DAMAGED SHIP HYDRODYNAMICS

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SUMMARY

A series of model experiments were undertaken to qualify and (if possible) quantify the level of contribution of damage and ensuing flooding to the overall ship hydrodynamic properties using a 1:40 scale model of a modern passenger Ro-Ro vessel (EU Research code PRR1). These entailed a forced oscillations of the model in intact and damaged conditions in heave and roll modes of motion, with the use of a purposely designed mechanical forcing system. The derived results have been compared with predictions using well-established numerical techniques leading to the general conclusion that whilst the effect of damage on hydrodynamic forces in heave is negligible, the corresponding effect in roll is considerable. In this respect, additional efforts must be expended to establish the relative importance of the anticipated causes of this effect, namely floodwater sloshing and water ingress/egress.

NOMENCLATURE

M_i, I_i	mass and mass moment of inertia of intact ship
M_d, I_d	mass and mass moment of inertia of damaged/flooded ship
m_d, i_d	mass and mass moment of inertia of floodwater
a_{ix}, b_{ix}, c_{ix}	added mass, damping and restoring coefficients for x mode of motion of an intact ship, x=3 heave, x=4 roll
F_{ix}	amplitude of total hydrodynamic force on intact ship in x mode of motion
a_{dx}, b_{dx}, c_{dx}	added mass, damping and restoring coefficients for x mode of motion of damaged ship, x=3 heave, x=4 roll
F_{dx}	amplitude of total hydrodynamic force on damaged ship in x mode of motion
$\ddot{u}_x$, $\dot{u}_x$, u_x	acceleration, velocity and displacement in x mode of motion
D, D^*	rotation matrix
L, B	length and beam of ship

All the hydrodynamic coefficients are rendered dimensionless according to Table 4.

1 INTRODUCTION

Understanding of stability of a damaged ship in waves has attracted considerable attention in recent years, as the interest of the scientific community in the subject, driven by both academic curiosity and a strong focus on safety at an international scale, has given rise to the development of numerical models at various level of sophistication capable of addressing the damaged ship dynamics problem with some success.

One of these involves time-domain simulation of ship response in random waves during progressive flooding through an opening in the hull. Popularity of this method derives to a great extent from ease of consolidating existing know-how of intact ship hydrodynamic properties and basic rigid body dynamics into a model that can effectively predict damaged vessel dynamic stability. On this basis, a recent ITTC benchmarking study [11] has shown that despite differences in details of implementation, available numerical models employing this philosophy, provide relatively consistent predictions of design-useful vessel survivability (capsize sea state).

However, notwithstanding the concluded success of this study (this apparently strange outcome can be explained on the basis that the capsize mode considered is of quasi-static nature) the many inconsistencies between behaviour recorded experimentally and the numerical simulations have dispersed any latent prospects for complacency. More focused analyses of the simulated dynamic responses helped identify under-prediction of the effects of flooding on the vessel natural response in this condition. Although some questions remain as to the reliability of the experimental technique itself, efforts have been directed towards obtaining better clarification on the hydrodynamic qualities of a ship with typical hull damage.

This paper addresses this issue by providing a summary of the research undertaken by the Ship Stability Research Centre under the EU-funded project NEREUS, aiming to shed light on the hydrodynamic properties of a damaged vessel through experimental means.

2 PRESENTATION OF RESULTS

This section presents and discuses the substance of the results obtained during the aforementioned research [2], following a brief outline of the parametric study matrix considered and explanation on data interpretation and conventions adopted.

2.1 THE TEST PROGRAMME

The experimental programme undertaken comprised forced oscillations of the model in heave and roll motions for a series of frequencies (0.05 rad/s for restoring estimations, 0.2-1.3 rad/s), heel angles (0 deg, -10deg, -20deg) and amplitudes of oscillation (0.4m, 1.0m; 5deg, 10deg) in full scale. The minus sign designates heel to damaged, port side of the ship. Intact and damage conditions were considered, with the damage scenario chosen representing the worst SOLAS damage (D901) as shown in Figure 1 and Table 1. No coupling between the modes of motion was taken into account. Roll was designated as the motion around the ship longitudinal axis passing through her centre of mass with KG=12.892m. A summary of the test cases considered is given in Table 2 and Table 3, with the general experimental set-up shown in Figure 2.

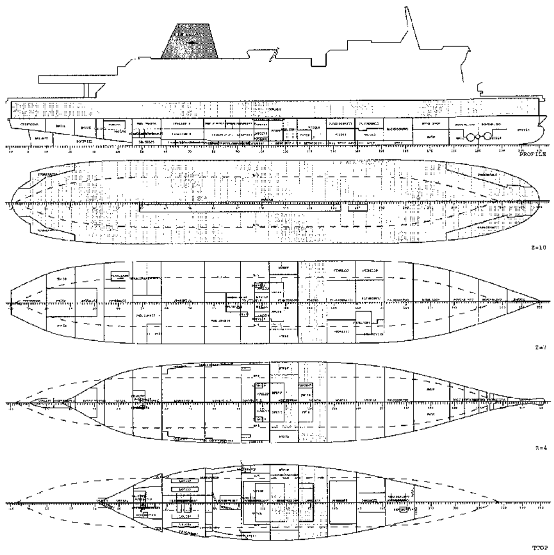

Figure 1 D901 damage case of PRR1

Table 1 Particulars of PRR1

Length between perpendiculars	170.00	m
Subdivision Length	178.75	m
Breadth	27.80	m
Depth to subdivision deck (G-Deck)	9.00	m
Depth to E-Deck	14.85	m
Draught (intact & flooded)	6.25	m
Displacement (intact/flooded)	17301.7 t / 14993.3 t	
KMT (intact)	15.522	m
KG	12.892	m

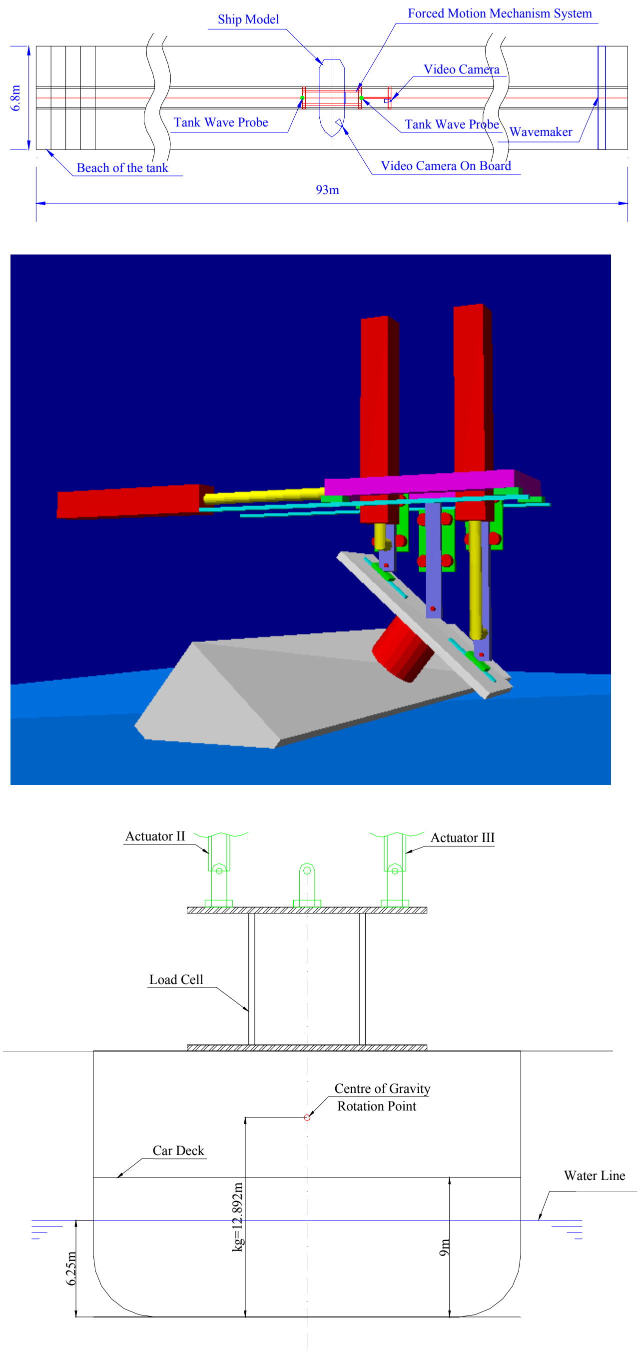

Figure 2 Experimental set-up

Table 2 Intact Condition

Case No.	Log File Name	Motion Mode	Amplitude	Static Heel (deg)
1	Run1~17	Roll	5deg	0
2	Run18~30	Roll	5deg	-10
3	Run 38~47	Roll	5deg	-20
4	Run52~67	Roll	10deg	0
5	Run69~83	Roll	10deg	-10
6	Run86~99	Roll	10deg	-20
7	Run103~116	Heave	1m	0
8	Run137~152	Heave	1m	-10
9	Run154~169	Heave	1m	-20
10	Run171~186	Heave	0.4m	0

Table 3 Damaged Condition

Case No.	Log File Name	Motion Mode	Amplitude	Static Heel (deg)
1	Drun1~16	Roll	5deg	0
2	Drun18~33	Roll	5deg	-10
3	Drun35~49	Roll	5deg	-20
4	Drun52~66	Roll	10deg	0
5	Drun69~81	Roll	10deg	-10
6	Drun86~99	Roll	10deg	-20
7	Drun103~116	Heave	1m	0
8	Drun120~132	Heave	1m	-10
9	Drun137~150	Heave	1m	-20
10	Drun154~169	Heave	0.4m	0
11	Drun171~186	Heave	0.4m	-10
12	Drun188~203	Heave	0.4m	-20

Table 4 Non-dimensional forms of hydrodynamic coefficients

$\omega_B = \omega \cdot \sqrt{\dfrac{B}{2 \cdot g}}$	
$b_3 = \dfrac{b_3}{\rho \cdot M_i \cdot \sqrt{\dfrac{g}{L}}}$	$a_3 = \dfrac{a_3}{\rho \cdot M_i}$
$b_4 = \dfrac{b_4}{\rho \cdot M_i \cdot B^2 \sqrt{\dfrac{2 \cdot g}{B}}}$	$a_4 = \dfrac{a_4}{\rho \cdot M_i \cdot B^2}$

2.2 DATA INTERPRETATION

Before embarking on discussion of the derived results, a number of issues must be clarified concerning data interpretation and conventions adopted, as outlined next.

2.2.a Loading issues

The ship model was tested in intact as well as damaged conditions, hence two loading (ballast) cases had to be considered. Mores specifically, to assure consistent comparisons between the hydrodynamic properties of the intact and damaged vessel, the submerged hull geometry was retained unchanged by adjusting the model mass and keeping the draught constant, see Table 1. In this respect, any difference would signify the contribution of the floodwater motions as well as its ingress/egress through the damage opening.

2.2.b Estimation of hydrodynamic coefficients

The experimental analysis involved calibrating and filtering raw data, removing the effects of restoring and real inertia and fitting of hydrodynamic coefficients to the two orthogonal components of the hydrodynamic reaction force. The damping force/moment is the component in phase with the linear/angular velocity and the added mass force/moment is the component in phase with linear/angular acceleration, respectively.

Estimation of the coefficients was carried out based on time series of the force signals and a least squares fit assuming that the two pertinent forces are orthogonal and independent. In this way, the damping force can be estimated independently of the values of the troublesome restoring and real inertia forces.

The outline of the algorithm is shown below. After removing the restoring and real mass terms, the hydrodynamic reaction force can be written as:

$$h(t) = A \cdot \ddot{x}(t) + B \cdot \dot{x}(t) \qquad (1)$$

The least squares estimator finds values for A and B, which minimise the square error ε between the measured and estimated forcing function. That is, the following has to be minimised:

$$\varepsilon^2 = \left[h(t) - A \cdot \ddot{x}(t) - B \cdot \dot{x}(t)\right]^2 \qquad (2)$$

Rewriting equation (2) using the notation of a sampled signal gives:

$$\varepsilon_i^{\,2} = \left[h_i - A \cdot \ddot{x}_i - B \cdot \dot{x}_i\right]^2 \qquad (3)$$

Where i =1,2,…n represents the signal sampled at 80 Hz

To proceed with the method ε is differentiated with respect to A and B and equating the derivatives to zero the following system of equations is obtained:

$$\begin{bmatrix} \sum \dot{x}_i^2 & \sum \dot{x}_i a_i \\ \sum \dot{x}_i a_i & \sum \ddot{x}_i^2 \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} \sum \dot{x}_i h_i \\ \sum \ddot{x}_i h_i \end{bmatrix} \qquad (4)$$

Rewriting (4) in the form AC=Y allows solving the above for A and B as follows

C=(A\`A)$^{-1}$A\`Y

For more information on this method see [3].

2.2.c Ship damage state

As mentioned in §2.2.a above, two loading conditions were considered in order to assure that the external ship geometry remained unchanged (constant draught). Denoting the displacements corresponding to intact and damaged conditions as M_i and M_d, respectively, allows expressing the mass of the floodwater entering the ship, m_d, as follows:

$$m_d = M_i - M_d \qquad (5)$$

Mass of floodwater entering the damaged ship, upright condition. The corresponding solid mass is removed from the ship.

To elucidate the consequences of keeping the draught in both intact and damaged conditions constant by removing the solid mass from the ship as shown in (5), consider the intact ship heave motion equation adopted in this study:

$$(M_i + a_{i3}) \cdot \ddot{u}_3 + b_{i3} \cdot \dot{u}_3 + c_{i3} \cdot u_3 = F_{i3} \quad \text{Heave motion equation for intact ship} \qquad (6)$$

According to the adopted method of derivation of the hydrodynamic reaction forces, see §2.2.b, the inertial and restoring terms should be subtracted from the total force measured during the experiment, that is equation (6) will take the following form:

$$a_{i3} \cdot \ddot{u}_3 + b_{i3} \cdot \dot{u}_3 = h_{i3} \qquad (7)$$

Where:

$$h_{i3} = F_{i3} - M_i \cdot \ddot{u}_3 - c_{i3} \cdot u_3 \qquad (8)$$

This is to be contrasted with equation (1). The resultant hydrodynamic coefficients of the intact ship can be derived from equation (7) directly. These are the coefficients presented in §2.3 below after being rendered non-dimensional according to Table 4.

Consider now the equation for heave motion of the ship in the damaged condition:

$$(M_d + a_{d3}) \cdot \ddot{u}_3 + b_{d3} \cdot \dot{u}_3 + c_{d3} \cdot u_3 = F_{d3} \quad \text{Heave motion equation for the damaged ship} \qquad (9)$$

Keeping in mind that the real mass of the damaged ship is decreased as shown in (5) to compensate for the loss of buoyancy due to flooding and thus to retain the ship submerged geometry constant, equation (9) can be rewritten as follows:

$$(M_i - m_d + a_{d3}) \cdot \ddot{u}_3 + b_{d3} \cdot \dot{u}_3 + c_{d3} \cdot u_3 = F_{d3} \qquad (10)$$

Removing the restoring (note that $c_{d3} \neq c_{i3}$) and inertia terms from the measured force F_{d3} leads to the following equation to be used for estimating the hydrodynamic coefficients by means of the least squares technique:

$$a^m_{d3} \cdot \ddot{u}_3 + b_{d3} \cdot \dot{u} = h_{d3} \qquad (11)$$

Where:

$$h_{d3} = F_{d3} - M_i \cdot \ddot{u}_3 - c_{d3} \cdot u_3 \qquad (12)$$

$$a^m_{d3} = -m_d + a_{d3} \qquad (13)$$

Coefficients a^m_{d3} and b_{d3} are the values shown in all the figures presented in §2.3 below corresponding to ship "flooded" state.

The noteworthy feature of the hydrodynamic force h_{d3} (12), is that the removed inertial force component is considered to be proportional to mass M_i when the actual mass of the damaged ship is M_d. Such manipulation implies that both the mass of the damaged ship M_d and the mass of floodwater in the damaged compartment m_d, (5), are translating with the same acceleration $\ddot{u}_3$. This assumption can be considered valid with heave motion considered not coupled to other modes of motion and the damaged ship sealed off after flooding in which case the floodwater will remain mostly undisturbed with the free surface still and horizontal. In other words, if the flooded ship was sealed again ($c_{d3} = c_{i3}$), there would be no difference between the coefficients in intact and damaged conditions, that is $a^m_{d3} = a_{i3}$ and $b_{d3} = b_{i3}$.

However, if the ship were left open, there will be instantaneous water ingress/egress resulting in fluctuations of the mass m_d as well as changing the character of the fluid flow in the vicinity of the opening. The effects of these two phenomena on the derived hydrodynamic coefficients are discussed in §2.3.

Similar reasoning can be applied to forced roll oscillations. The moment of inertia of the equivalent solid mass of floodwater in the damaged compartment can be expressed as:

$$i_d = I_i - I_d \quad \text{Moment of inertia of floodwater entering the damage ship in upright condition. The inertia of the solid mass removed is the same as the inertia of floodwater.} \qquad (14)$$

The linearised and uncoupled equation of roll motion can be expressed as follows:

$$(I_i + a_{i4}) \cdot \ddot{u}_4 + b_{i4} \cdot \dot{u}_4 + c_{i4} \cdot u_4 = F_{i4} \quad \text{Roll motion equation for the intact ship} \qquad (15)$$

Removing the inertial and restoring terms leads to the following equation for estimations the intact ship added moment and damping moment coefficients in roll motion:

$$a_{i4} \cdot \ddot{u}_4 + b_{i4} \cdot \dot{u}_4 = h_{i4} \qquad (16)$$

Where:

$$h_{i4} = F_{i4} - I_i \cdot \ddot{u}_4 - c_{i4} \cdot u_4 \qquad (17)$$

Again, the coefficients a_{i4} and b_{i4} are presented in §2.3 below in non-dimensional form as per Table 4.
The analogous equation for the damaged ship roll motion can be written as:

$$\left(I_d + a_{d4}\right) \cdot \ddot{u}_4 + b_{d4} \cdot \dot{u}_4 + c_{d4} \cdot u_4 = F_{d4} \qquad \text{Roll motion equation for the damaged ship} \qquad (18)$$

Keeping in mind that the real inertia of the damaged ship is decreased by (14) due to removal of the mass (5) when compensating for the loss of the buoyancy due to flooding, equation (18) can be rewritten as follows:

$$\left(I_i - i_d + a_{d4}\right) \cdot \ddot{u}_4 + b_{d4} \cdot \dot{u}_4 + c_{d4} \cdot u_4 = F_{d4} \qquad (19)$$

This finally leads to the following equation for estimating the damaged ship added moment and damping moment coefficients in roll motion:

$$a_{4d}^{m} \cdot \ddot{u}_4 + b_{d4} \cdot \dot{u}_4 = h_{d4} \qquad (20)$$

Where:

$$h_{d4} = F_{d4} - I_i \cdot \ddot{u}_4 - c_{d4} \cdot u_4 \qquad (21)$$

$$a_{4d}^{m} = -i_d + a_{d4} \qquad (22)$$

Removing the component $I_i \cdot \ddot{u}_4$ of the inertial moment from the hydrodynamic reaction F_{d4}, see (21), is not entirely equivalent to the operation applied in (12). In the case of roll motion this manipulation implies that the removed inertial moment component is composed of both, the moment due to the damaged ship inertia I_d rotating with acceleration $\ddot{u}_4$ as well as the moment due to the inertia of the equivalent solid mass of the floodwater in the damaged compartment i_d, also rotating with the same acceleration $\ddot{u}_4$. However, it is rather obvious that the latter assumption is not valid because the mechanics of floodwater behaviour are largely independent of ship motions, even though it is the ship motions that induce floodwater motion. Therefore the acceleration of floodwater is not equal to $\ddot{u}_4$. Moreover, as the centre of buoyancy of floodwater changes instantaneously, the inertia of floodwater estimated with respect to the fixed axis of ship rotation is not constant, i.e. $i_d = i_d(t)$. Therefore, even if the damaged ship were considered sealed again with constant amount of floodwater in the damaged compartment, there would still be a difference between the hydrodynamic coefficients in intact and flooded cases, due to floodwater dynamic motions.

The implication of this is that when interpreting the hydrodynamic coefficients in roll motion, shown in §2.3, it should be borne in mind that the differences between the coefficients in intact and damaged cases derive from the following:

- Water ingress/egress with the ensuing fluctuations of inertia i_d as well as fluid flow changes in the vicinity of the opening.
- The instantaneous oscillation of the centre of buoyancy of floodwater due to ship rotation as well as the fluctuations of the inertia i_d.

The latter phenomenon is not present in the heave forced oscillations.

Having outlined the background of the data analysis and interpretation, it is worth emphasising that it is not clear to what extent, if at all, the orthogonal decomposition of these effects applied in this study is valid, as the phenomena are of strongly non-linear character and, therefore, could be neither in phase with velocity nor acceleration of ship motion. The exact nature of the effects of flooding is not known.

Therefore, the main aim of this investigation is to qualitatively assess the *nature and scale* of the effects of damage and ensuing flooding on ship hydrodynamics and motions, with further rigorous study to quantify these effects left for future work.

2.2.d Ship attitude variation

As shown above the hydrodynamic coefficients are derived from equations (7), (11), (16) and (20), for heave-intact, heave-damaged, roll-intact and roll-damaged conditions, respectively. Each of these cases, when considered for the up-right ship attitude is rather straightforwardly understood. However, when different ship attitudes are considered, as is the case in this research, some explanation concerning data interpretation is necessary and this is outlined next.

A commonly used approach to assessing damaged ship behaviour involves a set of equations of the ship motion formulated and solved in the time domain by using a system of reference fixed to the ship, as otherwise the ship *real mass inertia* would have to be evaluated for every new attitude the vessel attains. Consequently, all the external forces considered have to be expressed in this body-fixed system of reference, see for example the system of axes denoted by *yz* in Figure 3 and Figure 4.

However complex the implications of this requirement are, they are overcome by the application of the linear fluid flow theory, within the scope of which the amplitudes of the ship harmonic motions as well as the amplitudes of the induced/incident free surface disturbances are considered small. It is well established that this theory allows assessment of ship dynamic behaviour in waves with acceptable engineering accuracy, deriving from its ability to accurately represent the predominant constituents of the physical phenomenon such as the *mass* forces and moments.

A practical implication of the linearity assumption, of significance in this study, is that the hydrodynamic coefficients (here the added mass and damping) are considered to be the same in either the body-fixed *xy* or the earth-fixed *YZ* co-ordinate systems. For further clarification, consider harmonic oscillation in coupled modes of motion and the resultant force (23) when expressed in the inertial co-ordinate system YZ, Figure 3. Note that the roll moment is illustrated as a pair of vertical forces.

$$h_j = a_j \cdot \ddot{u}_j + b_j \cdot \dot{u}_j \quad \text{Hydrodynamic reaction forces in the inertial system of reference} \qquad (23)$$

The equivalent linear force when expressed in the body-fixed system of reference is given in the form (24) where the hydrodynamic coefficients remain constant and only the acceleration and velocity vectors are resolved in the body-fixed system of reference as shown in (25).

$$h'_j = a_j \cdot \ddot{u}'_j + b_j \cdot \dot{u}'_j \quad \text{Hydrodynamic reaction forces in the body-fixed system of reference} \qquad (24)$$

$$u' = D \cdot u \qquad (25)$$

Where the rotation matrix is expressed as:

$$D = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\varphi) & \sin(\varphi) \\ 0 & -\sin(\varphi) & \cos(\varphi) \end{bmatrix} \qquad (26)$$

The subtlety of equation (24), which is to be used only for coupled ship motions is noteworthy. When pure modes of motions are considered, say roll motion, as was the case with the experiments carried out in this study, the velocity as well as the acceleration of the forced motion around the ship longitudinal axis are the same in either system of reference, that is $h_j = h'_j$. However, when the mean ship attitude deviates significantly, from that of the up-right, see Figure 5, differences arise between the directions along which the motions are applied during the experiment (or numerically, where the boundary value problem is set-up) and the attitude that can be considered as the mean of ship oscillations. Again, for clarification purposes, consider for instance heave motion as shown in Figure 5. The motion in the experiment is applied along the vertical axis *Z*, whereas the mean heave attitude is designated by the axis Z^*. This difference should be accounted for in the numerical considerations and, therefore, the coefficients must be transformed to the co-ordinate system that designates the mean ship attitude in the manner suggested next.
The forces and moments due to oscillation of a ship, with attitude different from the up-right, can be expressed in an analogous manner to equation (23) as:

$$h_{tj} = a_{tj} \cdot \ddot{u}_j + b_{tj} \cdot \dot{u}_j \qquad (27)$$

The subscript "t" is to indicate the "non-up-right" ship mean attitude. The corresponding force in a system corresponding to the "mean" ship attitude can be expressed as:

$$h^*_{tj} = D^* \cdot \left(a_{tij} \cdot \ddot{u}_j + b_{tij} \cdot \dot{u}_j \right) \qquad (28)$$

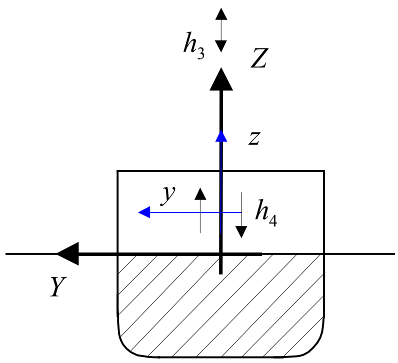

Figure 3 The hydrodynamic coefficients are obtained for the mean immersed ship geometry

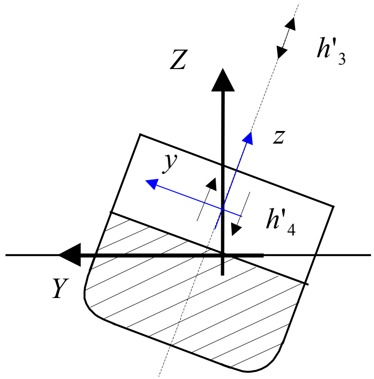

Figure 4 During time domain simulation of ship response the hydrodynamic forces are assumed to be constant and corresponding to the up-right mean attitude

In case the ship attitude refers to non-zero heel the transformation matrix is a function of the ship heel, $D^* = D(heel)$. The above equation is better presented in a rearranged form:

$$h_{tj}^* = \left(D^* \cdot a_{tij}\right) \cdot \ddot{u}_j + \left(D^* \cdot b_{tij}\right) \cdot \dot{u}_j \qquad (29)$$

As can be seen the coefficients cannot be considered as resulting from "pure" modes of motions due to matrix D^* operation. Therefore, the cross-coupling terms have to be accounted for and hence the index "i".

The time realisation of the above force in the body-fixed system of reference can be obtained through the same operation as used in equation (24), see Figure 6.

$$\left(h_{tj}^*\right)' = \left(D^* \cdot a_{tij}\right) \cdot \ddot{u}'_j + \left(D^* \cdot b_{tij}\right) \cdot \dot{u}'_j \qquad (30)$$

For the purpose of comparing coefficients for different ship attitudes, formulae (29) should be used, as during numerical predictions it would be these values, transformed further by (30), that will affect motions. However, since only heave and roll motion were analysed to date with the sway and cross-coupling terms awaiting further analysis, the coefficients presented in this work are compared on the basis of equation (27), which is also reflecting directly the reference system in which they are derived by means of both experiments and numerical predictions.

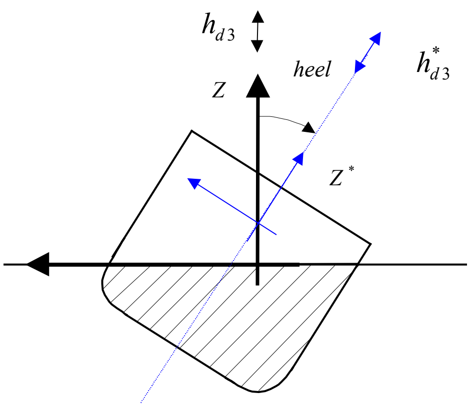

Figure 5 For the damaged ship, the mean attitude results from the equilibrium following flooding

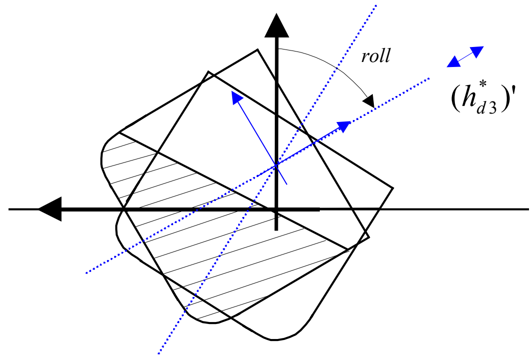

Figure 6 Ship deviations from mean attitude are assumed to be small and hence the coefficients are kept constant but corresponding to the mean attitude.

2.3 PRESENTATION AND DISCUSSION OF RESULTS

Considering the discussion offered above, an attempt will be made to rationalise the results derived in this research. All the hydrodynamic coefficients for heave motion are presented in Figure 7 to Figure 13, and the coefficients for roll in Figure 14 to Figure 20.

2.3.a Heave motion

Figure 7 is provided by way of examining data referring to heave motion, where the coefficients in question are derived numerically with two separate codes, one based on strip-theory [9] and one on three-dimensional panel code [4]. Two attitudes are considered, the up-right and -20deg of heel. Only the intact ship external geometry was used as input in both cases.

As can be observed in Figure 7, with perhaps some exception at the low frequency range, $\omega_B < 0.5$, the results derived by both methods are virtually identical. This gives some confidence as to the quantitative outcome deriving from this exercise, namely that the effect of ship attitude on the hydrodynamic coefficients in heave motion is negligible.

Figure 8 to Figure 10 seem to support this conclusion with the data derived experimentally in the course of this research. In particular the heave added mass shows consistently no variation with heel angles up to 20deg. The damping coefficients in these figures display a somewhat erratic behaviour, with some consistently occurring discontinuity at the frequency $\omega_B \approx 0.5$ beyond which damping remains constant or slightly increasing, with increasing frequency, contrary to the common knowledge of steadily decreasing damping values with frequency exceeding approximately the corresponding natural heave frequency. This trend is not confirmed here and thus far no clear explanation has been suggested as to the most likely cause of this discrepancy. However, since the data presented here is consistent, some qualitative conclusions can be drawn. The damping coefficients further confirm that the ship attitude does not affect the ship hydrodynamic properties in heave motion.

No numerical data are available concerning the same heave added mass and damping coefficients for a ship with a hull opening. Therefore the results derived experimentally and shown in Figure 11 to Figure 13 are of particular value.

Considering now the effects of flooding, test results indicate a noticeable effect on ship hydrodynamics in heave motion. The added mass coefficients show consistently a decrease in the whole frequency range when in the up-right condition. A further consistent decrease of these coefficients by about 20-30% with increasing ship heel, again for the whole frequency range, can be explained by the increased instantaneous floodwater ingress and egress due to the higher opening area involved in the flooding process in such attitudes (opening reaching the car deck spaces). It is rather difficult to reach any firmer conclusions on the impact of flooding on damping, other than whatever the effects are, they are of very small importance for the conditions tested.

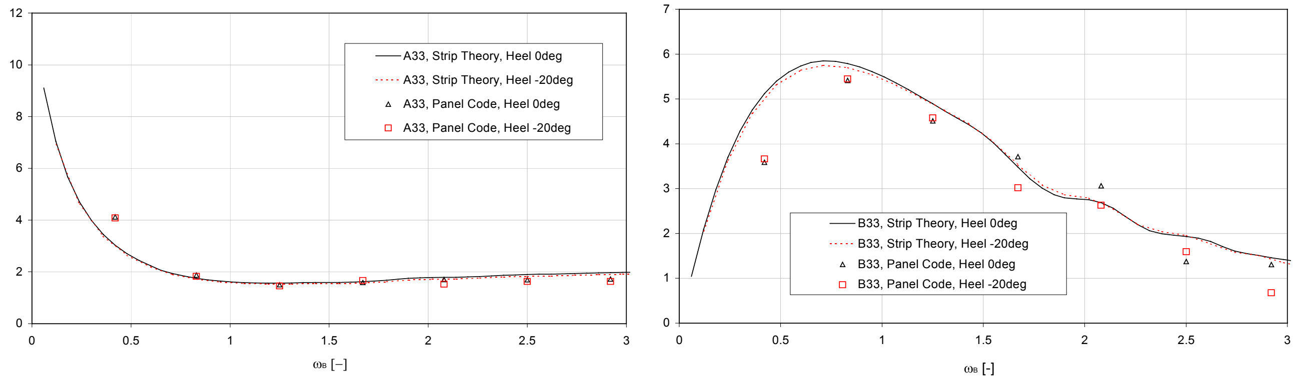

Figure 7, Heave hydrodynamic coefficients: comparison between strip theory and panel methods, intact condition (effect of heel)

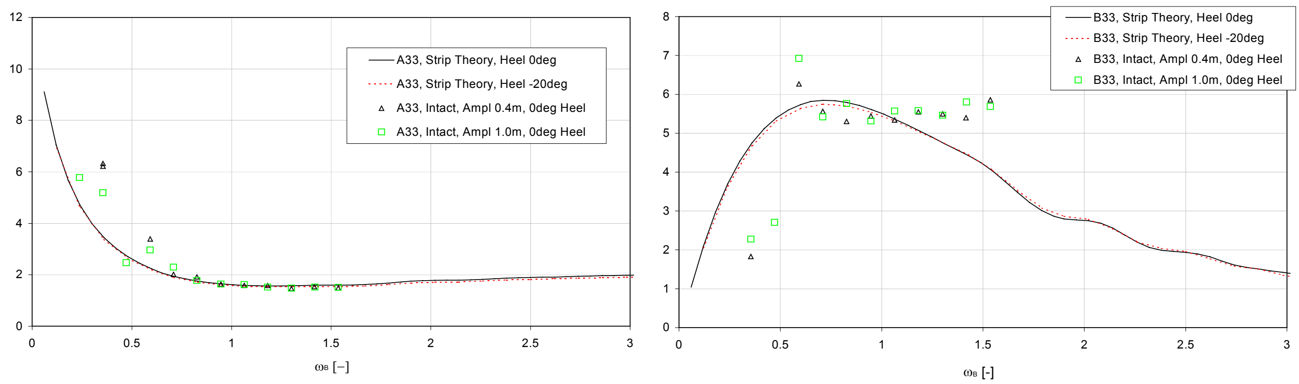

Figure 8 Heave hydrodynamic coefficients, comparison between strip theory and experiments, intact condition

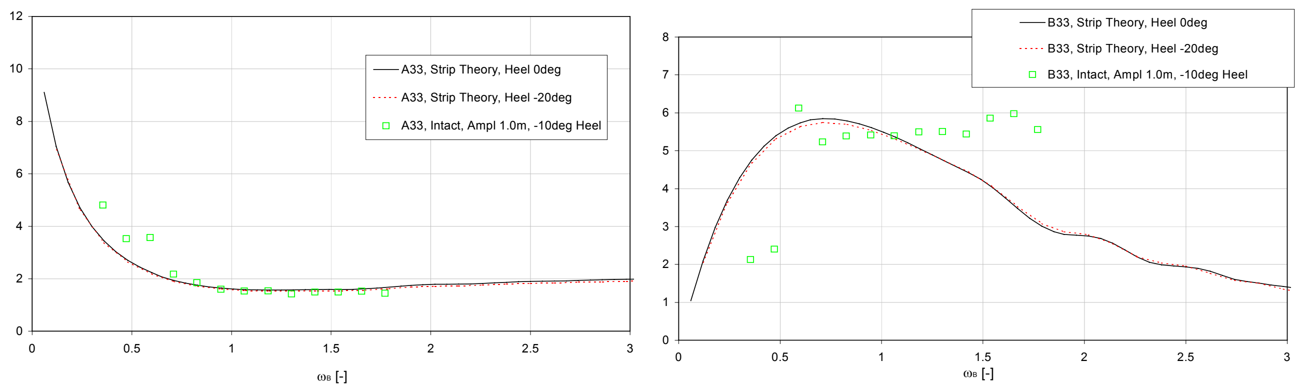

Figure 9 Heave hydrodynamic coefficients: comparison between strip theory and experiments, intact condition (-10deg)

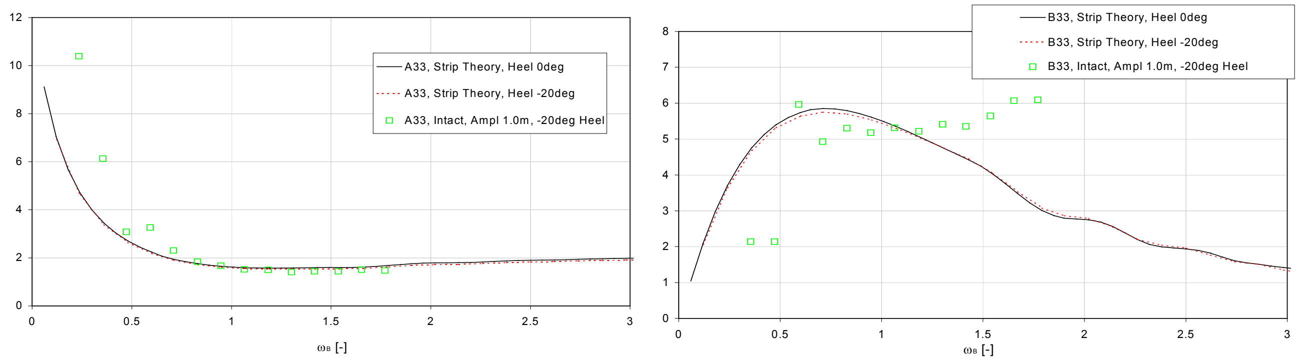

Figure 10 Heave hydrodynamic coefficients: comparison between strip theory and experiments, intact condition (-20deg)

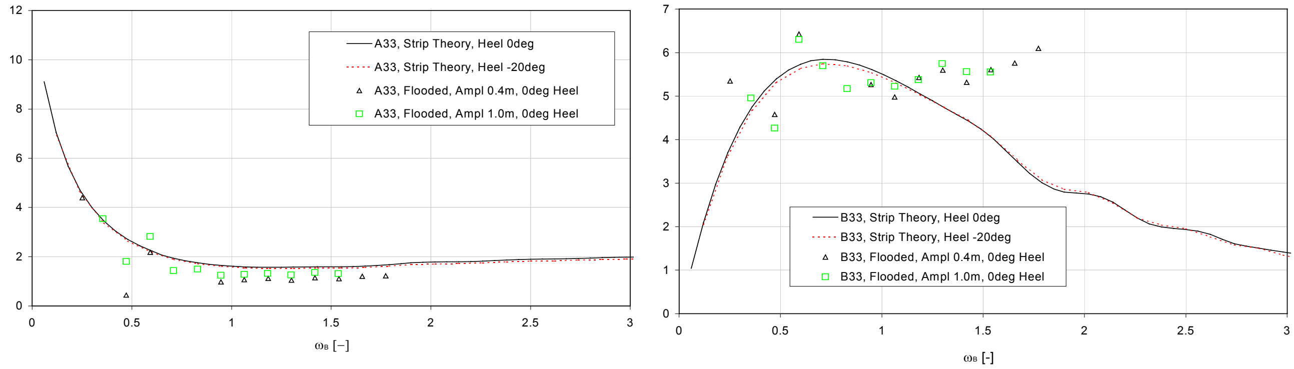

Figure 11 Heave hydrodynamic coefficients: comparison between an “intact ship” strip theory and experiments with the damaged ship (: effect of flooding)

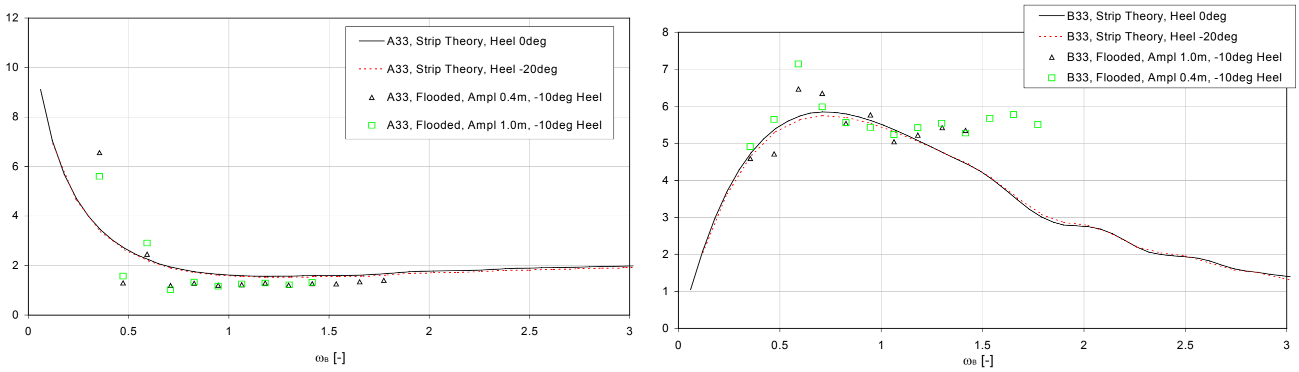

Figure 12 Heave hydrodynamic coefficients: comparison between an “intact ship” strip theory and experiments with the damaged ship (effect of flooding in -10deg heel)

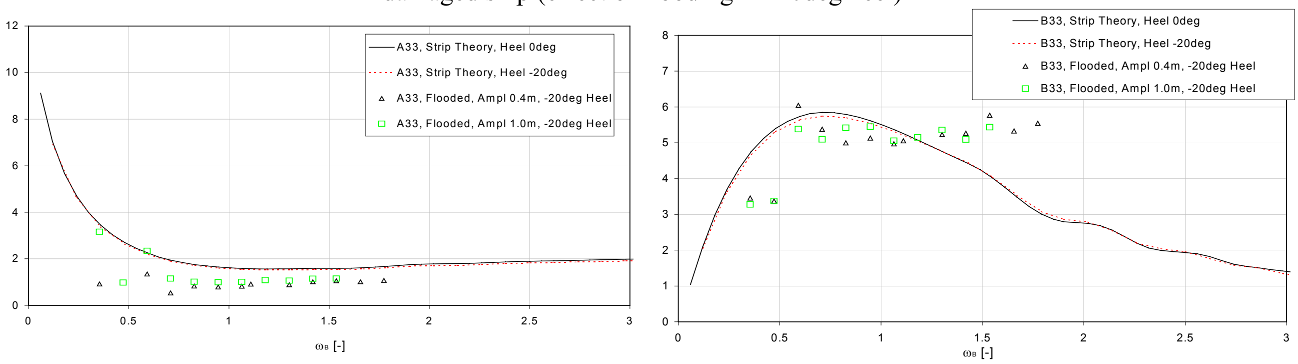

Figure 13 Heave hydrodynamic coefficients: comparison between an “intact ship” strip theory and experiments with the damaged ship (effect of flooding in -20deg heel)

2.3.b Roll motion

Unlike the case with heave , the numerical predictions of roll added mass moment of inertia and roll damping moment display some dependency on the vessel attitude, with the added inertia increasing at frequencies in the range of $\omega_B < 0.5$ and $\omega_B > 1$, and the damping increasing at lower frequencies, $\omega_B < 1$, see Figure 14.

Discussion of these with reference to physical test results is however not quite straightforward as the experimentally derived roll added inertia is somewhat different quantitatively from the numerical values, se Figure 15 to Figure 17. In particular, the added inertia at frequencies of up to approximately $\omega_B < 1.2$ is considerably lower. This is quite likely a result of inaccuracies in accounting for the roll restoring, which especially at lower frequencies is by far the most predominant component of measured moment.

However, an attempt to reason in qualitative terms can be made. It can be seen, for instance, that at lower frequencies the added inertia increases consistently with increasing heel, which confirms the trends derived numerically. Furthermore, some asymptotic value of added mass emerges at a frequency of about $\omega_B \approx 1.5$, which happens to coincide quantitatively with numerical predictions. Unfortunately the scale of the model used did not allow testing at frequencies higher than this, and hence no experimental confirmation of this trend has been possible.

The damping moment presents an even more complex issue. As is well known, wave making roll damping is but a small contribution to the energy dissipation mechanism, which is mostly dominated by the consequences of fluid viscosity, such as eddy making or friction. These effects have not yet found any rigorous mathematical treatment, and hence only some empirical formulations are being used, notably that of [10]. The increase of roll damping with frequency roughly in linear proportion can also be seen in Figure 15 to Figure 17 below, which show a further increase of the slope of the damping "line" with increasing heel.

Considering damage and the ensuing flooding adds to the difficulty in clearly interpreting the derived results, mainly due to reasons outlined in §2.2.c above. Some trends can however be commented on. Figure 18 to Figure 20 present the hydrodynamic coefficients in roll motion in the damage case. The compound effect of flooding on the added inertia in such condition is quite surprising. At the up-right ship attitude, the higher frequency value of added inertia increases by roughly 30%. With the ship heeled to -20deg this value decreases suddenly by roughly 70% with no sign of reaching an asymptotic value within the frequency range considered. These drastic changes are by and large attributable to the water flooding onto the car deck and all the resultant dynamic effects due to sloshing, exacerbated further by the water ingress and egress. The damping values, on the other hand, to great surprise do not display much of a change with respect to the intact condition. This is quite difficult to accept in view of compelling experiential evidence that the damaged ship roll motion is overly damped. This leads to conclusions that alternative mechanisms of damping are at play other than dissipative mechanisms and this ought to be more thoroughlt investigated. It is only at the -20deg heel that the damping increases almost twofold for the whole frequency range considered, most likely due to water flooding in and out of the car deck.

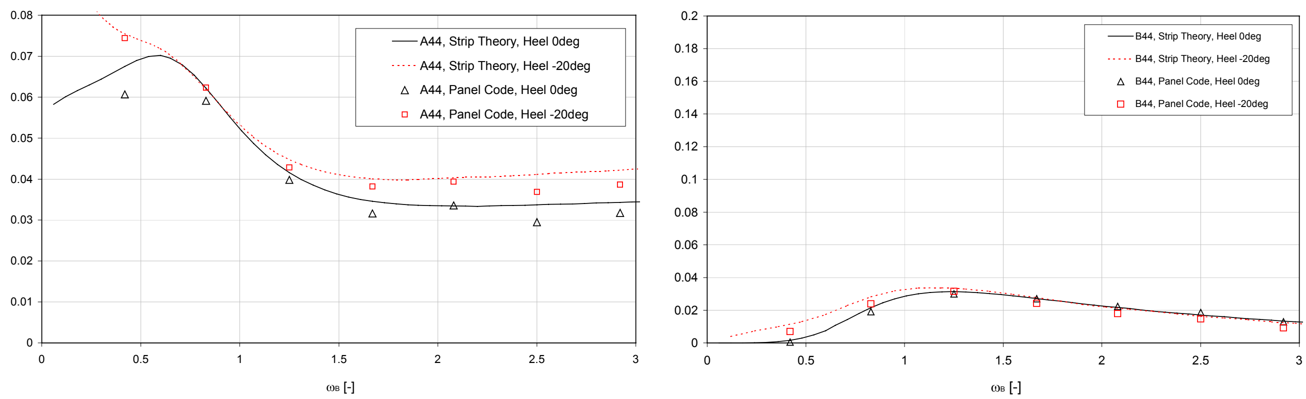

Figure 14 Roll hydrodynamic coefficients: comparison between strip theory and panel methods, intact condition (effect of ship heel)

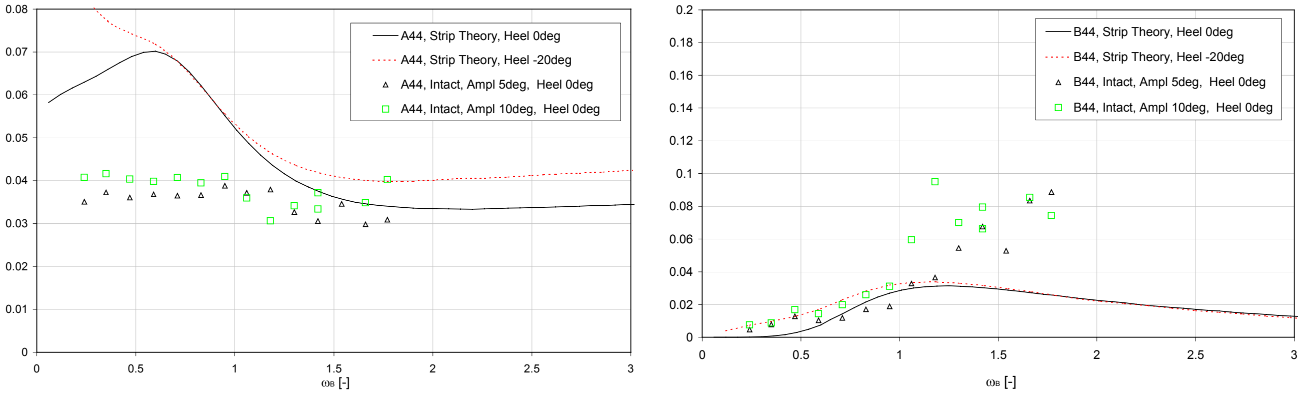

Figure 15 Roll hydrodynamic coefficients: comparison between strip theory and experiments, intact condition

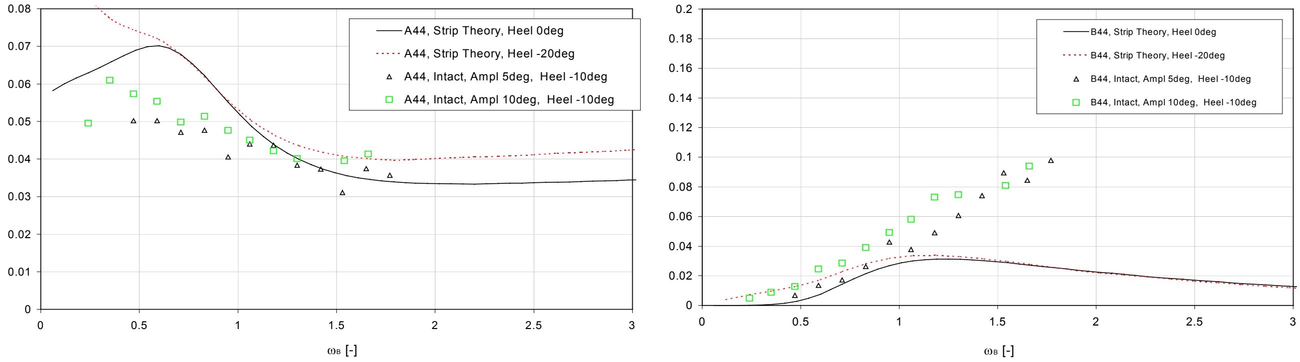

Figure 16 Roll hydrodynamic coefficients: comparison between strip theory and experiments, intact condition (-10deg heel)

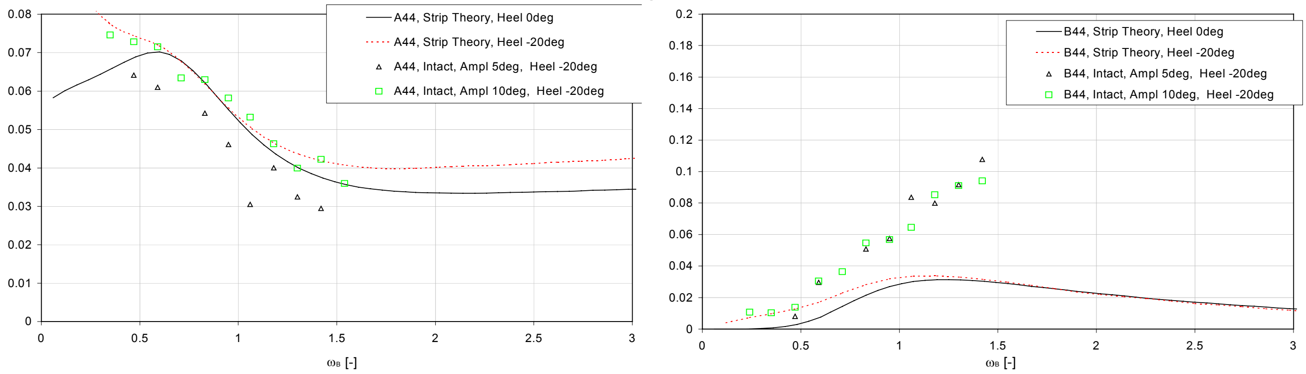

Figure 17 Roll hydrodynamic coefficients: comparison between strip theory and experiments, intact condition (-20deg heel)

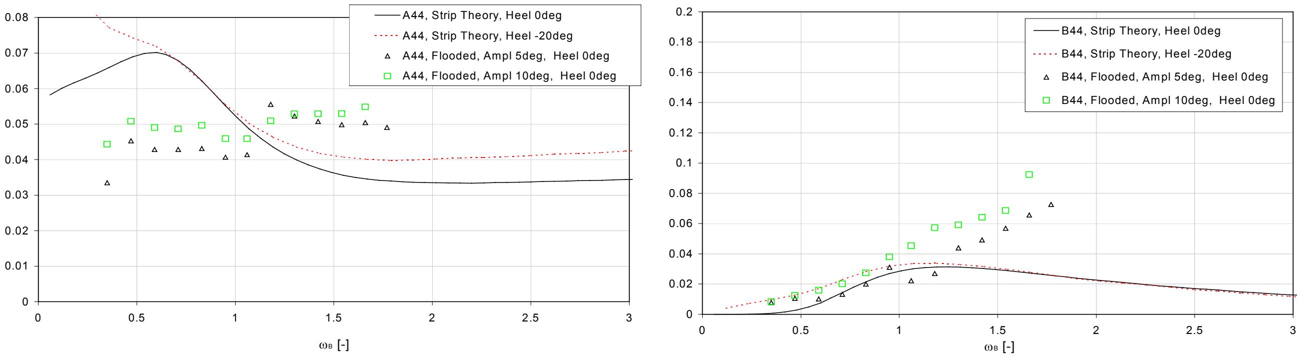

Figure 18 Roll hydrodynamic coefficients: comparison between the “intact ship” strip theory and experiments with the damaged ship (effect of flooding)

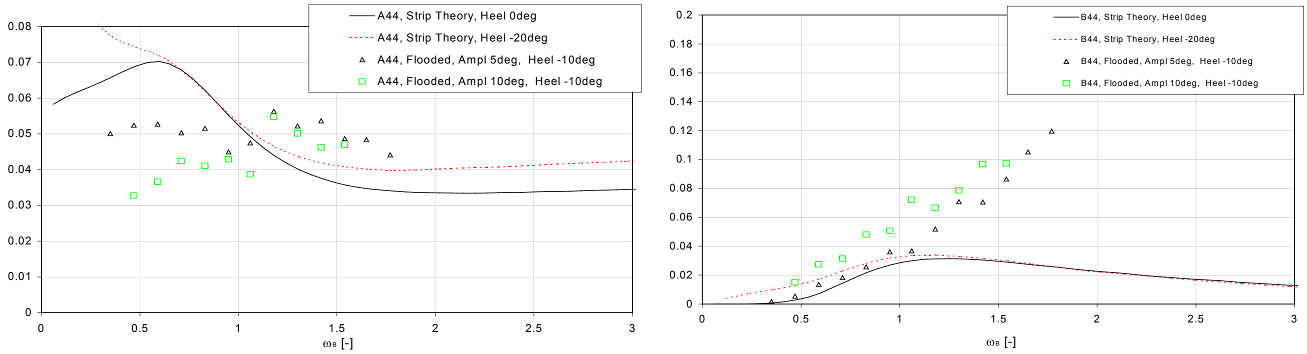

Figure 19 Roll hydrodynamic coefficients:, comparison between the "intact ship" strip theory and experiments with the damaged ship (effect of flooding at -10deg heel)

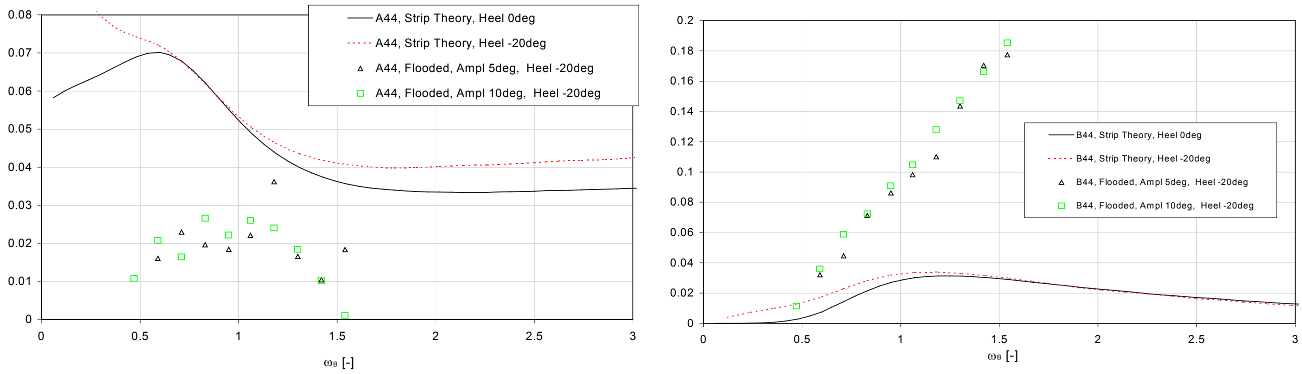

Figure 20 Roll hydrodynamic coefficients:, comparison between the "intact ship" strip theory and experiments with the damaged ship (effect of flooding at -20deg heel)

2.4 ADDITIONAL COMMENTS

Considering the results derived to date, in particular for the case of damaged ship rolling, it is obvious that the process of flooding influences greatly the hydrodynamics of damaged ships. However, due to high complexity of the phenomena involved the, analysis performed has not been successful in identifying the specific physical reasons responsible for this influence other than at a speculative level. There are clearly three interrelated processes involved: ship dynamics, floodwater dynamics and water ingress/egress in the hull and on the car deck.. In this respect, it would seem that research focus should be directed towards establishing the relative contributions of the latter two on the first, individually and combined.

In this respect, use can be made of the latest research undertaken within the scope of this project addressing the phenomenon of flooding, such as tests involving PIV laser measurements of floodwater accumulation and motions.

Naturally, interesting observations derived from this work shall also be carefully considered. These can be summarised as follows:

- The floodwater free surface undergoes oscillations of different amplitude than that of the roll motion and vary significantly with frequency of excitation.
- The amplitude of floodwater free surface oscillation varies with the direction of roll, i.e. it depends on whether the ship rolls towards the damage side or away from it.
- The phase angle between roll motion and floodwater free surface oscillation varies with frequency and amplitude of excitation.

3 CONCLUSIONS

The experimental campaign undertaken to address damaged ship hydrodynamics has been successfully completed. A suitable apparatus has been assembled for performing forced-oscillation tests and combined with a state of the art six-component balance to allow for these unique measurements to take place, likely to lead to a breakthrough in our understanding of damaged ship hydrodynamics..

Based on the results derived thus far, the following conclusions may be drawn:

- The heave added mass and damping are marginally affected by ship heel variations within the range considered (up to 20deg). Flooding has a rather small effect on heave hydrodynamic coefficients.
- Roll hydrodynamic coefficients increase with increasing ship heel. The effect of flooding on roll hydrodynamics is significant.

The relative importance of the expected causes of the above effects, due to floodwater sloshing and water ingress/egress remains to be established.

4 ACKNOWLEDGEMENTS

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