RECENT RESEARCH PROGRESS ON INTACT STABILITY IN FOLLOWING / QUARTERING SEAS

Naoya UMEDA[*1] and Andrew PETERS[*2]
*1 Osaka University, 2-1 Yamadaoka, Suita, Osaka, 565-0871, Japan.
e-mail: umeda@naoe.eng.osaka-u.ac.jp
*2 QinetiQ, Haslar, Gosport, Hampshire, PO12 2AG, United Kingdom
e-mail: AJPETERS@QinetiQ.com

SUMMARY

This paper explains the current research directions on intact stability in following and quartering seas. An overview of recent research progress including theoretical modelling, non-linear dynamics and model experiments is made, including an examination of factors affecting quantitative accuracy of numerical models. The two invited discussion papers are then introduced.

1. INTRODUCTION

Recent model experiments (for example, Umeda et al. 1999) demonstrates that a ship complying with the current Intact Stability Code (IS Code) of International Maritime Organisation (IMO) rarely capsizes in non-breaking beam waves but could occasionally capsize when she runs in following and quartering seas. Non-linear dynamics applied to such observed results successfully but qualitatively explains surf-riding, broaching and parametric resonance as global or local bifurcations. This July at IMO, the Sub-committee on stability, load lines and fishing vessel safety has started to review the IS Code with introduction of direct assessment by physical or numerical tests. At this stage numerical models are required to provide not only qualitative agreement but also quantitative one with model experiments. For this purpose, the International Towing Tank Conference (ITTC) conducted benchmark testing of several numerical models by utilising capsizing model experiments in following and quartering seas, which cover parametric rolling and broaching. As a result, it was confirmed that only a few numerical models could qualitatively predict capsizing and none could do it quantitatively. (Umeda & Renilson, 2001, Vassalos et al., 2002) Therefore, it is time to upgrade our numerical modelling techniques to quantitatively predict capsizing in following and quartering seas. For this specified target, it is necessary to systematically examine all factors relevant to capsizes in following and quartering seas further. This is the reason why we planned to have a discussion session at this workshop following the previous one in Trieste.

2. QUALITATIVE ASPECTS OF CAPSIZING

Capsizing model experiments (Umeda & Hamamoto, 2000) identified the following four capsizing modes of a ship model complying with the IS code with measured time series as well as videos.

2.1 PARAMETRIC ROLL RESONANCE

The righting arm of a ship in longitudinal waves can vary with time sometimes drastically, although linear theory requires us to ignore it as one of the higher order terms. As a result, if the encounter period is a multiple of half of the roll period, the roll motion develops with a period equal to the natural roll period. This is commonly known as the parametric roll resonance. The regime of parametric resonance in which the encounter period is half of the natural roll period is often called low cycle resonance or principal resonance; it is the most significant regime and may easily lead to capsize.

In the experiment of a container ship model (Ship A-1) complying with IS code, the model capsized due to low cycle resonance. This data (Hamamoto et al., 1996) was used for the benchmark testing of the ITTC. Such capsizes occur with relatively small metacentric heights (GM) in model runs with low Froude number in following seas. Due to the limitation of the IS code, this danger occurs mainly for ships with a small GM and high free board. In this case the encounter period is so long that the pitch and heave motion can be regarded as static. When the heading angle increases, this danger decreases.

Experimental evidence also exists (for example, Umeda et al. 2002) of parametric roll motion in head and beam seas. In this case low cycle resonance requires a larger GM and does not easily lead to capsize. In addition, when the natural pitch period is half as the natural roll period and equal to the encounter wave period, this phenomenon in head seas can be significant. Here the coupling between roll and pitch is essential (Oh et al., 2000) , unlike the phenomenon in following seas.

2.2 BROACHING

Broaching is a phenomenon in which a ship cannot maintain a constant course despite the maximum steering effort of her helmsman. This phenomenon could be realised in full or model scale when she runs in following and quartering seas with relatively high speed. The data from the experiment of a purse seiner model (Ship A-2) complying with the IS code, was used for the benchmark testing of the ITTC. (Umeda et al., 1999) The model was accelerated by the approaching wave and then captured on the down slope of the wave face. This is known as surf-riding. Whilst the ship is captured on the down slope of the wave the ship is directionally unstable due to negative stiffness in yaw. Despite the maximum rudder application due to an auto pilot, the ship course deviates from the desired one. Such uncontrollable yaw angular velocity together with sway velocity resulted in capsizing. While a ship in waves normally experiences a periodic motion, broaching is a transition from a stable periodic motion to a non-periodic motion. This transition can be explained as hetero- or homoclinic bifurcation by executing invariant manifold analysis of an unstable surf-riding equilibrium as a saddle. (Umeda, 1999) The trajectories connecting two saddles in different wave slopes, which appears only at heteroclinic bifurcation point, looks like a periodic orbit but has a period of infinity because the velocity on a saddle in eigen direction asymptotically tends to zero. Thus this trajectories can be regarded as a limit of periodic orbits and under the control parameter beyond this point no periodic orbit exist. This is the reason why the heteroclinic bifurcation represents the transition between periodic and non-periodic responses.

At IMO, the Guidance to the master for avoiding dangerous situations in following and quartering seas, MSC / Circ. 707, was adopted in 1995, in which critical nominal Froude number for avoiding surf-riding, e.g. 0.3, was determined with results calculated from heteroclinic bifurcation of surf-riding in stern seas using a wave steepness of 1/10 for various hull forms. Recently Spyrou (2001) obtained an analytical formula of critical wave force amplitude for surf-riding as a heteroclinic bifurcation.

Another type of broaching was investigated by Spyrou (1997), and is predicted to occur at slower speed without surf-riding. Here a ship suffers a transition from a small-amplitude periodic yaw motion to a large-amplitude periodic yaw motion as a cyclic –fold bifurcation. This phenomenon has not yet been reported in experimental observations.

2.3 LOSS OF TRANSVERSE STABILITY ON A WAVE CREST

If the nominal speed of the ship is lower than the critical speed of surf-riding, the ship experiences a periodic motion. The vessel spends a longer duration on the wave crest than in the wave trough due to the non-linear nature of periodic surging motion with potential surf-riding equilibria. During the duration on a wave crest the righting arm of a ship could decrease significantly. In the case of pure following seas, e.g. heading angle of zero degrees, a ship could capsize simply due to loss of static balance by such a reduction of transverse stability. This phenomenon is known as pure loss of stability. Some numerical studies with use of an analytical solution of non-linear surging was reported by Spyrou (2000). Typical experimental observation can be found in Matsuda et. al. (2001).

If the heading angle is changed to stern quartering seas, the ship suffers both reduction of the restoring arm on a wave crest and the wave exciting roll moment. Here dynamically coupled sway-yaw-roll motion becomes significant and then can finally cause a capsize on a wave crest. This cannot be named as ‘pure loss’ because of a significant dynamic motion before capsizing. Experimental observation can be found in Umeda and Hamamoto (2000). Sometimes this dynamic roll motion can be subharmonic due to a flip bifurcation. (Kan, 1994) This is different to parametric roll resonance because its motion period is far from the natural roll period.

2.4 BOW-DIVING

Once surf-riding occurs, there are three main possibilities that can occur; stable surf-riding, broaching and bow-diving. Bow diving can occur when the nominal ship speed is very close to wave celerity and her bow height is relatively small. As a larger nominal ship speed means larger propeller thrust, the stable equilibrium point in surge shifts towards the wave upslope, where the bow is likely to submerge. Typical experimental example for a purse seiner model can be found in Umeda and Hamamoto (2000). Recently Matsuda et al. (2002) reported that the possibility of bow-diving observed in the experiments can be reasonably well explained by statically calculating the vertical distance of the bulwark top from the wave surface.

3. FACTORS AFFECTING QUANTITATIVE ACCURACY

The ITTC benchmark testing of numerical models for intact stability was carried out with positive participation of several major research organisations. (Vassalos et al., 2002) The main conclusion of this work is that only a few organisations qualitatively predicted extreme motions and capsizing but none could do it quantitatively.

Therefore, it is necessary to improve our models further. Since the numerical models take many factors taken into account, it is desirable to examine effects of several factors affecting quantitative accuracy one by one.

The numerical model providing the best agreement among them for Ship A-1 is based on the following modelling procedures:

- 6 degrees of freedom model based on a body fixed coordinate system.
- radiation and diffraction are estimated by a linear strip theory.
- hydrodynamic memory effect is ignored.
- wave effect on the restoring arm is estimated within the Froude-Krylov assumption.
- manoeuvring coefficients are obtained from the circular motion tests in calm water
- roll damping are obtained from the roll decay tests without forward velocity with Takahashi's empirical correction formula for forward speed effect.
- resistance and propulsion coefficients are obtained from conventional propulsion tests.

The numerical model providing the best agreement among them for Ship A-2 is based on the following modelling procedures:

- 4 degrees of freedom model based on a horizontal body fixed coordinate system.
- hydrodynamic lift due to wave fluid velocity is estimated by a slender body theory with low frequency assumption.
- linear Froude-Krylov forces are calculated.
- wave-making radiation and diffraction are ignored.
- hydrodynamic memory effect is ignored.
- wave effect on the restoring arm is ignored.
- linear manoeuvring coefficients are obtained from the circular motion tests in calm water
- linear roll damping are obtained from the roll decay tests without forward velocity with Takahashi's empirical correction formula for forward speed effect.
- resistance and propulsion coefficients are obtained from conventional propulsion tests.

Here the authors examine several factors with recent studies in this direction.

3.1 DEGREES OF FREEDOM (6 DOF VS. 4 DOF OR 1 DOF)

Motions of a rigid body have 6 degrees of freedom (DOF). However, if constraints exist, the degrees of freedom are reduced with the number of the constraints.

For Ship A-1, Munif (2000) conducted a systematic comparative study in prediction of the capsizing boundaries with a 1 DOF model, a 4 DOF model ignoring heave and pitch motions (4 DOF A model), a 4 DOF model with static equilibria of heave and pitch motions (4 DOF B model) and a 6 DOF model. Here the first three models were obtained by simplifying the 6 DOF model. As a result, the following conclusions were drawn:

- The 1 DOF model overestimates capsizing danger.
- The difference between the 4 DOF A model and the 6 DOF model can be significant.
- The results from the 4 DOF B model are in reasonable agreement with those from the 6 DOF model and the experiment. The small difference between the 4 DOF B model and the 6 DOF model derives from the fact that the natural frequency of heave and pitch motions is far from the encounter frequency with the ship running in following and quartering seas (Matsuda, et al., 1997). This indicates that static equilibria of heave and pitch can be regarded as two constraints.

Of course, if a 6 DOF model can accurately estimate these constraints, the 6 DOF model shall reproduce the results from the 4 DOF model. However, in the case of broaching where the encounter frequency is very low, the existing modelling of coupling between vertical motions and manoeuvring motions is not so accurate. This might be the reason why only 4 DOF model can provide reasonable results. After the ITTC benchmark testing, Ayaz et al. (2002) attempts to solve this problem with their new 6 DOF modelling.

3.2 HYDRODYNAMIC MEMORY EFFECT

It is well known that the linear transient motions of a ship with frequency-dependent hydrodynamic forces can be calculated using the convolution integral for hydrodynamic memory effect. However, for capsizing prediction, an extreme motion leading to capsizing is definitely non-linear. In addition, the hydrodynamic forces acting on a ship running in following and quartering seas do not depend largely on the encounter frequency. Thus, further discussion is required.

Hamamoto and Saito (1992) carried out a comparative study for a container ship in following seas with and without the memory effect on heave and pitch motions. They concluded that no significant difference exists if the added mass and damping coefficients are calculated for the natural frequency of heave and pitch motions. Matusiak (2001) investigated this problem and concluded that memory effects can improve agreement with experiments for Ship A-1. However, it is noteworthy that calculation with memory effects should be carried out from the start of the waves. Thus the ITTC benchmark testing, which does not specify the initial conditions of fluid motions, is not appropriate for this purpose. Model experiment data specially designed for this purpose is expected in the near future. Recently Ayaz et al. (2002)

attempted such an experimental effort with a numerical study.

3.3 MANOEUVRING COEFFICIENTS

In following and quartering waves, prediction of manoeuvring coefficients is important because the hydrodynamic lift is a dominant factor. The first question is whether the effect of non-linear terms of manoeuvring forces on capsizing prediction is important or not. For Ship A-2, Umeda et al. (2002) produced time domain simulations with and without these non-linear terms and concluded that the effect of non-linear terms is negligibly small. This is because the sway velocity and yaw angular velocity non-dimensionalised with the higher forward velocity are not large even during the process of broaching.

The wave effect also causes issues in relation to the linear manoeuvring coefficients. This problem has been discussed for many years but its effect on capsizing prediction has not yet been fully investigated. Hashimoto and Umeda (2001) tackled this problem with Ship A-2. Their main conclusion is that the effect of waves on the derivatives of hull manoeuvring forces can be important with respect to sway velocity but they are not so significant with respect to yaw angular velocity. Hashimoto et al. (2002) are further investigating this problem to cover the derivatives of manoeuvring forces with respect of rudder angle also together with their new captive model tests of Ship A-2.

3.4 RADIATION AND DIFFRACTION

In following and quartering seas, the encounter frequency of a ship is generally low and hence the wave-making effect is not so significant. In this respect, it is difficult to predict pitch and heave motions near zero encounter frequency because of divergence of the 2D added mass. Matsuda et al. (1997) solved the problem by calculating the limit of the solution set of strip theory for the zero encounter frequency and confirmed that the new method explains the experimental results. In the case of a 3D theory at very low encounter frequency, it is essential to use the Green function both forward speed effect and frequency effect taken into account. This is because the wave related to frequency, the k_2 wave, disappears at the zero encounter frequency and only the wave related to forward speed, the k_1 wave, remains.

3.5 HYDRODYNAMIC LIFT DUE TO WAVE FLUID VELOCITY

The very small effect of the wave-making does not mean that there is small effect from the incident waves. Since a ship behaves like a lifting surface with a time-varying angle of attack due to wave fluid velocity and ship forward velocity. Within the assumption of small wave steepness, this hydrodynamic lift can be calculated as an end term of slender body theory or strip theory, which represents trailing vortices as a line doublet shed from the aft end (Umeda, 1988). For a 3D theory, it is necessary to include free vortex layers shed from the hull surface. Comparison between calculations with and without the hydrodynamic lift due to wave fluid velocity for Ship A-2 can be found in Umeda (2000). The results indicate that prediction of broaching is largely affected by this term.

3.6 ROLL DAMPING MOMENT

Roll damping moment consists of wave-making, eddy-making, lift and friction components, with the main non-linearity deriving from the eddy-making component. However, as the experimental work of Ikeda et al. (1988) showed, roll damping can be regarded as linear when the Froude number is greater than 0.2. Since eddies are shed away at high speed, the eddy-making component disappears. In addition, the wave-making component is not significant because of the low encounter frequency and the friction component is generally small. Therefore, roll damping relating to this benchmark testing scheme consists of mainly the lift component, which is linear and depends on forward velocity. A comparison of predictions of broaching boundaries using different empirical methods of calculating the lift component was presented by Umeda (2000) for the Ship A-2, and indicates that the predicted results depend on the selection of empirical methods.

3.7 WAVE EFFECT ON ROLL RESTORING MOMENT

Although wave effects on the restoring arm is well known, only numerical models ignoring this effect could provide reasonable agreements for Ship A-2. This situation requires further investigation. Hashimoto et al. (2002) attempt to solve this problem with their new captive model experiments for Ship A-2.

3.8 NON-LINEAR WAVE FORCES

At the workshop in Trieste discussion was raised on the effects of non-linear wave forces including wave-induced stationary forces. Umeda et al. (1995) experimentally confirmed that effects of wave nonlinearity on amplitudes and phases of wave forces are very small by their systematic model experiments for a trawler in quartering waves. In addition, Takagi’s theoretical calculation (1991) shows that the wave-induced stationary forces in following and quartering waves under relevant conditions are negligibly small. However, Hashimoto et al. (2002) examined these effects again with their captive model experiments for Ship A-2.

3.9 ROLL-SWAY / YAW COUPLING IN MANOEUVRING FORCES

When a ship runs in calm water with a constant heel angle, sway force, yaw moment and roll moment act on the hull in addition to conventional manoeuvring forces and moments. In the ITTC benchmarking scheme, data from the captive tests for Ship A-2 at NRIFE was provided. However, such data is not always available and reliable empirical or theoretical methods have not yet been established. Renilson and Manwarring (2000) reported a comparison in predictions of broaching boundary with and without the roll-yaw coupling for a trawler. The results indicated that the prediction without the roll-yaw coupling can underestimate the danger of broaching. Recently Hashimoto et al. (2002) is attempting to identify the effect of manoeuvring sway / roll coupling on capsizing boundaries of Ship A-2.

3.10 RESISTANCE AND PROPULSION

It is well accepted that predictions of hull resistance and propulsive performance have been the most crucial issue at ITTC. This is also the case in the prediction of capsizing of intact ships. This is because surf-riding, which can trigger off broaching and then capsizing, depends on hull resistance and propeller thrust in addition to wave-induced surge force. In the benchmarking study, data from calm-water model tests were provided in advance. However, since such data are not always available, an accurate prediction method is still desirable.

3.11 WAVE IRREGULARITY AND SHORT-CRESTEDNESS

The applicability of numerical models to realistic seaways, that is, short-crested irregular waves, should be examined in the future. Although capsizing model experiments for Ships A-1 and A-2 were carried out in both long-crested and short-crested irregular waves (Umeda et al., 1995), the benchmark testing programme deals with only the case of regular waves. The experimental results indicate that capsizing danger is lower in short-crested irregular waves than long-crested waves which is also lower than regular waves. However, numerical simulations in time domain for capsizing in short-crested irregular waves are very limited. Only recently Sera and Umeda (2001) published numerical calculation results in both short-crested and long-crested irregular waves with a 1 DOF model, and confirmed the qualitative conclusion, from the experiments, that wave short-crestedness reduces capsizing danger. Ayaz et al. (2002) also discuss the applicability of his model with hydrodynamic memory effect together with their free running model experiments in long-crested irregular waves with both ITTC and JONSWAP spectra.

4. CONCLUDING REMARKS

After considering the above progress in this area following the ITTC benchmark testing, the session organisers have invited two speakers, e.g. Messrs Ayaz and Hashimoto to this session. In order to stimulate further discussion among participants of this workshop they will present their current finding from their research in this subject.

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