# SOME REMARKS ON THEORETICAL MODELLING OF DAMAGE STABILITY

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**SUMMARY**

The authors raise several points for discussion to develop theoretical modelling of damaged stability in waves. Firstly, hydrodynamic modelling of behaviours of a damaged ship in waves is discussed in the light of multiple time scale expansion. This provides a theoretical background to calculate hydrodynamic forces acting on a hull with sinkage and heel due to water accumulation inside the hull taken into account. Secondly, the reason why the ITTC benchmark testing for a damaged ship resulted in insufficient prediction of roll motions is discussed based on results of model experiments with a flooded compartment model. Thirdly, survivability of a damaged ship with multiple decks in a damaged compartment is discussed in the light of model experiments on flooding of a pure car carrier (PCC) in calm water and waves. The experimental study shows that survivability of such a ship is different from that obtained in a static assumption even in calm water and its dynamic behaviours in waves significantly depend on initial state and transient process of flooding. If so, the model test method used in the Stockholm Agreement can be inappropriate for such type of ships.

**NOMENCLATURE**

| | |
|---|---|
| g | gravitational acceleration |
| h | water depth of tank |
| $H_W$ | wave height |
| **n** | unit vector normal to hull surface $(=(n_{y*}, n_{z*}) or (n_{\bar{y}}, n_{\bar{z}}))$ |
| **r** | ship displacement vector |
| S | body surface equation |
| t | normal time |
| $T_W$ | wave period |
| $y_0$ | sway amplitude |
| $\varepsilon$ | perturbation parameter |
| $\phi_0$ | roll amplitude |
| $\Phi$ | fluid velocity potential |
| $\tau$ | modified time |
| $\xi_2$ | sway |
| $\xi_3$ | heave |
| $\xi_4$ | roll |
| $\omega$ | circular frequency |

## 1. INTRODUCTION

Several Disasters of RoRo Passenger ships in European Waters resulted in Stockholm Agreement as a regional standard in 1995. This opened a door to assess damage stability of a RoRo ship by means of a physical model experiment. This also forces us to establish a numerical prediction method for minimizing the size of the experiment because the experiment can be expensive and time-consuming. Then several points to be examined are raised.

Numerical prediction of a response of a damaged ship in waves cannot be realised with a simple application of existing seakeeping methods. While a conventional seakeeping model assumes the centre of ship harmonic motion is stationary, the centre of harmonic motion of a damaged ship is gradually changing with increase of water accumulation inside her hull. At the stage of a pioneering model by Turan and Vassalos (1994) ignored such difference. As a result, they calculated radiation and diffraction forces around initial states of the hull. Then Vassalos and Letizia (1998) improved this point with other enhancements. Here radiation and diffraction coefficients are updated instantaneously by interpolating a table of calculated values as a function of sinkage, heel, trim and heading but without sufficient theoretical evidence of their method. Then recently one of the authors (Umeda, Mizogami et al., 2002) provided it by use of multiple expansion method. More details of his method is described in this paper for the discussion.

To standardise numerical modelling, the ITTC specialist committee for prediction of extreme motions and capsizing (Vassalos et al, 2002) conducted a benchmark test of numerical modelling for a damaged ship with the set of experimental data of a damaged RoRo ship model from the University of Strathclyde (Vassalos, 2001) and five ITTC member organisations participated in it. As a result, their predictions of capsizing threshold are generally acceptable but their agreement in the response amplitude operator (RAO) of roll is not sufficient. One of the authors (Umeda, Mozogami et al., 2002) presumed that this is because shape of the particular flooded compartments under the RoRo deck is similar to one of a flume-type anti-rolling tank. Based on the experimental results by one of the authors (Ikeda and Yoshiyama, 1991), this fact is discussed in details.

Survivability of a damaged ship is usually assessed on the basis of a static assumption first, and dynamic effects are taken into account. Most of model experiments and numerical simulations for this purpose start with an equilibrium state with flooding in calm water. A question, however, remains here because damage due to collision happens rather sudden and transient behaviors affects the equilibrium state. Thus, some of the authors conducted model experiments of ships after sudden occurrence of a damage opening in calm water and in waves, and pointed out that for a ship with multiple-decks in a compartment, like PCC, the transient behaviors significantly affect the equilibrium state in calm water (Ikeda & Kamo, 2001) and the steady state in waves.

## 2. EFFECT OF SLOW MOTIONS ON FASTLY VARYING HYDRODYNAMIC FORCES

### 2.1 THEORY WITH MULTIPLE TIME SCALE EXPANSIONS

Dynamic behaviours of a damaged ship in waves can be regarded as the sum of large-amplitude and slow motions and small-amplitude but fast motions. Here the slow motions mean sinkage and heel due to water accumulation inside hull and wave drift; the fast motions are harmonic sway, heave and roll motions due to wave excitation. Since a conventional seakeeping theory deal with harmonic motions only, new methodology is expected for ship motions of a damaged ship. This problem had been pointed out by one of the authors (Umeda, 1994) as a written discussion to the paper by Turan and Vassalos (1994).

Similar phenomena occur in a moored ship in waves, that is, a coupled surge-sway-yaw motion having slowly-varying parts and fast-varying parts. Triantafyllou (1982) formulated a consistent theory by a multiple time scale expansion. His methodology was also used for manoeuvring motion in waves, which is also a coupled surge-sway-yaw motion. (Nonaka,1990) In the current attempt (Umeda, Mizogami et al., 2002), Triantafyllou's method is applied to a coupled sway-heave-roll motion of a damaged ship in waves with the new time scale,

$$\tau = \varepsilon t \qquad (\varepsilon << 1) \tag{1}$$

other than the normal time scale, t. In addition, as shown in Figure 1, the space-fixed co-ordinate system, O-$y_0$,$z_0$, and the body-fixed system, $\overline{\mathrm{O}}$-$\bar{y}, \bar{z}$, are used. Furthermore, the horizontal body-fixed system, O*-y*, z*, is also introduced, and its centre moves with sinkage and drift but it does not heel.

Then, the displacement vector, $\mathbf{r} = \left(\xi_2, \xi_3, \xi_4\right)$, is assumed to be the sum of fast small-amplitude motion and slow large-amplitude motion as follows:

$$\mathbf{r}(t,\varepsilon) = \varepsilon \mathbf{r}_f(t) + \mathbf{r}_s(\varepsilon t) \tag{2}$$

where the suffices *f* and *s* correspond to the fast and slow motions, respectively. As a result, the velocity is calculated as follows:

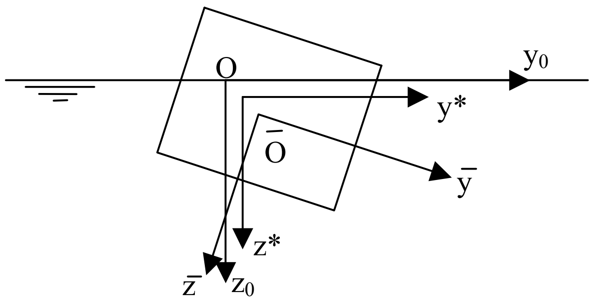


Figure 1 Co-ordinate systems

$$\frac{d\mathbf{r}(t,\varepsilon)}{dt} = \varepsilon \frac{d\mathbf{r}_f(t)}{dt} + \varepsilon \frac{d\mathbf{r}_s(\tau)}{d\tau} \tag{3}$$

In the framework of a conventional wave-making boundary value problem (for example, Kan, 1977), the body surface condition is obtained by

$$\frac{DS}{Dt} = 0 \qquad \text{on } S(y_0, z_0, t) = 0 \tag{4}$$

Here the body surface equation, S, is defined on the body-fixed co-ordinate system as follows:

$$S(\bar{y}, \bar{z}) = \bar{z} - f(\bar{y}) = 0 \tag{5}$$

By using co-ordinate transformations, Equation (5) is converted to one on the space-fixed system and then neglecting higher order terms of ε, the following outcomes are obtained with the fluid velocity potential of Φ.

$$\frac{\partial\Phi_s}{\partial n} = \dot{\xi}_{2s} n_{y*} + \dot{\xi}_{3s} n_{z*} + \dot{\xi}_{4s}(y^* n_{z*} + z^* n_{y*}) \tag{6}$$

$$\frac{\partial\Phi_f}{\partial n} = \dot{\xi}_{2f} n_{y*} + \dot{\xi}_{3f} n_{z*} + \dot{\xi}_{4f}(y^* n_{z*} + z^* n_{y*}) \tag{7}$$

where

$$\Phi = \Phi_s + \varepsilon\Phi_f \tag{8}$$

$$\xi_2 = \xi_{2s} + \varepsilon\xi_{2f} \tag{9}$$

$$\xi_3 = \xi_{3s} + \varepsilon\xi_{3f} \tag{10}$$

$$\xi_4 = \xi_{4s} + \varepsilon\xi_{4f} \tag{11}$$

$$n_{y*} = \frac{\partial y^*}{\partial n}, \quad n_{z*} = \frac{\partial z^*}{\partial n} \tag{12}$$

and **n** indicates the unit vector normal to the hull surface.

By contrast, in the case without slow motion, the following hull surface condition is well established.

$$\frac{\partial\Phi_f}{\partial n} = \dot{\xi}_{2f} n_{\bar{y}} + \dot{\xi}_{3f} n_{\bar{z}} + \dot{\xi}_{4f}(\bar{y} n_{\bar{z}} + \bar{z} n_{\bar{y}}) \tag{13}$$

where

$$n_{\bar{y}} = \frac{\partial\bar{y}}{\partial n}, \quad n_{\bar{z}} = \frac{\partial\bar{z}}{\partial n} \tag{14}.$$

While the conventional theory represents geometrical form of submerged hull surface without any ship motions, the present theory does with slow ship motions but without fast motions.

By considering $\dot{\Phi}_s = O(\varepsilon^2)$, the water surface condition is obtained as follows:

$$\frac{\partial\Phi_s}{\partial z} = 0 \qquad \text{on } z = 0 \tag{15}$$

$$\frac{\partial^2\Phi_f}{\partial t^2} + g\frac{\partial\Phi_f}{\partial z} = 0 \qquad \text{on } z = 0 \tag{16}.$$

The above theoretical outcomes indicate that 1) the water surface condition for the slow motion tends to a rigid wall one; 2) the body surface condition for the fast motion is provided around the slow motion displacements as mean positions. Therefore, the new boundary value problem for a damaged ship can be solved with a conventional manner but with instantaneous sinkage and heel taken into account. This coincides with the procedure by Vassalos and Letizia (1998) in principle. Although the above formulation is obtained for a 2D case, the conclusion can be applicable also to a 3D case.

## 2.2 NUMERICAL RESULTS

Based on the above theoretical conclusions, numerical simulation of coupled sway-heave-roll motion of a damaged ship in irregular waves were conducted. Here the slowly-varying motions, e.g. heel and sinkage are obtained by numerical filter and then all radiation and diffraction coefficients of the fast motion are calculated with a ship with instantaneous heel and sinkage at every step of time. Other than this part, the simulation model used here is similar to the pioneering model by Turan and Vassalos (1993). (Umeda, Mizogami et al., 2002)

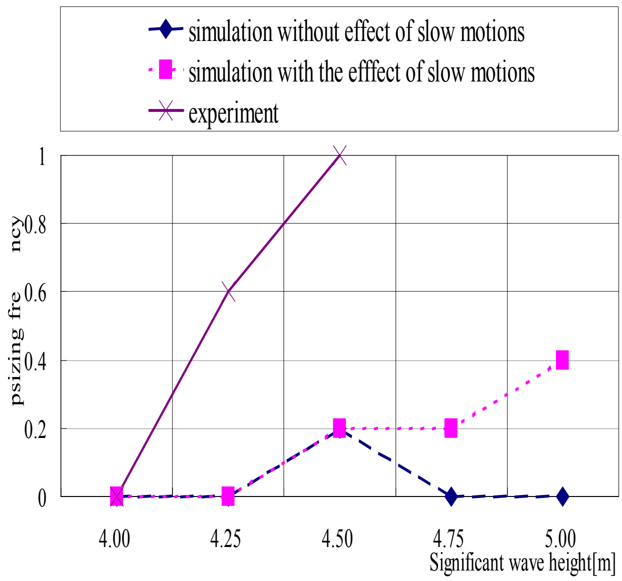


Figure 2 Capsizing boundaries at the damaged condition with and without effect of slow motions on hydrodynamic coefficients

Folowing the ITTC benchmark procedure, the survival tests were simulated and compared with the experiments as shown in Figure 2. Both the simulations with effect of slow motions on hydrodynamic coefficients of fast motions and that without it were performed. The simulations slightly overestimated the critical wave height of 4.00 metres in the experiment. The capsizing frequency calculated with the model with the effect of slow motions on the hydrodynamic coefficients increases with the wave height, while that without it dose not. No capsizing at higher wave heights in the simulation without the effect of slow motions on the hydrodynamic coefficients appears as a result of the transition from a weather side heel to a lee side heel. Once a ship heels towards the lee side, the damage opening is exposed and further water ingress terminates. Thus this comparison suggests the effect of slow motions on the hydrodynamic coefficients results in more realistic outcomes. The discrepancy between the experiment and the simulation seems to require further improvement of other elements, such as coupling effect of trim.

## 3. ANTI-ROLLING EFECT OF FLOODED COMPARTMENTS

Some discrepancy in RAO of roll between the model experiment and numerical simulation even using the roll decay test result exists, as shown in Figure 3. Since the calculation limiting water velocity on the RoRo deck is not improved very much, the main reason is presumed to be due to dynamic behaviour of flooded compartments under the RoRo deck. However, a question why the use of roll decay test cannot exclude this effect still remains.

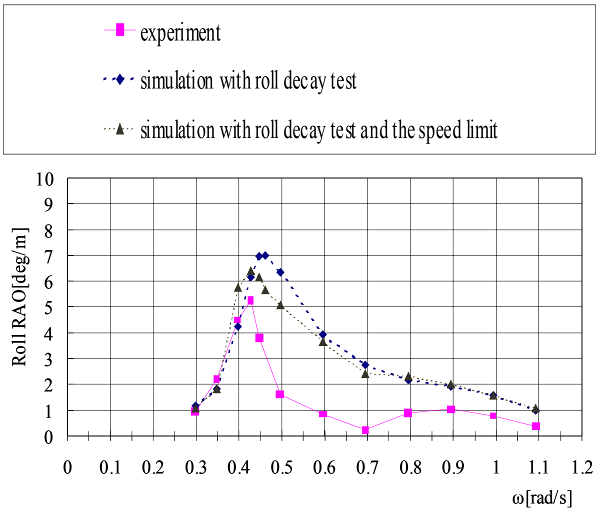


Figure 3 Roll RAO of the damaged ITTC RoRo Ship

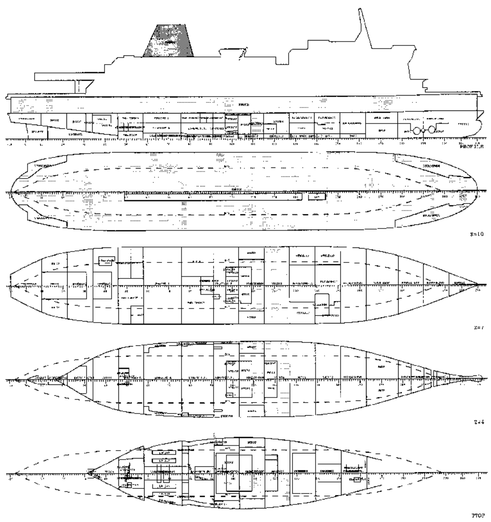

Figure 4 General arrangement of the ITTC RoRo ship where shaded areas are flooded.

As you see in Figure 4, the shapes of the flooded compartments are similar to those of flume-type anti-rolling tanks. By using Barr's formula, the natural frequencies of the flooded compartments are from 0.5 to 0.6 rad/s, and is larger than the natural roll frequency of a ship model. Since this coincides with the region where discrepancy between the experiment and the simulation, it can be understood that the flooded compartments act as anti-rolling tanks.

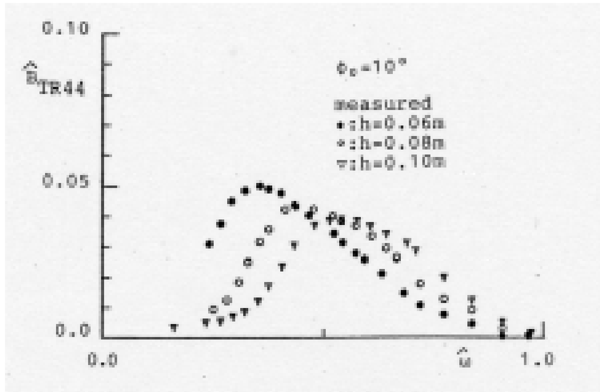


Figure 5 Roll damping coefficient obtained by forced roll test of an ART model. 'h' in the figure denotes depth of water in ART.

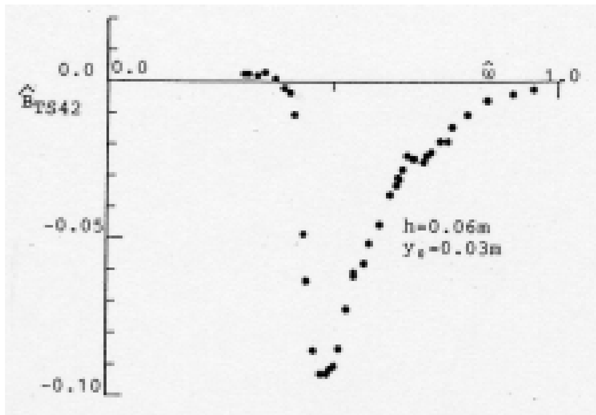


Figure 6 Coupling damping coefficient from sway to roll obtained forced sway test of an ART model. '$y_0$' in the figure denotes sway amplitude.

One of the authors (Ikeda and Yoshiyama, 1991) experimentally investigated the effect of flume-type anti-rolling tanks with coupling effect from sway taken into account. Examples of the experimental results are shown in Figures 5 and 6. Figure 5 shows the roll damping created by the tank model of 0.58m wide and 0.216m long, which is forced to make a pure roll motion. Figure 6 shows the coupling roll damping moment created by sway motion. These results demonstrate the anti-rolling effect by a flume-type anti-rolling tank depends on motion frequency very much. Thus, the anti-rolling effect at the natural frequency range of the flooded compartment can be different from that at the natural frequency of ship roll, which can be obtained from a roll decay test of a ship model. Appropriate roll damping at each frequency should be used.

## 4. EFFECTS OF TRANSIENT MOTIONS

### 4.1 INCREASE OF SURVIVAL PROBABILITY OF PCC BY TRANSIENT EFFECT IN CALM WATER

In a static assumption for flooding into a symmetry compartment, the ship is considered to sink gradually in keeping an upright condition. The experimental studies on flooding in calm water for a pure car carrier (PCC) by some of the authors (Ikeda & Kamo, 2001, Kamo & Ikeda, 2002), however, demonstrated that this is not always true because of the effects of transient motions in intermediate stages of flooding on the final stage, and the results suggested that real survival probability is much larger than that calculated in a static assumption. The arrangement of the PCC model used in the experimental studies is shown in Figures 7 and 8.

The cause of this outcomes mentioned above can be explained as follows. In the intermediate stages, the ship heels due to decrease of stability by shallow water on deck at earlier stage. As the heeling moment created by the water increases with number of decks, a ship like a PCC with multiple decks has large heel angle. Then, the bottom end of the damaged opening comes up above water surface due to large heel angle, and flooding stops. Although the watertight loading deck of the horizontal compartment of the PCC, which is shown in Figures 7 and 8, would be immersed in the static assumption, such results rarely appears in the experiments. The heel angle in the final stage depends on initial GM, the depth of the lowest end of the damage opening, number of decks in the damaged compartment, and area, breadth and height of each deck.

It should be noted that similar characteristic might be seen for a large passenger ships, too. A large passenger ship has more complex deck arrangement in a compartment than a PCC, and the complexity may affect the transient motions in intermediate stages and its survival probability. Furthermore, for a passenger ship, the large heel in intermediate stages of flooding as well as survival probability at final stage must be a critical issue to guarantee the safety of small, old and handicapped passengers. The authors believe that more detailed experimental and theoretical studies are necessary to obtain the full understanding of the survivability of a ship with complex multiple-deck arrangement in a compartment.

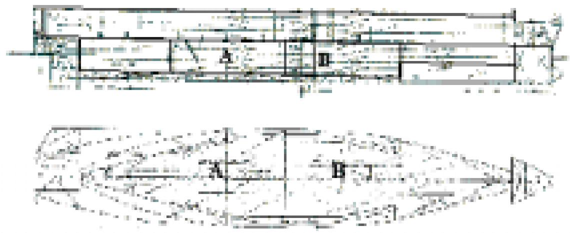


Figure 7 General arrangement of a PCC model used for experiments

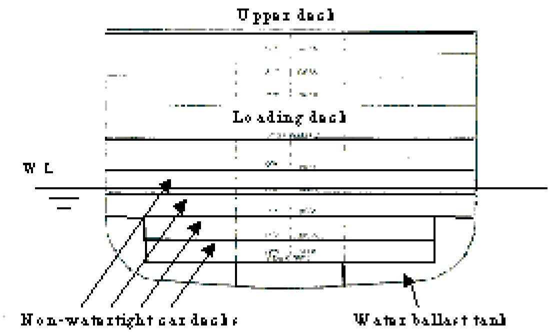


Figure 8 Mid-ship section of the PCC model

### 4.2 EFFECTS OF INCIDENT WAVES

Measurements of ship motions of a damaged and flooded PCC model in regular waves were carried out to reveal the effects of waves and ship motions on progressive flooding into a damaged compartment through a damaged opening which is located above still water level. The length and beam of the model is 1.5m and 0.268m, respectively. GM value is 0.014m in intact condition. The model is flooded and heeled by about 8 degree in calm water first, and then regular beam waves with 0.018-0.02m of wave-height and 0.92-2.25seconds of wave-period hit it. Total experimental number is twelve. For these twelve cases changing wave conditions, roll and heave motions are measured. Measurements continue until end of flooding.

Among the twelve cases, no additional flooding occurs in eights cases even in incident waves. Only in four cases, the attitudes of the model change to other attitudes due to additional flooding in waves. Time histories of roll and heave motions of these four cases are shown in Figures 9-12. The results shown in Figure 9 show that the model heels at 10 degrees and rolls in amplitude of 2 degrees in the beginning. The time history of heave motion shows that the mean line of the motion, which means average sinkage, decreases gradually. This is because that flooding through the damage opening by waves progresses very slowly. At 220 seconds of time, both motions suddenly change. At the time, the ship moves to upright condition for a moment, and rapidly sinks. After then, flooding stops, and steady heel angle changes from about 10 degrees to about 5 degrees. It is observed that when the ship moves to upright condition, trapped air near ceiling of the damaged compartment is released, and water rushes into the compartment through the damaged opening. Similar tendency can be seen in the result shown in Figure 10. In longer waves, heel angle changes to larger angle of about 13 degrees as shown in Figures 11 and 12. The present experimental results demonstrate that in about 33% of cases additional flooding occurs due to waves and the final state in calm water changes to other state.

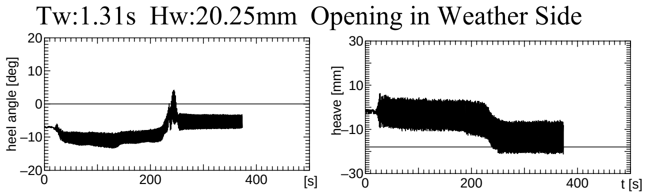


Figure 9 Measured motions of a flooded PCC in regular waves

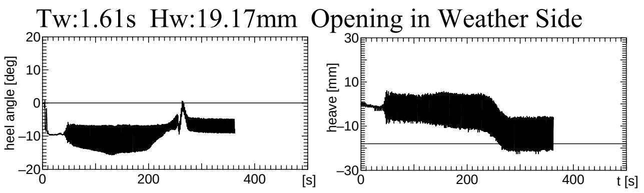


Figure 10 Measured motions of a flooded PCC in regular waves

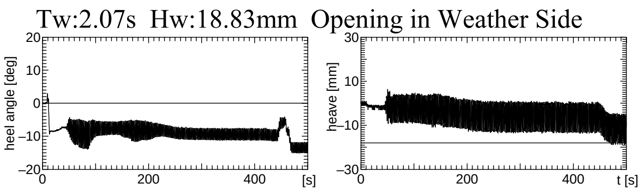


Figure 11 Measured motions of a flooded PCC in regular waves

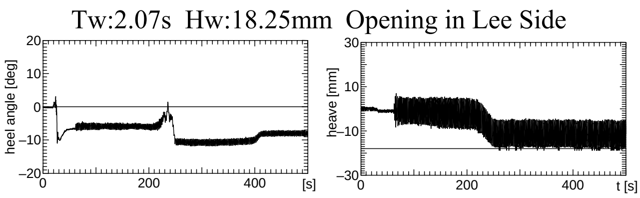


Figure 12 Measured motions of a flooded PCC in regular waves

## 5. CONCLUSIONS

The following conclusions are based on the results obtained from described researches for RoRo vessels and PCCs.

1) By using multiple time scale expansions, the method for taking the interaction between slow and fast motion into account is presented for a damaged ship in waves.

2) Flooded compartments having obstacles inside could have anti-rolling effect as a flume-type tank, which depends on motion frequency.

3) Final states of a damaged ship with multiple-decks in a compartment both in calm water and waves could depend on transient behaviours in intermediate stages of flooding.

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