Benchmark Testing of Numerical Prediction on Capsizing of Intact Ships in Following and Quartering Seas

Naoya UMEDA, Department of Naval Architecture and Ocean Engineering, Osaka University,
2-1 Yamadaoka, Suita, Osaka, 565-0871, Japan
umeda@naoe.eng.osaka-u.ac.jp
Martin R RENILSON, Australian Maritime College,
Now at: QinetiQ Haslar, Gosport, Hampshire, PO12 2AG, United Kingdom
MRRenilson@QinetiQ.com

SUMMARY

This paper describes results of the ITTC benchmark testing of intact stability. For these tests, a container ship and a fishing vessel were selected and their hull forms, captive test data and results of capsizing model experiments were provided in advance. Then eight research organisations submitted their own numerical results. By comparing with the experimental results, it was found that some numerical models are able to qualitatively well predict extreme motions, which include capsizing due to parametric resonance and due to broaching. Moreover, the importance of several elements for capsize prediction is noted by mutual comparisons of numerical studies.

1. INTRODUCTION

Responding the reduction of acceptable risk level for safety of lives at sea, performance-based criteria, which may require model experiments to guarantee the safety, are often under discussion at the International Maritime Organisation (IMO) instead of rule-based criteria. For the performance-based criterion, numerical prediction is required before expensive model experiments. However, a standard numerical prediction technique for capsizing has not yet been established. Therefore, in 1999 the International Towing Tank Conference (ITTC)[1] organised a specialist committee for this purpose and planned benchmark testing of numerical predictions with selected data from free running model experiments. For intact stability eight organisations took part in this benchmark testing. This paper summarises the results of these benchmark tests and examines the importance of several elements for numerical prediction of capsizing.

2. FRAMEWORK OF ITTC BENCHMARK TESTING

In the intact benchmark testing programme, two sets of free running model experiments were utilised. The first set was carried out with a 1/60 scaled model of a 15000 gross tonnes container ship (Ship A-1) at the seakeeping and manoeuvring basin of the Ship Research Institute by Hamamoto et al.[2] Here the ship model capsized mainly due to parametric resonance in the lower speed region. The second set was carried out with a 1/15 scaled model of a 135 gross tonnes purse seiner (Ship A-2) at the seakeeping and manoeuvring basin of the National Research Institute of Fisheries Engineering (NRIFE) by Umeda et al.[3] Here the model capsized mainly due to broaching in the higher speed region. The principal particulars and body plans of these ships are shown in Table 1 and Figs 1-2. In the experiment each ship model was steered on a specified course using auto pilot in regular following and quartering waves. They were self-propelled and completely free from any restraints. The angular velocities and angles were measured using an optical gyroscope, and were recorded by an onboard computer. The reference system used in this paper is shown in Fig. 3.

Among the several hundreds of model runs, four runs for each ship were selected for the ITTC benchmark tests as shown in Tables 2-3. Here the nominal Froude number, Fn, and the auto pilot course from the wave direction, χ_c, are control parameters and the wave height, H, and wave length, λ, are the wave parameters. The initial values of ship motions were specified based on measured data except for the sway velocity, which was assumed to be zero because of the limitation of the measurements.

For ships A-1 and A-2, the captive model experiments, e.g. resistance test, self-propulsion test, propeller open test, circular motion tests (CMT), roll decay test and so on, were carried out mainly in NRIFE's seakeeping and manoeuvring basin using an X-Y towing carriage. These data together with hull offset data and the above-mentioned initial values were provided in advance for the participating organisations.

3. RESULTS

The ITTC benchmark test programme for intact stability commenced in March of 2000 and the following organisations submitted their own numerical results by the deadline, March of 2001. For Ship A-1: Flensburger Schiffbau Gesellschaft (attn. Ms. Heike Cramer); Helsinki University of Technology (attn. Prof. J. Matusiak); Maritime Research Institute Netherlands, (attn. Dr. J. O. de Kat); Osaka University (attn. Dr. N. Umeda); Technology University of Malaysia (attn. Dr. A. Maimun); University of Strathclyde (attn. Prof. D. Vassalos) and University of Tokyo (attn. Prof. M. Fujino) participated. For Ship A-2: Memorial University of Newfoundland (attn. Prof. D. Bass); Osaka University (attn. Dr. N. Umeda) and University of Strathclyde (attn. Prof. D. Vassalos) did. Numerical prediction methods used by the above organisations were summarised in the Appendix and numerical results were shown in Figs. 4-6 with the experimental results. Based on the agreement with the participating organisations, throughout this benchmark programme the results have been presented anonymously. Thus the code used in this paper is not relevant to the above order of organisation names.

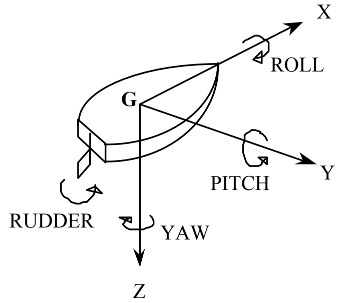


Fig. 3 Reference system.

Table 1 Principal particulars of the ships.

Items	*Ship A-1*	*Ship A-2*
length : L_{pp}	150.0 m	34.5 m
breadth : B	27.2 m	7.60 m
depth : D	13.5 m	3.07 m
draught at FP : T_f	8.5 m	2.50 m
mean draught : T	8.5 m	2.65 m
draught at AP : T_a	8.5 m	2.80 m
block coefficient : C_b	0.667	0.597
pitch radius of gyration : $\square_{yy}/L_{pp}$	0.244	0.302
longitudinal position of centre of gravity from the midship : x_{CG}	1.01 m aft	1.31 m aft
metacentric height : GM	0.15 m	1.00 m
natural roll period : $T_{\square}$	43.3 s	7.4 s
rudder area : A_R	28.11 m^2	3.49 m^2
propeller diameter : D_P	5.04 m	2.60 m
time constant of steering gear : T_E	1.24 s	0.63 s
proportional gain: K_R	1.2	1.0
differential gain: $K_R\ T_D$	53.0 s	0.0 s

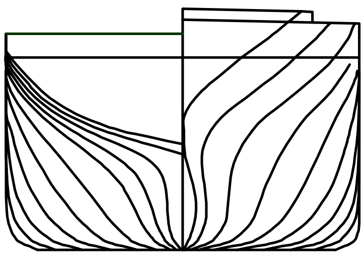


Fig. 1 Body plan of Ship A-1.

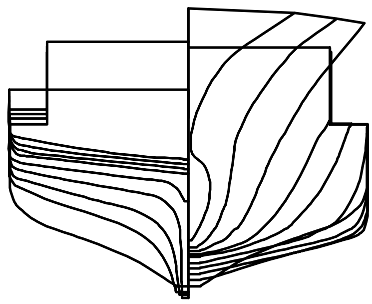


Fig. 2 Body plan of Ship A-2.

The numerical predictions are firstly required to qualitatively agree with the model experiments. Thus, qualitative nature of the results obtained from the experiments and the numerical calculations are overviewed in Tables 4-5. This nature includes capsize, non-capsize, harmonic roll, sub-harmonic roll, surf-riding and broaching. Here as a judging criterion of broaching the authors' proposal[4] is used. That is, broaching is a phenomenon in which both the yaw angle and yaw angular velocity increase despite the maximum opposite rudder angle. The cases where the numerical result does not qualitatively agree with the experimental one are identified with shading.

Table 2 Calculated conditions for Ship A-1.

	H/λ	λ/L_{pp}	Fn	χ_c
(a)	1/25	1.5	0.2	0 degrees
(b)	1/25	1.5	0.2	45 degrees
(c)	1/25	1.5	0.3	30 degrees
(d)	1/25	1.5	0.4	30 degrees

Table 3 Calculated conditions for Ship A-2.

	H/λ	λ/L_{pp}	Fn	χ_c
(a)	1/10	1.637	0.3	-30 degrees
(b)	1/10	1.637	0.43	-10 degrees
(c)	1/8.7	1.127	0.3	-30 degrees
(d)	1/8.7	1.127	0.43	-30 degrees

4. DISCUSSION

For Ship A-1 all the participating organisations used 6 degrees of freedom (DOF) models. However, only Organisation-A submitted results that qualitatively agree with the experiments. Organisation-A calculated radiation and diffraction forces using a strip theory and dealt with manoeuvring forces by the MMG model, utilizing a body coordinate system. It evaluated the Froude-Krylov forces, including roll restoring moment in waves, by integrating incident wave pressure up to the instantaneous water surfaces. With this numerical model, capsizing with sub-harmonic rolling in case (a) and capsizing with harmonic rolling in case (d) were well predicted.

Organisation-G also shows similar agreement but results in capsizing with harmonic rolling in case (a), which was not observed in the corresponding experiment. The method used here is almost the same as Organisation-A except for radiation and diffraction modelling.

Organisation-E has difficulties in the prediction of the heading angle. In some cases the ship course is changed to bow sea and then a completely different situation occurs. This model is different from the above two organisations in some elements. The radiation forces were calculated using a 3D Green function method with hydrodynamic memory effect. The manoeuvring forces, roll damping moments, resistance and propulsion forces were estimated with databases instead of the captive test data provided.

Table 4 Overview of qualitative results for Ship A-1*.

	exp.	*A.*	*B*	*C*
(a)	cap. (s)	cap. (s)	cap. (h)	no roll
(b)	(s)	(s)	(s)	N/A
(c)	(h)	(h)	N/A	N/A
(d)	cap. (h)	cap. (h)	N/A	N/A

	D.	*E.*	*F*	*G*
(a)	(s)	cap. (s)	cap. (h)	cap. (h)
(b)	cap.(h)	(h)	(h)	(s)
(c)	(h)	cap.	cap.	(h)
(d)	(h)	cap.	cap.	cap. (h)

*Here (h) and (s) mean harmonic and sub-harmonic roll motions, respectively. *cap*. indicates capsizing.

Table 5 Overview of qualitative results for Ship A-2*.

	exp.	*A.*	*B*	*C*
(a)	non-cap	non-cap	non-cap	non-cap
(b)	surf,broach, cap.	surf,broach, cap.	cap.	cap
(c)	non-cap	non-cap	non-cap	non-cap
(d)	cap.	cap.	cap.	cap.

*Here surf and broach mean surf-riding and broaching, respectively.

The method used by Organisation-B is based on a conventional seakeeping approach. That is, the heave, pitch, sway and yaw are assumed to be linear around the averaged course. This organisation reported that this method is not able to calculate the ship runs with a Froude number of 0.3 and over. Organisation-D proposed a method to avoid such the limitation of the seakeeping model by a two-stage approach. Here the motions are assumed to be the sum of linear parts with hydrodynamic memory effect and nonlinear ones. This means that the linear motion was calculated around the instantaneous heading angle instead of the auto pilot course. The agreement between the experiment and this calculation is not so satisfactory. This may be partly because the initial values were different from the specified ones to take the memory effect into account. Organisation-F is a unique example ignoring diffraction forces but the results do not agree well with those from the experiment. In particular, the calculated pitch amplitude is much larger than the measured one.

CFD application to the present problem was attempted by Organisation-C, which had succeeded in several seakeeping predictions. Here the Euer equation was solved by a finite difference method with fully nonlinear free surface and body surface conditions. However, it can provide a solution only for case (a) without lateral motions. If the specified initial values for lateral motions are input, even for case (a) the calculation process failed. In addition, it cannot deal with cases (b), (c) and (d), in which the desired heading angles are not zero. This fact demonstrates that the CFD approach is not yet appropriate for practical use in capsize prediction.

For Ship A-2, only Organisation-A obtained qualitative agreement with the experiment. Here a 4 DOF model was used by assuming that heave and pitch motions trace their static equilibria, which are calculated as the limit of solution sets of a strip theory at zero encounter frequency. The manoeuvring forces were estimated with the MMG model and the wave-induced forces, including hydrodynamic lift due to wave fluid velocity, were calculated with Ohkusu's slender body theory. The wave effects of both the roll restoring moment and the manoeuvring forces were ignored as higher order terms. As a result, this organisation succeeded in predicting capsizing due to broaching associated with surf-riding as well as periodic motions.

Organisation-C used the method that is almost similar to Organisation-A but the nonlinear terms in the manoeuvring models, those of the Froude-Krylov forces and the radiation forces were added. For case (b) it predicted capsizing without surf-riding and with a smaller rudder angle compared to the results from the experiment and those predicted by Organisation-A.

Organisation-B applies a 6 DOF model in which radiation and diffraction were calculated with the 3D Green function for zero forward velocity. Here the change of roll restoring moment due to waves was taken into account but the hydrodynamic lift due to wave fluid velocity was ignored. The hydrodynamic memory effect was included in this calculation, although the initial values were not exactly equal to the specified one. While the predictions of mean yaw angle for cases (a), (c) and (d) are better than those from the other organisations, the predicted rudder angle for case (b) is smaller than the experimental results.

As a whole, these three organisations predicted the results relatively well compared to the experiments for Ship A-2, however, this does not mean that prediction of broaching is easier, because some organisations did not include their own results.

5. SEVERAL ELEMENTS AFFECTING PREDICTION ACCURACY

As mentioned above, the mathematical models for capsizing prediction cover so many elements and there is no guideline which elements should be taken into account.

Mutual comparisons among the organisations do not easily clarify the importance of each particular element because more than two elements are often different from one organisation to another. Therefore, this paper reviews comparative studies of numerical simulations with and without each particular element for Ships A-1 and A-2.

6 DOF vs. 4 DOF or 1 DOF

Although all organisations submitted results with 6 DOF models for Ship A-1, many theoretical studies with 1 DOF models can be found for capsizing due to parametric rolling. Munif [5] estimated the capsizing boundaries for Ship A-1 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, as shown in Fig. 7. Here the first three models were obtained by simplifying the 6 DOF model. As a result, the following conclusions were made. (1) The 1 DOF model overestimates capsizing danger. (2) The difference between the 4 DOF A model and the 6 DOF model can be significant. (3) The results from the 4 DOF B model almost agree with those from the 6 DOF model and the experiment. The reason for the small difference between the 4 DOF B model and the 6 DOF model is that the natural frequency of heave and pitch motions is far from the encounter frequency in case of ship runs in following and quartering seas.[6]

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, it is not so clear for capsizing prediction whether the hydrodynamic memory effect should be taken into account or not. This is because an extreme motion leading to capsizing is nonlinear and the hydrodynamic forces acting on a ship running in following and quartering seas do not significantly depend on the encounter frequency.

Hamamoto and Saito[7] carried out a comparative study for a container ship in following seas with and without the memory effect in 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. For the present workshop, Matusiak[8] investigated this problem and concluded that the memory effect can improve the agreement with the experiment for Ship A-1. Here it is noteworthy that exact calculation with memory effect should be carried out from the start of the waves. Thus the present benchmark testing, which does not specify the initial conditions of the fluid motions, is not appropriate for this purpose.

Manoeuvring coefficients

In ship runs in following and quartering waves, prediction of manoeuvring coefficients is important because hydrodynamic lift is dominant. The first question here is whether the effect of nonlinear terms of manoeuvring forces on capsizing prediction is important or not. For Ship A-2, Umeda et al.[9] calculated time series with these nonlinear terms and without them and concluded that the effect of nonlinear terms is negligibly small, as shown in Fig.8. 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 next problem is the wave effect on the linear manoeuvring coefficients. This problem has been discussed for many years but its effect on capsizing prediction has not yet been fully investigated. Therefore, Hashimoto and Umeda[10] tackled this problem with Ship A-2 for the present workshop. Their main conclusion is that the effect of the waves on the derivatives of manoeuvring forces with respect to the sway velocity can be important.

Nonlinearity in yaw

In a seakeeping theory, ship motions, such as yaw, are often linearised around the inertia system moving with the averaged speed and course of a ship. On the other hand, ship motions are described with a body fixed coordinate system in the field of manoeuvring. Recently Hamamoto [11] introduced a horizontal body coordinate system, which is body fixed but not allowed to roll. At the present workshop, Cramer [12] reported the effect of linearisation of yaw motion with an inertia coordinate system.

Other elements to be examined can be listed as follows:

- wave effect on roll restoring moment
- hydrodynamic lift due to wave fluid velocity[13]
- 3D effect of hydrodynamic forces
- modelling roll damping moment[13]
- roll-yaw coupling[14]
- coupling effect from heave and pitch motions
- trapped water on deck.

Cramer [12] referred to the applicability of numerical models to short-crested irregular waves. Although the capsizing model experiments for Ship A-1 were carried out in both long-crested and short-crested irregular waves [15], the benchmark testing programme deals with only the case in long-crested regular waves. Recently Sera and Umeda [16] executed numerical calculation in short-crested irregular waves with a 1 DOF model, and confirmed the qualitative conclusion, from the experiments, that wave short-crestedness reduces capsizing danger.

6. CONCLUSIONS

As a result of benchmark testing of intact stability, it was found that some numerical models can qualitatively predict capsizing due to parametric resonance and that due to broaching in the limited cases tested. For improving quantitative prediction accuracy further, it is essential that several elements should be examined by comparative studies with and without these elements. For wider validation studies, it is desirable to execute benchmark tests in capsizing boundary curves as shown in Fig. 7 for Ship A-1.

7. ACKNOWLEDGEMENTS

The authors are grateful to all eight organisations participating this benchmark testing programme and Professor D. Vassalos, the chairman of the ITTC specialist committee on prediction of extreme motions and capsizing. The authors acknowledge effective assistance of Mr. H. Hashimoto, a graduate student of Osaka University. This work was supported by a Grant-in-Aid for Scientific Research of the Ministry of Education, Culture, Sports, Science and Technology of Japan (No. 13555270).

8. REFERENCES

1. The Specialist Committee on Stability (1999) Final Report and Recommendation to the 22nd ITTC, In: Proceeding of the 22nd International Towing Tank Conference, Seoul and Shanghai, 2 : 399-431.
2. Hamamoto, M., T. Enomoto, et al. (1996) Model Experiment of Ship Capsize in Astern Seas -2nd Report-, J Soc Nav Archit Japan, 179 : 77-87.
3. Umeda, N., A. Matsuda et al. (1999) Stability Assessment for Intact Ships in the Light of Model Experiments, J Mar Sci Technol, 4 : 45-57.
4. Umeda, N., A. Matsuda and M. Takagi : (1999) Model Experiment on Anti-Broaching Steering System, J Soc Nav Archit Japan, 185 : 41-48.
5. Munif, A. (2000) Numerical Modeling on Extreme Motions and Capsizing of an Intact Ship in Following and Quartering Seas, Doctor Thesis, Osaka University.
6. Matsuda, A., N. Umeda and S. Suzuki (1997) Vertical Motions of a Ship Running in Following and Quartering Seas, J Kansai Soc Nav Archit, 227 : 47-55, (in Japanese).
7. Hamamoto, M. and K. Saito (1992) Time Domain Analysis of Ship Motions in Following Waves, In : Proceeding of the 11th Australian Fluid Mechanics Conference, Hobart, 1:355-358.
8. Matusiak, J. (2001) Importance of Memory Effect for Capsizing Prediction, In : Proceedings of the 5th International Workshop on Stability and Operational Safety of Ships, Trieste.
9. Umeda, N., A. Munif and H. Hashimoto (2000) Numerical Prediction of Extreme Motions and Capsizing for Intact Ships in Following / Quartering Seas, In : Proceeding of the 4th Osaka Colloquium on Seakeeping Performance of Ships, Osaka, 368-373.
10. Hashimoto, H. and N. Umeda (2001) Importance of Wave Effects on Manoeuvring Coefficients for Capsizing Prediction, In : Proceedings of the 5th International Workshop on Stability and Operational Safety of Ships, Trieste.
11. Hamamoto, M., and Y.S. Kim (1993) A New Coordinate System and the Equations Describing Manoeuvring Motions of a Ship in Waves, J Soc Nav Archit Japan, 173 : 209-220, (in Japanese).
12. Cramer, H. (2001) Effect of Non-Linearity in Yaw Motion on Capsizing Prediction, In: Proceedings of the 5th International Workshop on Stability and Operational Safety of Ships, Trieste.
13. Umeda, N. (2000) Effects of Some Seakeeping/ Manoeuvring Aspects on Broaching in Quartering Seas, In: "Contemporary Ideas on Ship Stability", Elsevier Science Publications (Amsterdam), 423-433.
14. Renilson, M.,R. and T. Manwarring (2000) An Investigation into Roll/Yaw Coupling and Its Effect on Vessel Motions in Following and Quartering Seas, In: Proceedings of the 7th International Conference on Stability of Ships and Ocean Vehicles, Launceston, A:452-459.
15. Umeda, N., M. Hamamoto, Y. Takaishi et al. (1995) Model Experiments of Ship Capsize in Astern Seas. J Soc Nav Archit Japan, 177 : 207-217.
16. Sera, W. and N. Umeda (2001) Effect of Short-Crestedness of Waves on Capsize of a Container Ship in Quartering Seas, J Japan Institute of Navigation, 104: 141-146, (in Japanese).

APPENDIX

Brief descriptions on the prediction methods used by the participating organisations are as follows:

<u>Ship A-1</u>

Organisation -A

- 6 DOF model
- manoeuvring-based time-domain model
- hull radiation : linear strip theory + nonlinear axis transformation
- hull manoeuvring damping : ITTC exp data (linear and nonlinear terms)
- roll restoring: hydrostatics in waves
- roll damping: ITTC exp data + forward speed effect (empirical)
- Froude-Krylov force: nonlinear pressure integral
- diffraction force: linear strip theory + nonlinear axis transformation
- hydrodynamic lift due to wave: none
- hydrodynamic solution method: 2D multi-pole expansion method
- hydrodynamic memory effect: none
- ship resistance: ITTC exp data
- propeller thrust: ITTC exp data
- rudder force: ITTC exp data

Organisation -B

- 6 DOF model
- linear heave, pitch, sway, yaw (frequency domain) + nonlinear surge and roll (time domain)
- hull radiation : linear strip theory
- hull manoeuvring damping : none
- roll restoring: hydrostatics in waves
- roll damping: empirical formula

- Froude-Krylov force: linear strip theory
- diffraction force: linear strip theory
- hydrodynamic solution method: 2D Rankine source method
- hydrodynamic lift due to wave: none
- hydrodynamic memory effect: none
- ship resistance: ITTC exp data
- propeller thrust: none
- rudder force: none

Organisation -C
- 6 DOF model
- CFD time-domain model
- Euler equation (no viscosity)
- fully nonlinear free surface & body surface condition
- finite difference method in time domain
- fluid motion and ship motion are simultaneously solved.
- roll viscous damping: none
- ship resistance & propeller thrust: externally added
- rudder force: none
- H-H type grid (near-field 540,000 grids, far-field 2,600,000 grids)

Organisation-D
- 6 DOF model
- seakeeping-based two-stage model (linear part + nonlinear part)
- linear part (frequency domain): linear strip theory
- hydrodynamic solution method for the strip theory: Frank's close-fit method
- nonlinear part (time domain)
  1) cross-coupling terms of body dynamics: included
  2) nonlinear part of Froude-Krylov force & roll restoring : pressure integral up to wetted water surface
  3) nonlinear parts of radiation & diffraction: none
  4) hydrodynamic memory effect: included
  5) hull manoeuvring damping : empirical formula
  6) roll damping: critical damping ratio
  7) ship resistance: ITTC exp data
  8) propeller thrust: ITTC exp data
  9) rudder force: empirical formula
- quadrilateral panels for hull surface

Organisation-E
- 6 DOF model
- seakeeping-based time-domain model
- hull radiation : linear 3D theory
- hull manoeuvring: semi-empirical formula for hull forces
- roll restoring: hydrostatics in waves (as part of Froude-Krylov forces)
- roll damping: semi-empirical formula (lift damping + quadratic)
- Froude-Krylov force: linear pressure integrated up to free surface
- diffraction force: linear strip theory
- hydrodynamic lift due to wave: cross-flow drag model
- hydrodynamic memory effect: included as part of wave radiation forces
- ship resistance: database for actual ship (measured or calculated)
- propeller thrust: database for actual or standard propellers
- rudder force: semi-empirical formula

Organisation-F
- 6 DOF model
- seakeeping-based time-domain model
- hull linear damping in yaw: ITTC exp data for yaw
- hull linear damping in surge, sway: values for other fishing vessel
- roll restoring: hydrostatics in waves
- roll damping: Ikeda's method
- Froude-Krylov force: nonlinear pressure integral
- diffraction force: none
- hydrodynamic lift due to wave: none
- hydrodynamic solution method: 2D Green function method
- hydrodynamic memory effect: none
- ship resistance: values for other fishing vessel
- propeller thrust: values for other fishing vessel
- rudder force: values for other fishing vessel

Organisation - G
- 6 DOF model
- manoeuvring-based time-domain model
- hull wave-making damping: Tasai's empirical formula
- hull manoeuvring damping : ITTC exp data (linear & nonlinear terms)
- roll restoring: hydrostatics in waves
- roll damping: ITTC exp data + forward speed effect (empirical)
- Froude-Krylov force: nonlinear pressure integral
- diffraction force: Ohkusu's slender body theory
- hydrodynamic lift due to wave: as end term
- hydrodynamic solution method: 2D multi-pole expansion
- hydrodynamic memory effect: none
- ship resistance: ITTC exp data
- propeller thrust: ITTC exp data
- rudder force: ITTC exp data

<u>Ship A-2</u>

Organisation -A
- 4 DOF model with static heave and pitch
- manoeuvring-based time-domain model
- hull added mass : linear slender body theory with double model flow
- hull wave-making damping: none
- hull manoeuvring damping : ITTC exp data (linear terms only)
- roll restoring: hydrostatics in calm water
- roll damping: ITTC exp data + forward speed effect (empirical)
- Froude-Krylov force: linear pressure integral

- diffraction force: Ohkusu’s slender body theory
- hydrodynamic lift due to wave: as end term
- hydrodynamic solution method: 2D Green function method
- hydrodynamic memory effect: none
- ship resistance: ITTC exp data
- propeller thrust: ITTC exp data
- rudder force: ITTC exp data

Organisation -B

- 6 DOF model
- seakeeping-based time-domain model
- hull radiation : 3D Green function method (zero forward speed) + forward speed effect
- hull manoeuvring damping : empirical formula
- roll restoring: hydrostatics in waves with incident wave pressure taken into account
- roll damping: empirical formula + forward speed effect (tuning)
- Froude-Krylov force: nonlinear pressure integral
- diffraction force: 3D Green function method (zero forward speed) + forward speed effect
- hydrodynamic lift due to wave: none (no trailing vortex layer)
- hydrodynamic memory effect: included
- ship resistance: empirical formula
- propeller thrust: adjusted to realise the specified speed
- rudder force: empirical formula
- incident wave: second order Stokes wave

Organisation -C

- 4 DOF model with static heave and pitch
- manoeuvring-based time-domain model
- hull wave-making damping: included
- hull manoeuvring damping : ITTC exp data (linear & nonlinear terms)
- roll restoring: hydrostatics in calm water
- roll damping: empirical formula + forward speed effect (empirical)
- Froude-Krylov force: nonlinear pressure integral
- diffraction force: Ohkusu ュ s slender body theory
- hydrodynamic lift due to wave: as end term
- hydrodynamic solution method: 2D multi-pole expansion
- hydrodynamic memory effect: none
- ship resistance: ITTC exp data
- propeller thrust: ITTC exp data
- rudder force: ITTC exp data

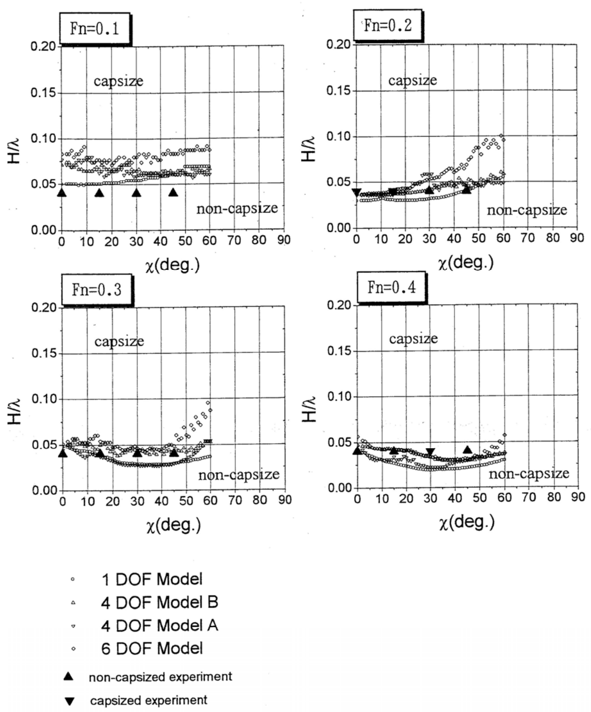


Fig. 7 Capsizing boundaries of Ship A-1 with $\lambda/L=1.5$[5]. Here χ indicates the auto pilot course.

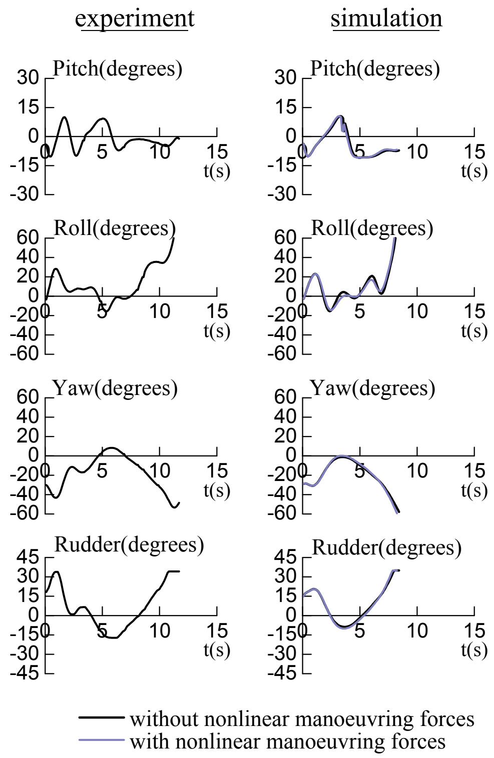
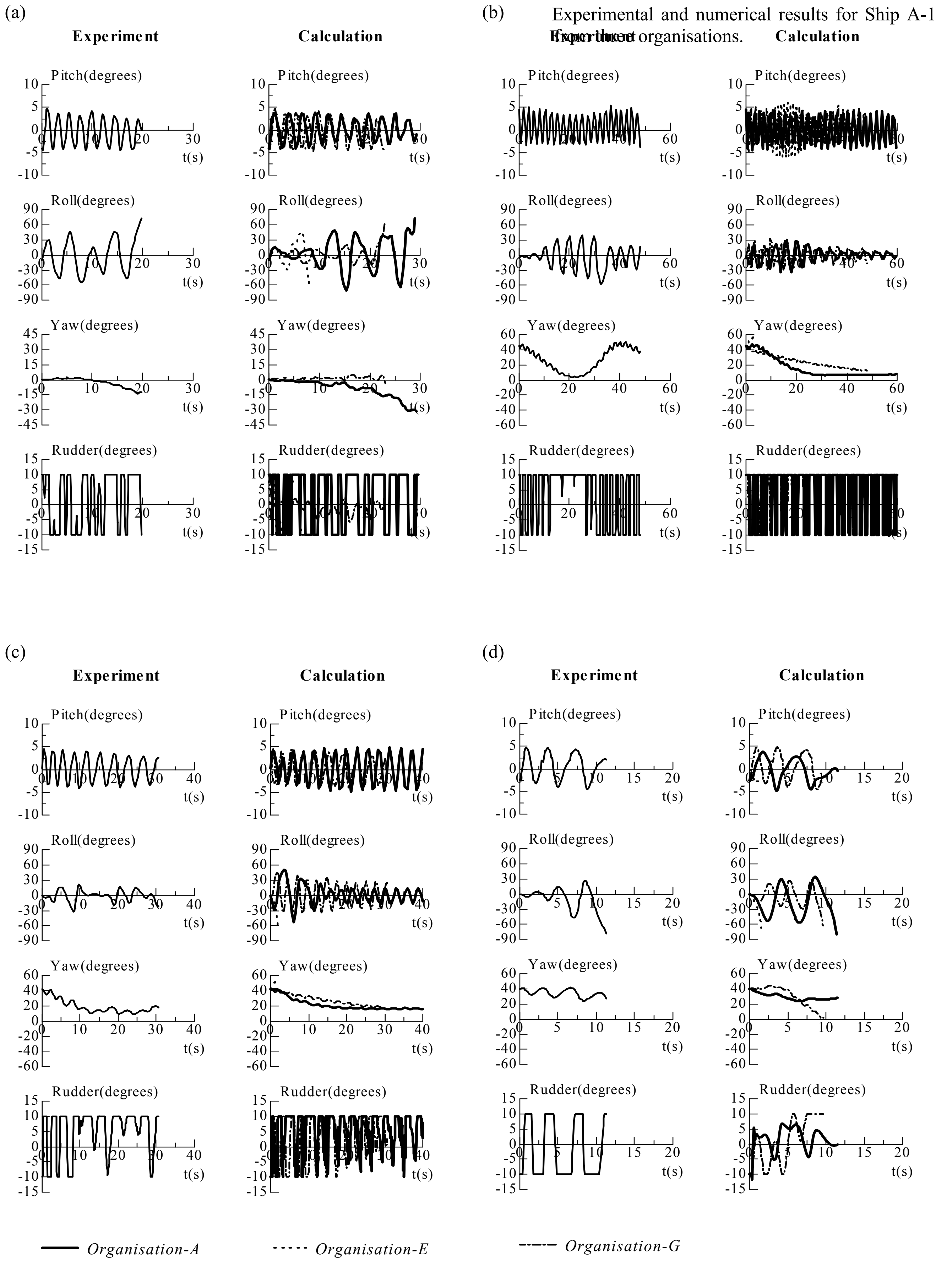


Fig. 8 Effect of nonlinear terms of monoeuvring forces on prediction for Ship A-2 at the case (b).[9]



Experimental and numerical results for Ship A-1 from three organisations.

from four organisations.

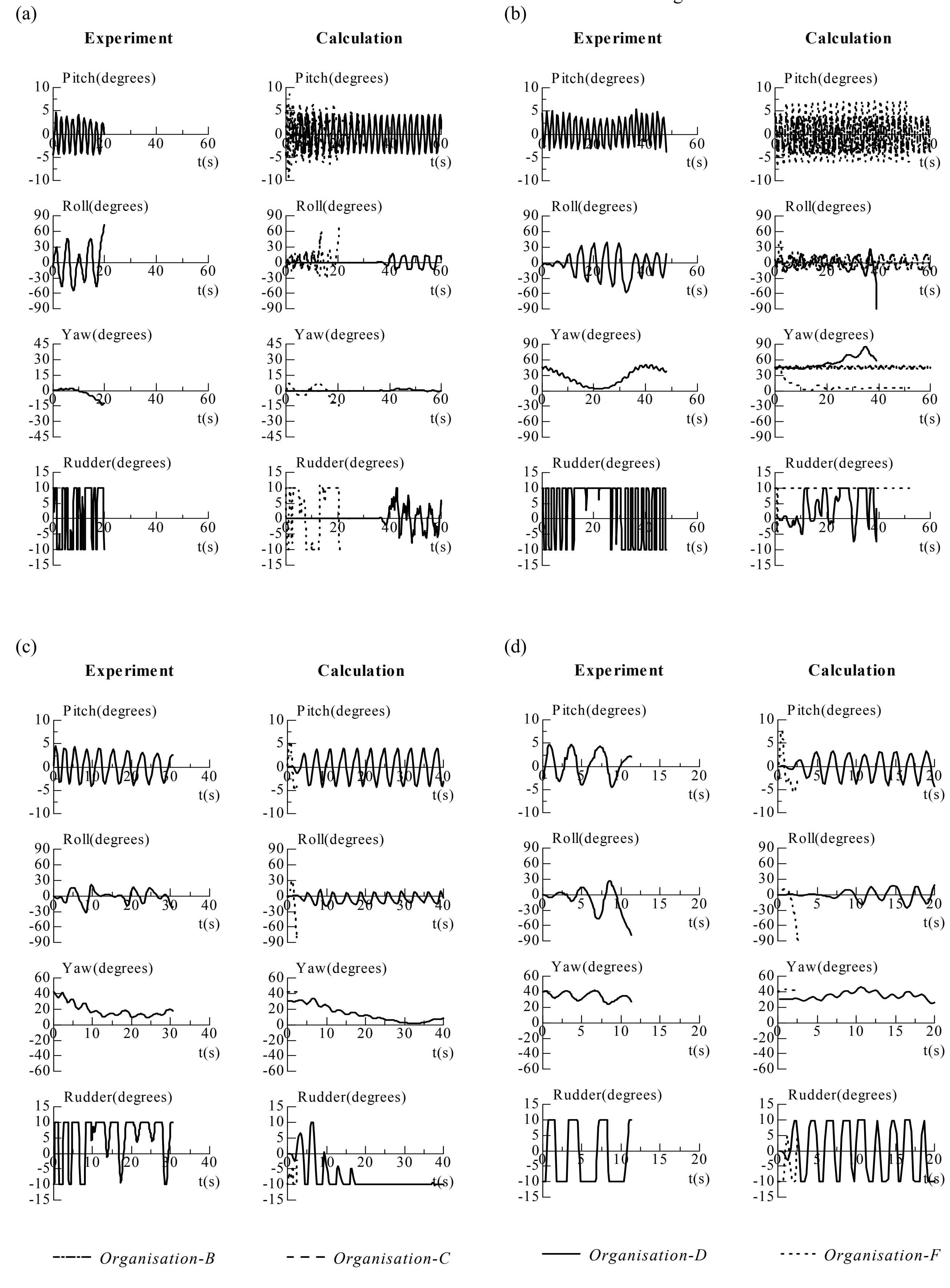


Fig. 5 Experimental and numerical results for Ship A-1

Fig. 6 Experimental and numerical results for Ship A-2.