Experiments on a Floating Body Subjected to Forced Oscillation in Calm Water at the Presence of an Open-to-Sea Compartment

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ABSTRACT

This paper presents results of the physical experiments carried out at the SSRC, aiming at measurements of hydrodynamic reactions on a cylindrical body forced to roll in calm water with an open-to-sea compartment. The research addresses the problem of ship-floodwater interaction – an issue of fundamental importance in predicting roll damping for ships in damaged condition.

KEYWORDS

Damaged ship hydrodynamics, ship-floodwater interaction, physical experiments

INTRODUCTION

The methodology of forced oscillations induced by an internal forcing apparatus as well as its validation for intact ship measurements have been already presented (Cichowicz et al., 2009, 2010) - the results depicted here illustrate applicability of the technique to more complex dynamical systems. Although the measurements on a floating body have certain disadvantages, e.g. limitation in imposed modes of oscillation, on the other hand they offer a unique possibility to study complex, multi-modal response of the vessel – a feature of major significance in the research of multi-mass dynamic systems, which generally cannot be fully explored with tests on a constrained model. Specifically, the authors discuss technical aspects of the measurements with particular emphasis on accuracy and uncertainty assessment. This is followed by broader-context considerations on mathematical modelling, post-processing of data and general remarks regarding dynamics of damaged ships and applicability of the demonstrated technique to systematic experimental research.

EXPERIMENTS

Experiments set-up

The experiments presented in this paper were conducted at the Kelvin Hydrodynamics Laboratory (KHM), the testing facilities of the University of Strathclyde[1]. The tested model was a 1.5 m (60 m full scale) cylindrical section of a RoPax ferry. Relevant particulars are shown in the table below:

Table 1 *Particulars of the tested model*

	Dim.	Intact	Dam.
L	m	1.5	1.5
B	m	0.695	0.695
T	m	0.158	0.157
KMT	m	0.343	0.344
KG (dry)	m	0.220	0.297

[1] http://www.strath.ac.uk/na-me/facilities/cmh/

KG (flooded)	m	-	0.232
GM	m	0.123	0.047
Mass	kg	156.8	116.7
kxx	Nm/rad	189.2	53.79
Roll inertia (air)	$kg \cdot m^2$	10.4	4.8
Radius of in. (i_{xx})	m	0.258	0.251
i_{xx}/B	-	0.370	0.36
Scale	-	40	40

The freely-floating model has been forced to roll in calm waters by an internal gyroscopic device, designed and manufactured at the KHM. As discussed earlier (Cichowicz et al., 2009), the produced periodic forcing (pure) moment can be also assumed harmonic and therefore, at least in the case of small motions of the intact ship, the measured hydrodynamic reaction can be decomposed into orthogonal components – added mass and damping. The case of damaged ship will be discussed later.

Ship motions were recorded with the use of optical motion capture system (Qualisys TM) but for reference measurements of the phase lag, a single axis accelerometer was also fitted to the model. The component of the (total) rolling moment was measured by a single axis 500lb transducer.

The draft of the model was kept constant in both conditions. However, due to some inaccuracy in positioning of the replacement masses (i.e. weights placed inside the floodable compartments to account for floodwater mass) the estimated position of the centre of gravity of the ship-floodwater system was 0.012 m (0.48 m full scale) higher than in the case of the intact ship.

During the damaged ship measurements, the flooded compartment was (on one side) open to sea with 0.071 m (2.82 m) freeboard and a prismatic damage opening of 0.203 m (8.1 m) width.

Intact ship measurements

Intact ship measurements were performed in order to validate the experimental set-up. According to the analysis performed previously, it has been shown that a major source of uncertainty, in case of intact ship experiments, is phase lag prediction. Given that the vertical centre of gravity lies close to waterline, the results were obtained with the use of a single DoF linear model. Furthermore, as the spectral techniques proved to be of insufficient resolution the steady-state parts of the time histories were approximated with sinusoidal fit and errors in coefficients' predictions were incorporated into the derived hydrodynamic components by means of a standard differential model. In the following, only errors associated with roll damping coefficients are presented as the remaining quantities exhibit much lesser sensitivity.

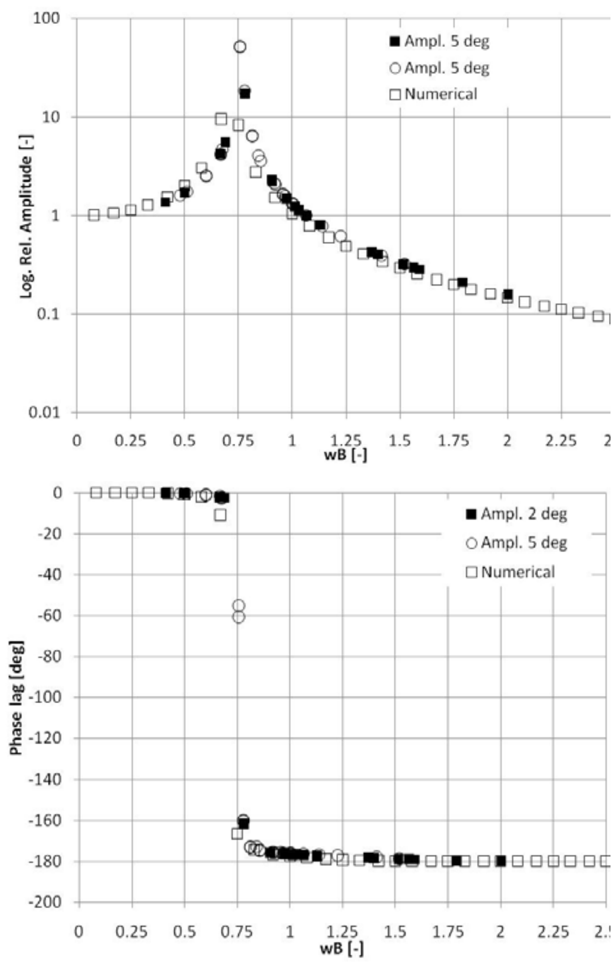

Fig. 1 : Amplitude – phase characteristics of the intact ship.

As can be readily seen from Figure (**1**) both, amplitude and phase lag, characteristics compare very well across experimental and numerical (based on potential flow code) predictions but from the relative amplitude graph it can be noticed that numerical data is shifted slightly towards lower frequencies (i.e. numerical results suggest slightly lower than measured natural frequency). There is, however, no observable distinction between experimental characteristics obtained for 2 and 5 degrees amplitude of roll.

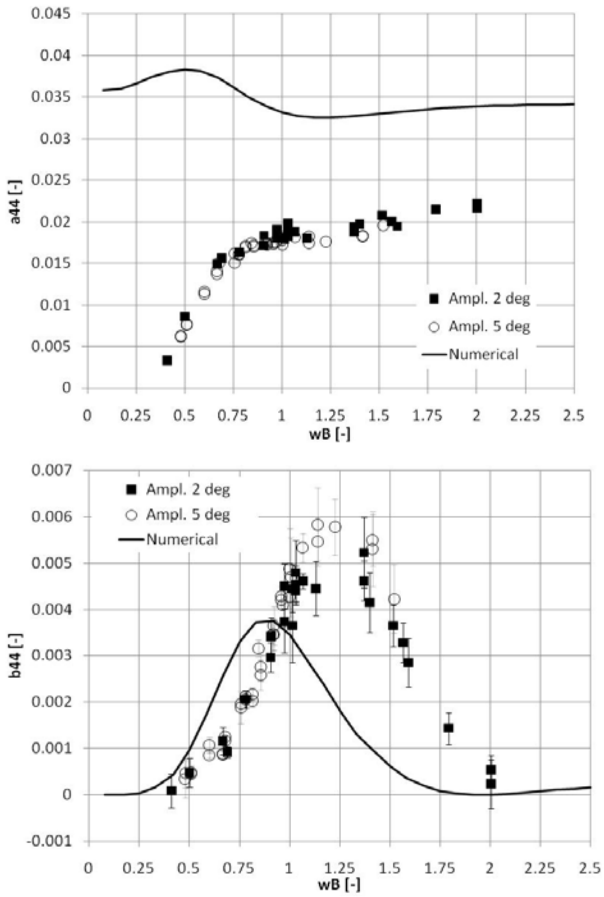

Fig. 2: Added inertia and damping derived with single DoF linear model.

Regardless of the close match in amplitude-phase characteristics, experimentally derived damping and added inertia exhibit significant dissimilarity with respect to the numerical prediction (Fig. 2). The added inertia coefficient is smaller over the entire frequency range and unlike the numerical data, it diminishes at low frequencies (the numerical prediction exhibits asymptotic behaviour at both extremities of the frequency range). The damping coefficient, on the other hand, is larger than the numerically predicted and its modal frequency is higher than the numerical counterpart. Finally, although it can be argued that there is indication of increased (nonlinear) damping at higher amplitude motion in the "peak region", the underlying large errors do not substantiate such conclusion. In any case, the experimental results demonstrate good repeatability and reasonable accuracy.

Damaged ship measurements

As mentioned earlier, although the draught in both conditions was kept virtually the same, the centre of gravity of the flooded hull was slightly (12 mm) higher in the damaged condition and therefore direct comparison of the results might be questionable. Nevertheless, as it will be reasoned in the following, the observed behaviour of flooded ship was so utterly different compared to intact vessel that the KG difference is overshadowed by other factors.

Regarding the mathematical model it has to be said that eventually, again for the reason discussed later, the same single DoF model as for the intact ship was used. Obviously, it should be stated that the model is inappropriate and cannot possibly capture the underlying physics and the subtle details of ship-floodwater interactions. However, it had been found that the interaction is governed mainly by low-order effects and the higher order effects, when present, were so minute that more complex models failed to capture them. Furthermore, although it was observed that the measured hydrodynamic reaction was periodic but not harmonic, it had also been found that multi-harmonic models (e.g. spring-coupled masses) did not perform any better than the single DoF model. Obviously, use of the "wrong" model resulted in large epistemic uncertainties and prohibited fully-quantitative assessment but on the other hand it has offered an interesting outlook of the scale of the effects associated with the ship-floodwater interaction. Unarguably, use of terms *added inertia* and *damping* in the case of a damaged ship cannot be justified. However, these terms will be used in the following to denote approximate harmonic components in phase with roll angular acceleration and velocity, respectively.

RESULTS

Amplitude-Phase Characteristics

The first feature that can be readily observed in the amplitude-phase characteristics, Figure (3), is a significant shift of the natural response towards lower frequencies, compared to intact ship. On one hand, the frequency shift results from lower GM and hull mass but on the other hand, given that dry-hull inertia is halved, the natural period of the flooded ship is still longer than expected – this indicates higher (by a factor of two) added inertia.

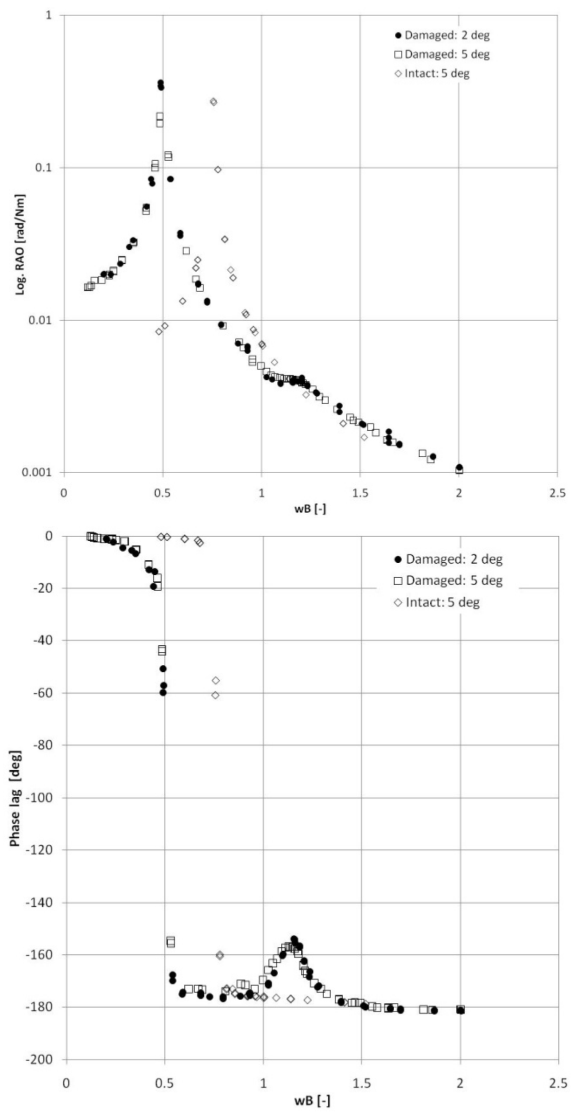

Fig. 3: Amplitude-phase characteristics of the flooded ship.

Furthermore, the damaged ship RAO is bi-modal with the second peak corresponding to the sloshing natural frequency at about ω_B=1.2 [-] (6.14 rad/s)[2]. It is noteworthy that the impact of sloshing on the response amplitude is rather modest whereas the phase lag is considerably more affected with a maximum lag decrease of about 25 degrees. These, i.e. small increase in RAO combined with a large decrease in phase lag accounts for a fifteen-fold increase in damping just by taking the ratio of the relevant sinuses (sin(-153)/sin(-178)) .

Finally, although it is not easy to notice, the phase lag characteristic is not a smooth function at ω_B=1.5 [-], where it “crosses” -180 degrees. The implication of this (given the single DoF model) is negative damping at higher.

Added inertia and damping

The added inertia and damping, or more appropriately, harmonic components of the hydrodynamic force in phase with roll angular acceleration and velocity are presented in Figure (4) below. It can be readily noticed that both components are much larger than in the case of intact ship –damping up to tenfold higher than the intact-ship value. Furthermore, it can be speculated that both characteristics are dominated by hull-floodwater interaction (large dip/peak at sloshing natural frequency).

There are two frequency ranges that may require special attention – relatively low (ω_B<0.5) and relatively high (ω_B>1.5) – at which either added inertia or damping become negative, respectively, based on the logic of the simple model being used here.

At the low-end of the frequency range the measurements indicate negative added inertia and there can be a few reasons for this - most likely it is caused by slightly underestimated restoring. At the high-end of the frequency range the damping becomes negative, which results from the aforementioned behaviour of the phase-lag characteristics.

In any case at (ω_B=1.5 [-]) there is a sharp change in the response characteristics caused by hull-floodwater interaction.

[2] The first two sloshing natural frequencies derived on the basis of the linear model for a rectangular compartment are 5.2 and 10.8 rad/s, respectively.

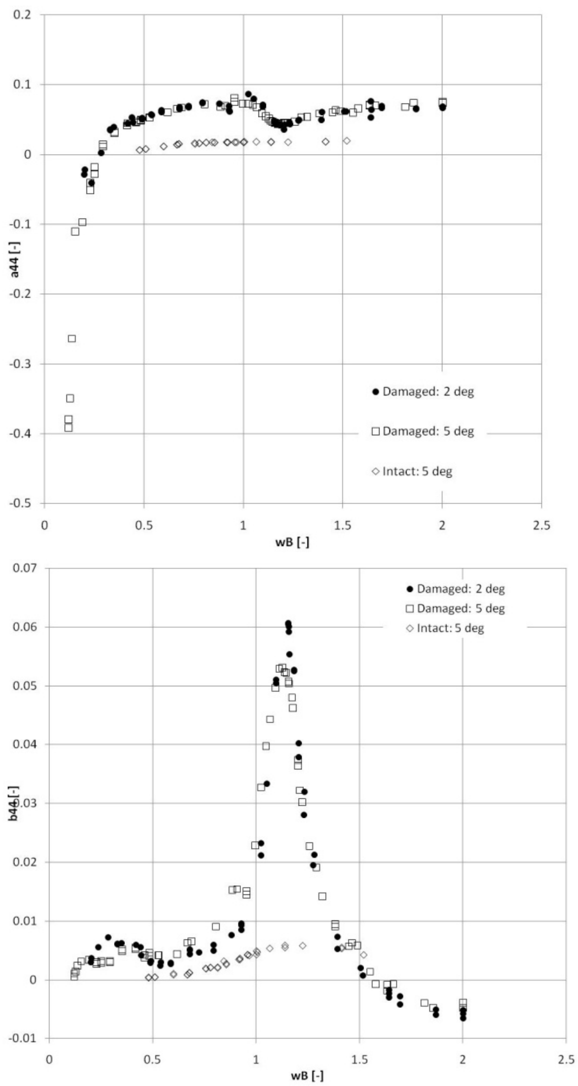

Fig. 4: Added inertia and damping coefficients – flooded ship.

Hull-floodwater interaction

The amplitude-phase and "added inertia – damping" characteristics show clearly that the hull response can be divided into two modes – the first, at relatively low frequencies, dominated by hull dynamics and, the second, predominantly affected by floodwater motions. In the former, the floodwater surface remains calm and virtually horizontal, so its impact on the ship response can be assumed static. The latter part corresponds to a range of local extremes in all the presented characteristics. Interestingly, the impact of sloshing seems to be unrelated to the motion amplitude at frequencies close to and higher than sloshing resonance. The behaviour, however, is not the same at lower frequencies where increased amplitude causes "deformation" of the hull-dominated part of the damping characteristics. In any case it is clear, that as relative motions of hull and floodwater increase, roll motion becomes heavily damped. Furthermore, close to sloshing resonance, flow through the opening becomes so violent that, among other effects, it generates a substantial spatial wave. Similar to these characteristics, the roll-induced heave, Figure (5), and sway, Figure (5), data indicate bi-modal behaviour with two peaks corresponding to hull and floodwater (sloshing) natural frequencies. With respect to sway, it implies that the natural axis of rotation lies (depending on frequency) between dry hull KG and flooded system KG except at low frequencies where higher than expected sway amplitudes suggest sideway rectilinear motions ("sliding").

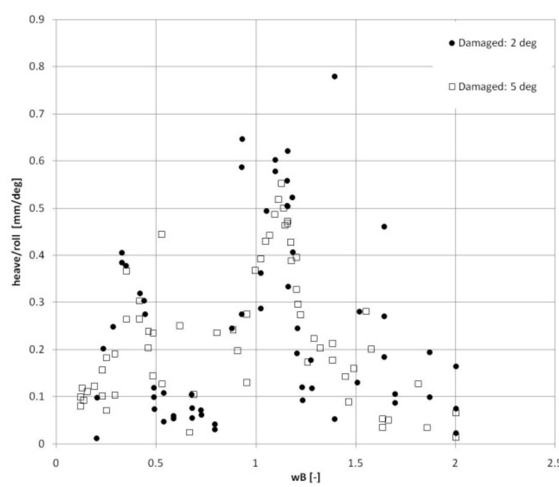

Fig. 5: Relative heave amplitude.

Deriving from the above, it has been shown that the hull-floodwater interaction has a major impact on roll damping and added inertia whereas other modes of motion are not affected significantly. There is, however, one additional mode of motion that is induced by floodwater dynamics – namely drift.

The drift, as expected, is not observed in the intact ship measurements as there is symmetry in both hull geometry and excitation. The situation changes dramatically with the presence of a large opening at the side of the ship. Given the prismatic shape of the opening, its impact on the restoring (due to the asymmetry in pressure distribution on the hull surface) can be considered negligible at small amplitude motions but the same cannot be said with respect to the dynamic effects.

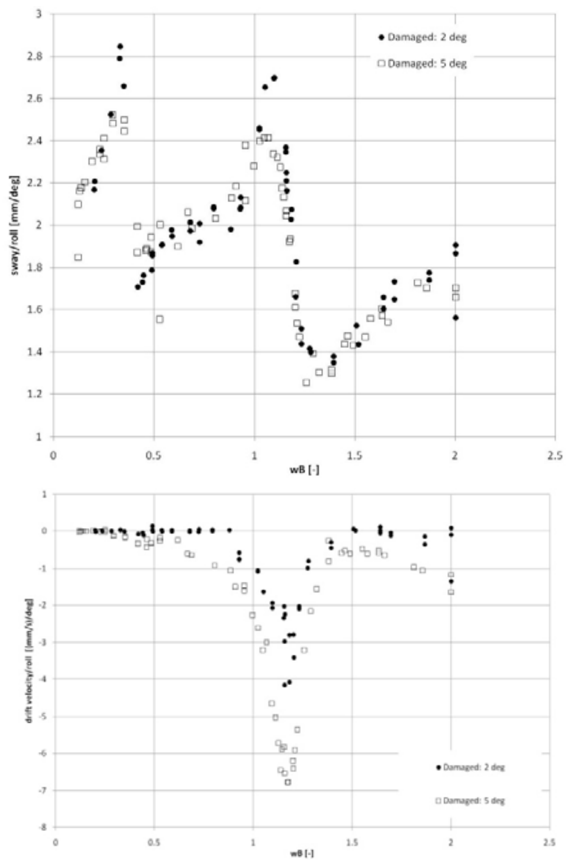

Fig. 6: Relative sway amplitude (top) and drift velocity (bottom).

Beginning with 2 degrees roll, it can be noticed that the frequency ranges at which the drift is being observed coincide with the natural frequencies of the hull and the floodwater (sloshing). In case of the former, the drift velocity is small, practically difficult to note, whereas at the higher frequency the drift velocity reaches almost 10 mm/s (0.12 knots full scale). Outside the relatively narrow frequency bands in the proximity of the resonant frequencies, there is no drift detected. When the amplitude of roll becomes larger, at 5 degrees, drift velocity at the natural frequencies increases significantly (3.5-fold increase of the drift velocity with 2.5-fold increase of the roll amplitude) and the frequency bands of non-zero drift widen, spanning practically over the entire frequency range.

Furthermore, after significant decrease beyond the sloshing natural frequency, it seems to be increasing again for frequencies (ω_B>1.5 [-]). This, combined with the observed C^0 continuity of the phase lag and related characteristics, suggest a sharp change in the character of the flow through the opening and/or floodwater dynamics that take place at this frequency range. Moreover, with some caution, it can be stated that increasing motion amplitude has rather minor impact on roll hydrodynamic reaction – it causes, observed mainly at lower frequencies, a deformation of the damping characteristics of the hull (rigid-body) "component". Apart from this, energy dissipation through roll and roll-induced sway and heave is linearly dependent on roll amplitude.

Finally – although at this stage it can be speculative - one could expect that removing asymmetry from the system, for example by closing the opening, might lead to a completely distinct (e.g. in terms of the observed linearity of coefficients/induced motion amplitudes) impact of floodwater sloshing on roll and other relevant oscillatory motions, due to inability of energy dissipation through drift (see for example: Murashige & Aihara, 1998).

Uncertainty in the results

As mentioned earlier, it has been initially assumed that the single DoF model would present a major source of errors and in principle it would prohibit quantitative assessment. Although this assumption is generally valid, the analysis has shown that more complicated systems have failed to provide better quality assessment. Starting from the artificial decoupling of roll from the roll-induced sway and heave it can be stated that their impact on the final results is expected to be small (Cichowicz et al., 2010) compared to errors in phase lag derivation (and moment amplitude at roll/sloshing natural frequency).

Furthermore, the errors associated with the least-squares averaging (fitting) show clearly that even if the measured force and hull motions are not purely harmonic the resultant uncertainties are small to moderate. Obviously, it is understood that ignoring coupling of roll with other modes of motion does not account for errors in the coupled modes. Nevertheless, it can be reasoned[3] that even if a proper model were available, the actual errors might not have been considerably larger.

In any case, although there are a number of mathematical models of damaged ship available (see: De Kat, 2000; Rakhmanin & Zhivitsa, 2000; Faltinsen & Timokha, 2002), usually the numerical or analytical solutions do not match the experimental data very well. This could be observed in the case of calm-water experiments (Jasionowski & Vassalos, 2002) just as in the case of in-waves tests (Kong & Faltisen, 2008). Therefore it is believed that the single DoF model should be sufficient to determine nature and scale of the dominant dynamic effects.

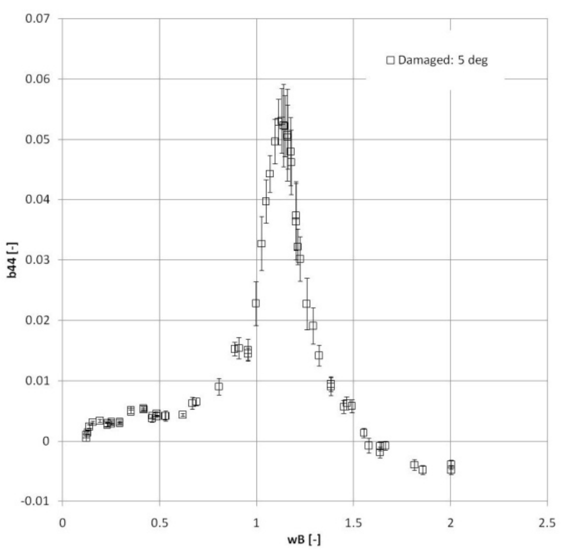

Fig. 7: Uncertainties in roll damping coefficient caused by propagation of least-squares errors in fit coefficients.

Additionally, an attempt made to decompose recorded signals into harmonic components following either coupled system solution or second order harmonic decomposition has not been successful. In the particular experimental set-up, more comprehensive models happened to be of little use – they did not improve accuracy of fitting but required much more computational effort and far too often failed to converge. On one hand, this can account for the common convergence problems of many of the least-squares algorithms. On the other hand, small-scale effects violating the assumption of harmonic force/response, are very difficult to capture due to the noise in the recorded signals and often very limited time of the steady-state measurements. The latter is particularly important in the case of low-frequency oscillations with prolonged transients where there is a risk of short-time wave reflections.

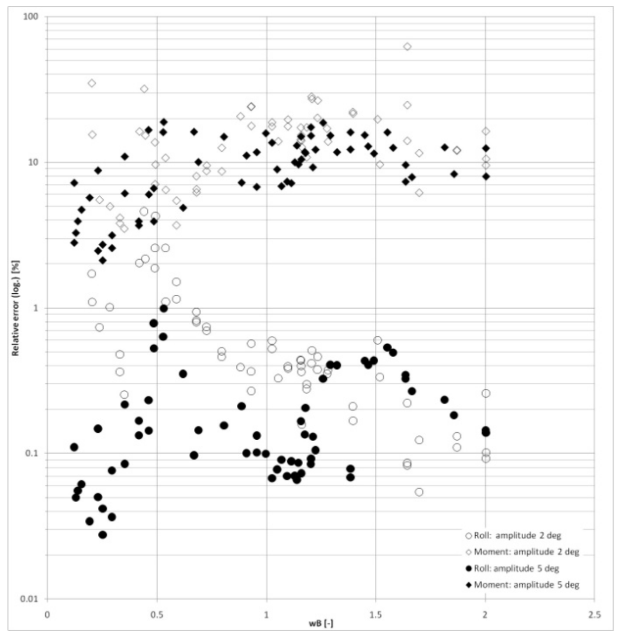

Fig. 8: Relative errors in least-squares amplitude predictions for roll motion and total measured moment for 2 and 5 degrees roll motion, respectively.

Moreover, as Figure (**8**) indicates, the least-squares errors in the moment amplitude are generally well below 1% and it confirms the harmonic nature of the measured moment. On the other hand, recorded roll exhibits much higher inaccuracies with an average error of 10% and substantial standard deviation. Thus, the response needs to be carefully examined as there is strong evidence that it may depart significantly from the assumed harmonic pattern. It is noteworthy however, that even very large errors in roll amplitude prediction have negligible impact on the damping errors outside the sloshing resonance range (Figure (**7**)).

[3] Based on the uncertainty assessment performed for coupled, intact ship, model.

Finally, although initially the authors intended to apply FFT-based techniques - these proved to be, given relatively low sampling frequency, of insufficient resolution.

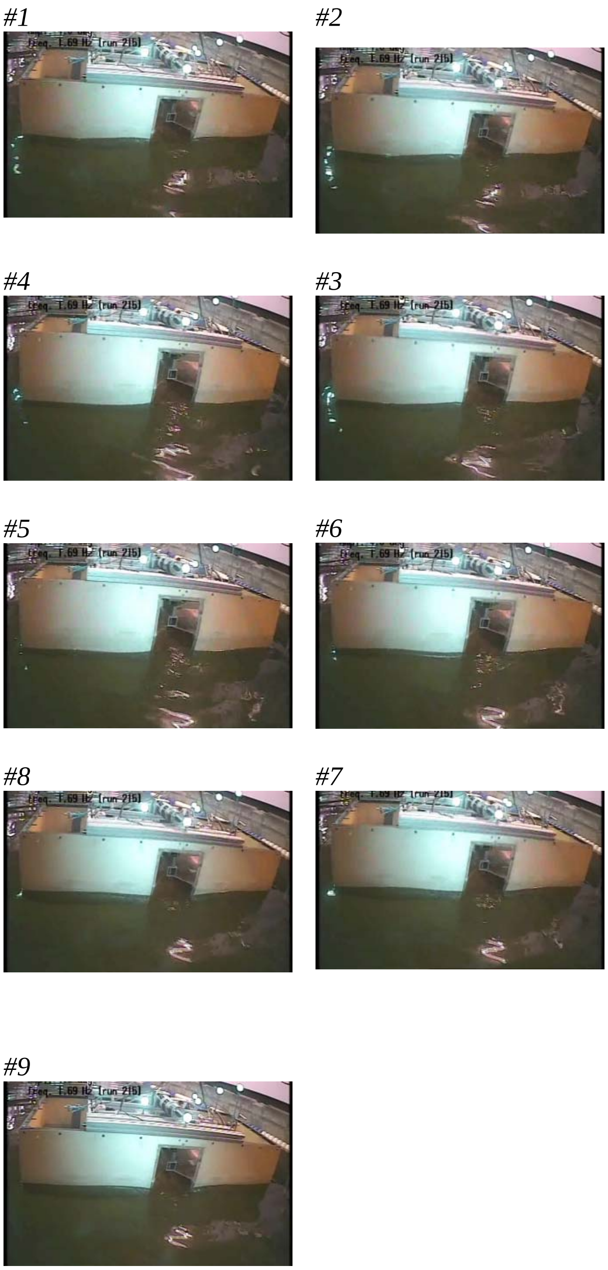

Fig. 9: Sequence of video frames (numbered above the pictures) showing pattern of the waves created by the flow through the opening at 1.69 Hz roll frequency (approximately 1 cycle).

CONLCUDING REMARKS

The results of the exercise presented in this paper do not come as a surprise, as damping effects of free surface have been studied for a very long time (Moaleji & Greig, 2007) but it is thought that the experiments reported here have shed more light on the complex phenomena of the hull – floodwater interaction. Use of an unconstrained model in calm-water allowed observing the scale of the effects associated with complex flow through an opening on the hull and floodwater dynamics and their impact on the behaviour of the ship. On the other hand, it is clear that unless the experiments presented here are followed by more systematic research, the results cannot be generalised or quantified, particularly due to the fact that a suitable mathematical model does not exist (to the authors knowledge).

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