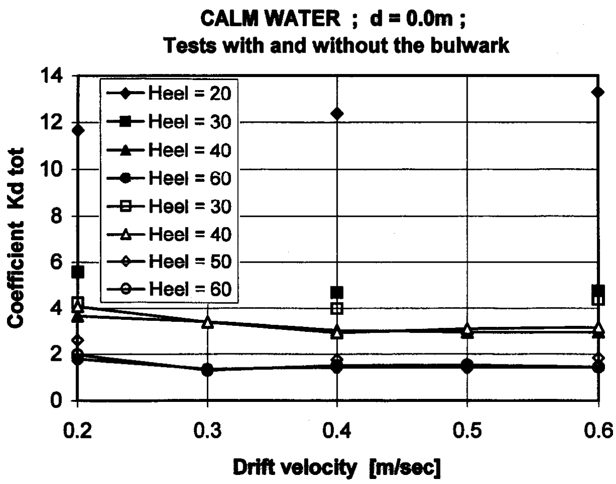

Figure 11. Correction coefficient for the total additional force on deck in calm water as the function of drift velocity.

The results for calm water tests are presented in Fig.11 and 12. It can be seen that $k_{d\ tot}$ strongly depends on the heel angle, while not significantly on the drift.

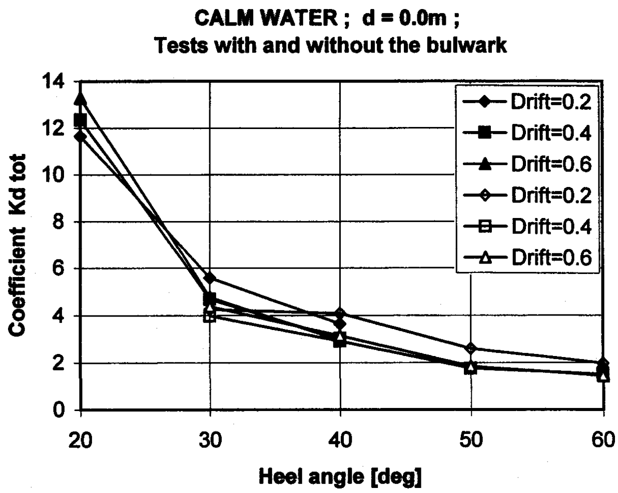

Figure 12. Correction coefficient for the total additional force on deck in calm water dependant on heel angle.

If the coefficient was to represent only the dynamic part of the additional force and thus calculated as formula (12) the results would be as in Fig.13, where the correction coefficient is marked as $k_{d\ V2}$.

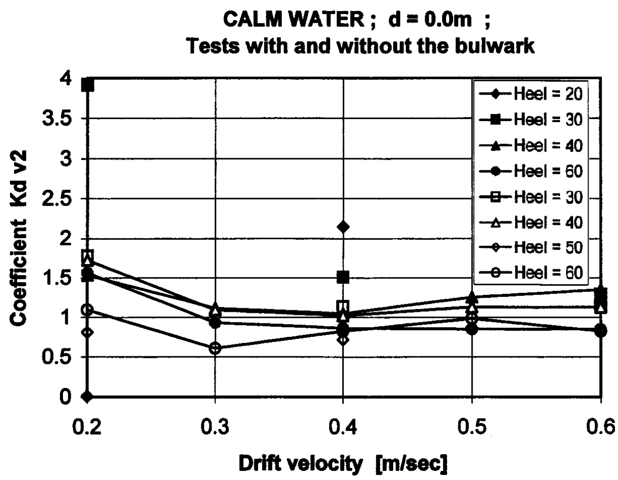

Figure 13. Correction coefficient for the dynamic component of the additional force on deck as a function of drift velocity.

It can be seen that the coefficient defined this way is very consistent. It oscillates closely around the value kd = 1.0. It does not depends on drift velocity, and only slightly changes with the heel angle. Only at a very small drift and small heel angle it displays some irregularities. This is triggered by some instability of the flow on deck in those conditions.

The Fig.11 and Fig.13 prove that the theoretical model developed here represents the dynamic part of the additional forces pretty well, as the correction coefficient oscillates closely around 1.0, and it can be assumed as $k_{d\ V2}$ = 1.0 in practical estimations. The mean value of all tests in calm water was $k_{dv2} = 1.07$.

Dramatically different situation is in the case of tests in waves. The results for the waves were inconclusive and unusable. Some examples of the k_d calculated from the experiments in waves are presented in Fig.14 and Fig.15.

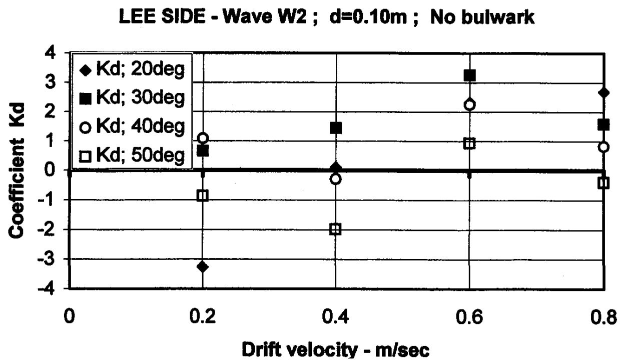

Figure 14. Coefficient K_d calculated from the tests in waves without the bulwark.

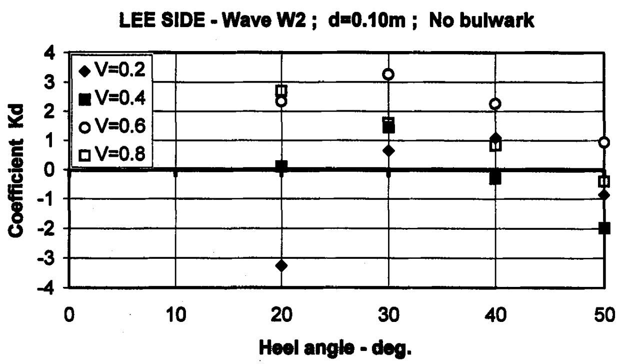

Figure 15. Coefficient K_d calculated from the tests with lee side deeply immersed in waves without the bulwark.

6. CONCLUSIONS

A mathematical model of the additional hydrodynamic forces caused by the movement of the submerged portion of a deck in waves has been worked out. Relevant computer code has been also developed. It provides possibility of numerical simulations of the "deck-in-water" effects.

Systematic computations of the influence of various deck positions and wave parameters on the generated forces on deck have been carried out. The results indicate a strong dependence of the forces on deck on the depth of submergence, heel angle and velocity of the relative motion of the deck.

The experimental results confirmed the same strong dependence of the measured forces on the variable parameters as it came out from the systematic computations.

The thorough analysis of the results of the cylindrical model tests revealed that the additional force on deck has two components: the dynamic effects dependent quadratically on the relative velocity of water hitting the deck, and the static load caused by the increased mass of water on deck.

The mathematical model presented in this report represents fairly well the dynamic part of the additional force. The correction coefficient for this part was found to be: kdV2 ≅ 1.07.

However, the additional static effect has to be added to the dynamic part in order to obtain the total additional force on the immersed part of the deck. This requires a combination with the theoretical model of water shipping on deck. Such a combination is yet to be developed.

It is possible to develop a formula for a kd which would predict the total additional forces on the deck from the model presented here, but this requires a new set of captive tests with the cylindrical model free to heave and pitch during the measurements in waves.

The full constraint of the model in the wave tests was the main reason that those tests turned to be a failure. Technical limitations of the facilities at the time of the testing did not allow to make those tests with more degree of freedom of the model.

7. AKNOWLEDGMENT

The model tests were performed at the NRC's Institute for Marine Dynamics (IMD) in St.John's, Canada. The involvement of the IMD staff in the model tests is gratefully acknowledged.

8. REFERENCES

Grochowalski, S., 1989, "Investigation into the Physics of Ship Capsizing by Combined Ca-ptive and Free Running Tests". Transactions SNAME, vol.97, 1989, pp. 169-212.

Grochowalski, S., 1993, "Effect of Bulwark and Deck Edge Submergence in Dynamics of Ship Capsizing". Proc. US Cost Guard Vessel Stability Symposium '93. New London, CT, 1993.

Grochowalski, S., 1997, "Experimental Investigation of the Hydrodynamic Forces and Pressure Distribution on the Submerged Part of Deck in Waves". NRC/IMD Report No. TR - 1997-09, March, 1997.

Grochowalski, S., Hsiung, C.C., Huang, Z.J., Cong, L.Z., 1998, "Theoretical Modeling of Ship Motions and Capsizing in Large and Steep Waves". Trans. SNAME, vol.106, 1998, pp.241-267.

Grochowalski, S., 1998 - "Analysis of the Hy drodynamic Forces on the Submerged Part of a Deck". CMVDR Report for Transport Canada, 1998.