Parameter Study of Numerical Simulation of Parametric Rolling of Ships

Martin Schreuder

Department of Shipping and Marine Technology Chalmers University of Technology, Sweden

ABSTRACT

A parameter study by numerical simulation of parametric rolling is presented together with results from the SAFEDOR benchmark study, Spanos and Papanikolaou (2009a). The parameter study consists of a variation of wave height and wave period around eight of the discrete test cases in regular waves of the benchmark study. The results are discussed and explained together with quasi-static calculations of metacentric heights and righting arms of the ship. Among the findings is an example of decreasing and disappearing of the parametric roll as the wave height is increased. A frequency shift, away from the principal frequency $\omega_e/\omega_{eg}=2$, for the highest amplitudes of parametric roll and for increased wave heights, is also identified.

KEYWORDS

Seakeeping, parametric rolling, parameter study, numerical simulation.

INTRODUCTION

The parametric rolling of ships has been given an increasing attention the last decades. Large container ships and PCTC carriers have been reported to experience dangerously large roll angles developed in a very short time, in some cases only a few wave encounters. One example is the APL China incident in 1998 where more than sixty percent of the cargo was lost or damaged due to parametric roll. More recent examples of ships encountering parametric roll resonance is the Maersk Carolina in 2003 where more than 130 containers were lost and the PCTC Aida in 2004 where the time series of the roll motion also has been recorded on board (Hua et al 2006). Parametric rolling can be very costly in terms of damaged or lost cargo and even damage and loss of the ship and its crew.

The phenomenon of parametric roll has been recognized and investigated both by numerical and experimental models by naval architects for more than fifty years (Paulling 2006). The earlier work has been mainly focused on smaller working ships and costal cargo ships. More recent accidents with larger ships have both increased and shifted the focus of interest the recent decades, see e.g. Umeda (2008), Spanos and Papanikolaou (2009) and Brunswig (2006).

The present paper comprises a parameter simulation study to investigate the sensibility of parametric roll with respect to ship loading, speed and wave climate. The bases for this study are eight of the regular wave test cases of the SAFEDOR benchmark study.

THEORY AND METHOD

Parametric rolling is a dynamic stability phenomenon that occurs due to transverse stability variations when longitudinal waves passes the ship hull in combination with an encounter period close to half the period of natural roll.

For a ship in longitudinal waves the roll motion will not be excited due to the port and starboard symmetry of the ship and wave. However, the transverse stability will change during a wave passage e.g. compare the water lines of a ship in a wave, with length close to the ship length, when a crest and trough respectively is amidships. The stability variation is more pronounced for slender ships and ships with large flares and is of course also related to the wave height. To initiate parametric rolling in longitudinal waves some perturbation in roll is needed. In practice this perturbation will always be present in the form of wind gusts, oblique waves or course deviations.

When parametric rolling occurs in regular waves the frequency of roll will be half the frequency of encounter, and pitch, heave and surge will be at the frequency of encounter and hence the ship-wave system will be symmetrical and the roll excitation for the starboard and port parts of the roll cycle will be the same. Typically the transverse stability will be high when rolling towards upright and low rolling away from upright and hence the roll motion will be “self amplified”. Ships are considered to have the largest susceptibility to parametric roll when the frequency of encounter is twice the frequency of natural roll. Parametric roll could also exist at other multiples of frequency of encounter to frequency of natural roll but this is not considered further in the following.

Apart from the hull geometry also roll damping and the loading condition are important ship characteristics for the development of parametric roll. If the energy loss from the roll damping is greater than the energy gain from the change of transverse stability parametric roll will not develop. The loading condition will affect the stability characteristics and natural roll period.

The governing phenomena of parametric roll are non-linear and cannot be assessed by a linear theory method e.g. linear strip methods. The simplest way to examine parametric roll is by the assumption of a sinusoidal GM variation put into a linear one degree of freedom roll equation. Through suitable substitutions and rearrangement this equation will be in the form of the Mathieu equation. By varying the parameters of the Mathieu equation, corresponding to mean value (non-dimensional natural frequency) and range of the time varying GM respectively, the stability of the equation can be studied through the well known Ince-Strutt diagram. The unstable regions correspond to possible parametric roll (ABS 2004).

Through the Mathieu equation an estimate of the susceptibility of occurrence of parametric roll can be made. However, no information about the severity, e.g. growth and steady state of the roll angle, can be found from this approach. There is a need for more sophisticated methods in order to assess and understand the phenomena of parametric roll. A first step of refinement would be the inclusion of a representation of the ships righting ability at large roll angles e.g. through an analytical expression of the righting moment, e.g. Bulian (2008), or through direct integration of the pressure on the submerged part of the hull, e.g. Hua and Palmquist (1995). Other refinement could be to include the coupling to other degrees of freedom e.g. heave, pitch and surge and a proper representation of the roll damping. Of course the refinements will come at a cost in CPU time, especially when closed form expressions are abandoned.

The simulation and analysis of parametric roll in the present studies were carried out using the SIMCAP numerical tool, see Schreuder (2005), with the implementation of arbitrary wave direction and speed. SIMCAP is a time domain code based on non-linear strip theory in which the incident wave forces, the Froude-Krylov forces, are calculated by integration of dynamic wave pressure over the momentarily wetted hull surface at each time step and the diffraction and radiation forces are determined through pre-calculated sectional hydrodynamic coefficients. Inclusion of viscous effects on the roll damping is made through a quadratic formulation where the coefficients have been tuned to match a roll decay model test. In the present studies forward speed effect on roll damping is not considered due to pertinent low speeds.

PARAMETER STUDY

Setup

A parameter study has been conducted to investigate the parametric roll sensitivity to ship loading, speed and environment. The ship used in the study is the container ship ITTC-A1 with main particulars and the different loading conditions used, listed in Table 1.

Other parameters in the study were ship heading and speed. Only regular waves were used in the study and wave height and wave period were treated as variables. A study setup matrix is shown in Table 2.

The bases for this study are a systematic variation of wave height and wave period around eight of the regular wave test cases of the SAFEDOR benchmark study. Fig. 1 the results from the model tests of the benchmark study together with the corresponding simulation results of the present numerical tool in terms of steady state roll amplitude. The test cases that were selected for the parameter study were T2-T5, head regular waves, and T13-T6, following regular waves.

Table 1 Main particulars and loading conditions of the ship used in the parametric study.

Item	Ship
Length: L_{pp}	150.0 m
Breadth: B	27.2 m
Depth: D	13.5 m
Draught at FP: T_f	8.5 m
Mean draught: T	8.5 m
Draught at AP: T_a	8.5 m
Block coefficient: Cb	0.667
Loading condition 1	
Metacentric height: GM	1.38 m
Roll radius of gyration: I_{xx}	10.33 m
Pitch radius of gyration: I_{yy}	38.2 m
Loading condition 2	
Metacentric height: GM	1.00 m
Roll radius of gyration: I_{xx}	10.33 m
Pitch radius of gyration: I_{yy}	38.2 m

Table 2 Setup matrix of parametric study.

Ship speed: Fn	0.04	0.08	0.12
Head seas (Load. cond. 1)		x	x
Following seas (Load. Cond. 2)	x	x	

In the simulations the ship was restrained to move in only three degrees of freedom; roll, heave and pitch. The roll angle was set to one degree at the start of each simulation in order to trigger a possible parametric roll development in the otherwise starboard-port symmetrical test cases. First order waves were used in all simulations. Coefficients for the quadratic roll damping where obtained through matching a roll decay experiment from the benchmark study.\

The solid lines of Fig. 2 show the GZ curves of the two loading conditions. Quasi-static GZ curves, where the ship is balanced by constant displacement and zero pitch moment in a "static wave" with wave crest and trough amidships respectively, were calculated for comparison and are shown as dotted lines in Fig. 2. These were calculated for two different wave heights, 4 m and 8 m, and for the wave length λ/L_{pp}=0.85. In the quasi-static calculations the pressure varies linearly with the vertical distance from the surface.

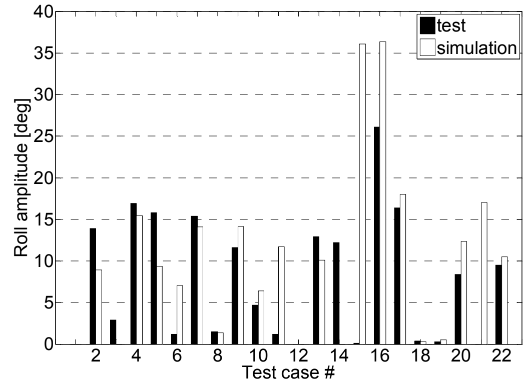

Fig. 1 Results of the test cases from the present simulations and model tests. T1 and T12 are the roll decay tests.

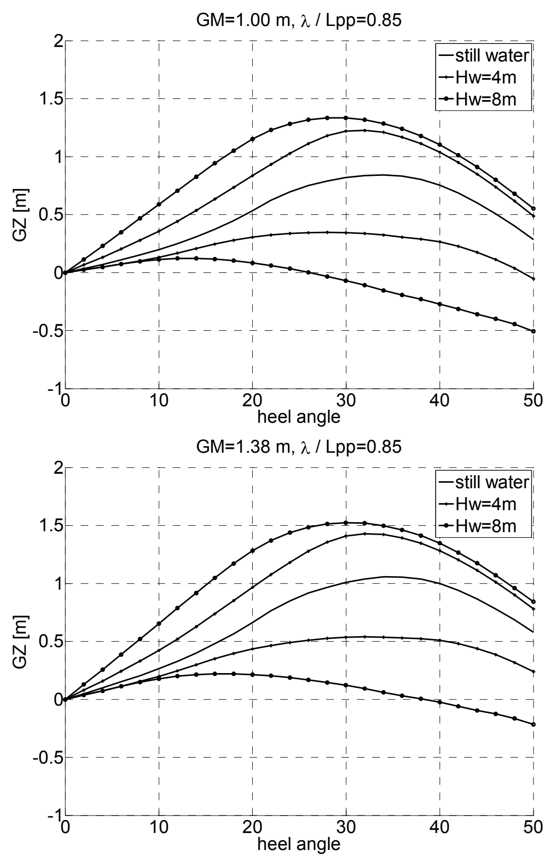

Fig. 2 GZ curves of the two loading conditions: GM=1.00 m (upper) and GM=1.38 m. Curves above still water curve: wave trough amidships. Curves below still water curve: wave crest amidships.

Similarly, the quasi-static GM was calculated for a range of wave lengths, wave heights and for 16 different instances of one wave encounter, for the loading condition GM=1.00 m. The maximum and minimum values occurred when wave trough and wave crest are situated amidships respectively. The span (δGM) (1) and mean values (2) are shown in Fig. 3 and Fig. 4. The mean GM and δGM with respect to wave height, as seen in the lower plots of Fig. 3 and Fig. 4, show a close to quadratic and linear dependence on the wave height respectively.

$$\mathrm{mean}(GM) = \frac{1}{T_p}\int_0^{T_p} GM(t)dt \qquad (1)$$

$$\delta GM = GM^{\max} - GM^{\min} \qquad (2)$$

Results

All results of the study are collected in Fig. 6 where the steady state roll amplitude is plotted for wave height versus non-dimensional encounter frequency and non-dimensional wave length.

In Fig. 5 the results are condensed to only include the occurrence of parametric roll and are presented in a wave frequency versus frequency of encounter plot with forward speed as a parameter. The range of occurrence is represented by thick line segments. In the enlarged lower plot the wave frequency corresponding to the ship length has been plotted as a vertical dotted line and twice the frequency of natural roll (ω_{eg}) for the two loading conditions have been plotted as horizontal dotted lines (ω_{eg} was determined from roll decay simulations). It is noteworthy that the high frequency boundary of occurrence is shared by the two cases in following seas and that it corresponds to a wave length of λ/L_{pp}=0.52. In the quasi-static *GM* calculations around this value the span of *GM* is comparatively small and also rapidly decreasing as the wave length is decreased, Fig 3, which indicates the existence of this distinct border.

Upper part of Fig. 5 shows: the frequency of encounter plotted against wave frequency for a range of ship speeds in head and following seas. On the four lines corresponding to the cases in the study the occurrence of parametric roll is indicated by thick line sections for head seas (GM=1.38m) and for following seas (GM=1.00m) respectively. Lower part of Fig 5 shows an enlargement where λ/L_{pp}=1 and twice the frequencies of natural roll have been indicated by dotted lines and the discrete cases from the benchmark study are indicated by dots

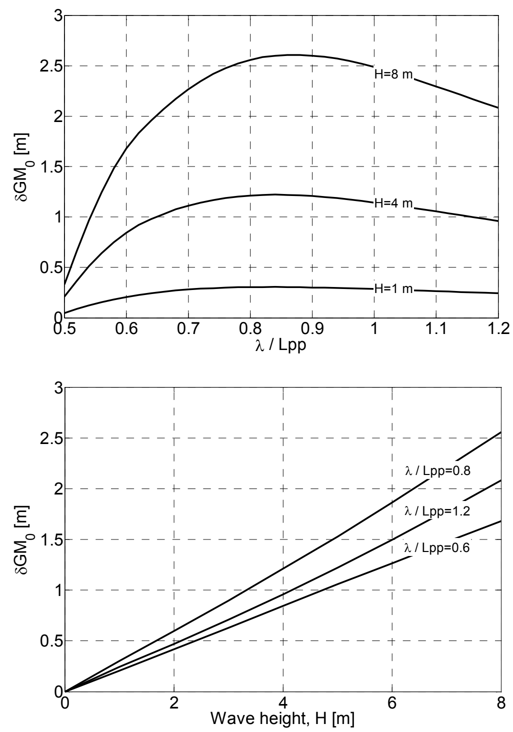

Fig. 3 The span of GM_0 plotted against wave length (upper) and wave height. Static GM_0=1.00 m.

Upper part of Fig. 5 shows: the frequency of encounter plotted against wave frequency for a range of ship speeds in head and following seas. On the four lines corresponding to the cases in the study the occurrence of parametric roll is indicated by thick line sections for head seas (GM=1.38m) and for following seas (GM=1.00m) respectively. Lower part of Fig 5 shows an enlargement where λ/L_{pp}=1 and twice the frequencies of natural roll have been indicated by dotted lines and the discrete cases from the benchmark study are indicated by dots

In Fig. 6 the magnitude of the steady state roll amplitudes from the simulations are represented by a gray scale, white represents no parametric roll occurrence. Note that the roll amplitude scales are different for the different cases and that a roll angles above 40° represents ship capsize, which occur only for Fn=0.04 in following seas. The frequency of roll was half the frequency of encounter in all cases. This is the typical mode of parametric roll and is commonly referred to as principal parametric roll.

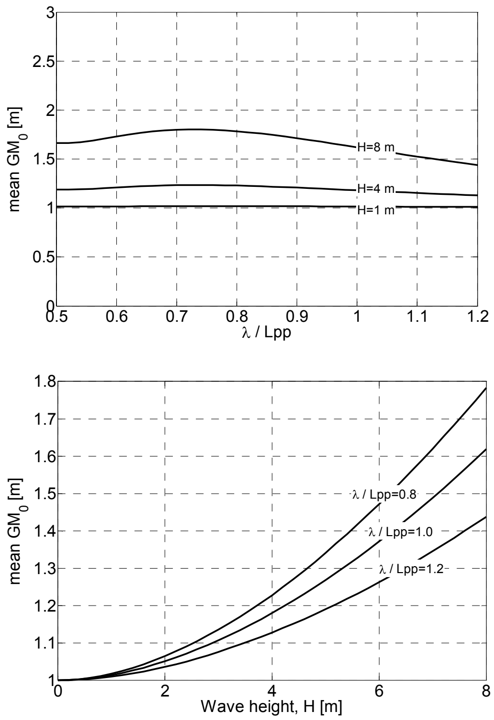

Fig. 4 The mean value of GM_0 during a wave encounter plotted against wave length (upper) and wave height. Static GM_0=1.00 m.

Even though the plots of Fig. 6 have quite different appearances some observations common to all of them can be made:

a) The largest roll angles occur at a frequency ratio larger than the principal ratio ω_e/ω_{eg} =2.

b) Starting from the lowest wave heights the largest roll angle for each wave height is shifted towards higher frequencies up to the maximum roll angle, i.e. there is a rightward upward trend of parametric roll occurrence in the plots.

c) There are abrupt changes in roll angle in the lower right boundaries of occurrence.

There are also some interesting observations to be made, common to some but not all of the cases:

a) The largest roll angles occur at a wave length λ/Lpp<1 with the exception of the Fn=0.12 head seas case.

b) The head wave cases have a larger shift to the right (see a)) compared to the following wave cases.

c) In the Fn=0.08 following wave case the roll angle start to decrease for wave heights above 3 m and the parametric roll disappear between 5 and 6 m. This trend can also be noticed in the head wave cases.

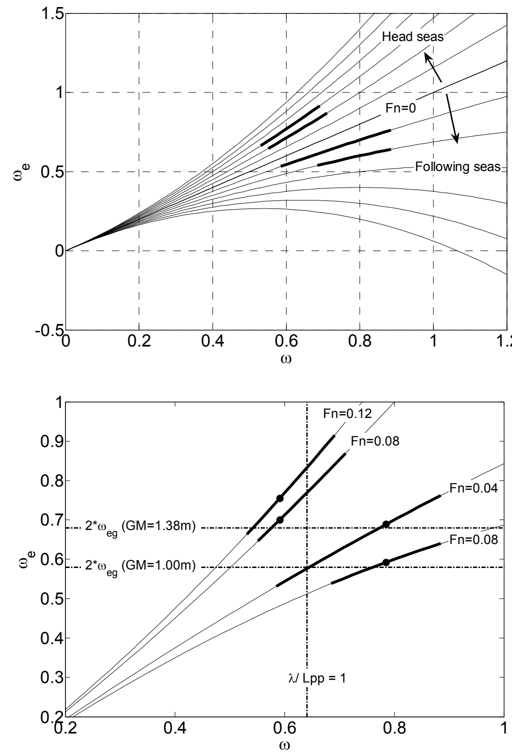

Figure 5 Occurrence of parametric roll from the parameter study.

Fig. 2 show that the slope of the *GZ* curve is increased for increased angles up to about 20° and for wave heights up to about 4 m. In Fig. 4 we can also see that the mean value of GM_0 is increased with the wave height i.e. both increased wave height in upright condition and increased roll angle leads to increased stiffness and natural roll of the ship. Even though all dynamic effects of ship motions are excluded in the calculations behind these figures, these qualities are believed to be the dominant causes to the behavior in a) and b). At low wave heights the mean GM_0 has a low rate of change and is close to the static value and occurrence of parametric roll will be close to ω_e/ω_{eg} =2, see Fig. 4 (upper) and Fig. 6.

Observation d) can be explained by inspection of Fig. 3 where the span of GM_0 has a maximum value below λ/L_{pp}=1 at about 0.85. However for the Fn=0.12 head seas case it seems that the encounter frequency is the governing parameter for the parametric roll excitation i.e. wave lengths with maximum GM span will render a too high frequency of encounter for parametric roll to be excited. The opposite seems to hold for the *Fn*=0.08 following seas case. Here the maximum *GM* span will render a too low frequency of encounter.

Observation e) is likely caused by an increased stiffness in roll due to a coupling with the significantly larger pitch response in head waves. This is not captured at all in the quasi-static calculations of *GM* and *GZ*.

The decay and disappearance of parametric roll as the wave height increase as observed in the present study, f), have also been observed in experimental results, (Spanos and Papanikolaou 2009). From Fig. 4 we can see that for a given wave length the GM_0 and thus the natural frequency of roll will increase with increased wave height. By this the parametric roll will be "detuned" and the roll angle decrease as the wave height is increased. A similar explanation is also discussed in Spanos and Papanikolaou (2009b) and Neves et al (2009).

The model test results of test case T2 and T3, Fig, show decreasing roll amplitude with increasing wave height. This is also evident in the numerical simulations. Test case T3 is however outside of the boundary of occurrence and shows zero roll amplitude, Figure 1. This tendency of decreasing roll can also be seen for T4/T5 and for T13/T14 in both test and simulations. The zero roll result of the simulation of T14 is also close to the boundary of occurrence. Test T15 can be distinguished as the worst prediction of parametric roll in the present study with a simulated steady state roll angle of over 35º and a model test without parametric roll, Fig. In Figure 1 the test T15 is close to the boundary of occurrence of parametric roll. In fact as the frequency of encounter in the simulation is increased by 2 % or if the wave height is lowered by about 0.5 m the parametric roll disappears. The occurrence of parametric roll seem to be very susceptible to both encounter frequency and wave height in the low wave height/high frequency regions i.e. lower right parts of the plots in Figure 1. If test T15 would be excluded from the benchmark the correlation would increase to 0.64 and the standard deviation decreased to 6.5º.

CONCLUSIONS

In the parameter study the regions of occurrence and magnitude of parametric roll with respect to wave height and wave frequency were derived for different speeds and two loading conditions for head and following waves. Several interesting features in the appearance of these regions were observed and explanations were indicated through analysis of simple quasi-static calculations and also dynamic coupling effects between ship motions; The largest roll amplitudes occur at higher frequencies than the principal frequency ω_e/ω_{eg} =2. Increased wave height results in a shift of maximum roll amplitudes towards higher frequencies. This frequency shift is higher for the head wave cases. There are abrupt changes in roll amplitude in the low wave height/high frequency boundary of occurrence. In most cases the largest roll amplitudes occur at a wave length λ/L_{pp}<1. In one of the test cases the parametric rolling decreases and eventually disappears as the wave height is increased.

The results from the benchmark study show that the present numerical code has a capability of predicting parametric rolling, both qualitatively and quantitatively. The quality of very narrow boundaries of parametric roll occurrence, from the parameter study, could also explain one of the worst results in the benchmark. Awareness of the possibility of these narrow boundaries is important for the assessment of parametric roll by any method.

REFERENCES

ABS (2004) Guide for the Assessment of Parametric Roll Resonance in the Design of Container Carriers. (Updated June 2008).

Brunswig, J., Pereira, R., Daewoong, K. (2006) "Validation of parametric Roll Motion Predictions for a Modern Container Ship Design". Proc. 9th Int. Conference on Stability of Ships and Ocean Vehicles (STAB 2006), Rio de Janeiro, Brazil,

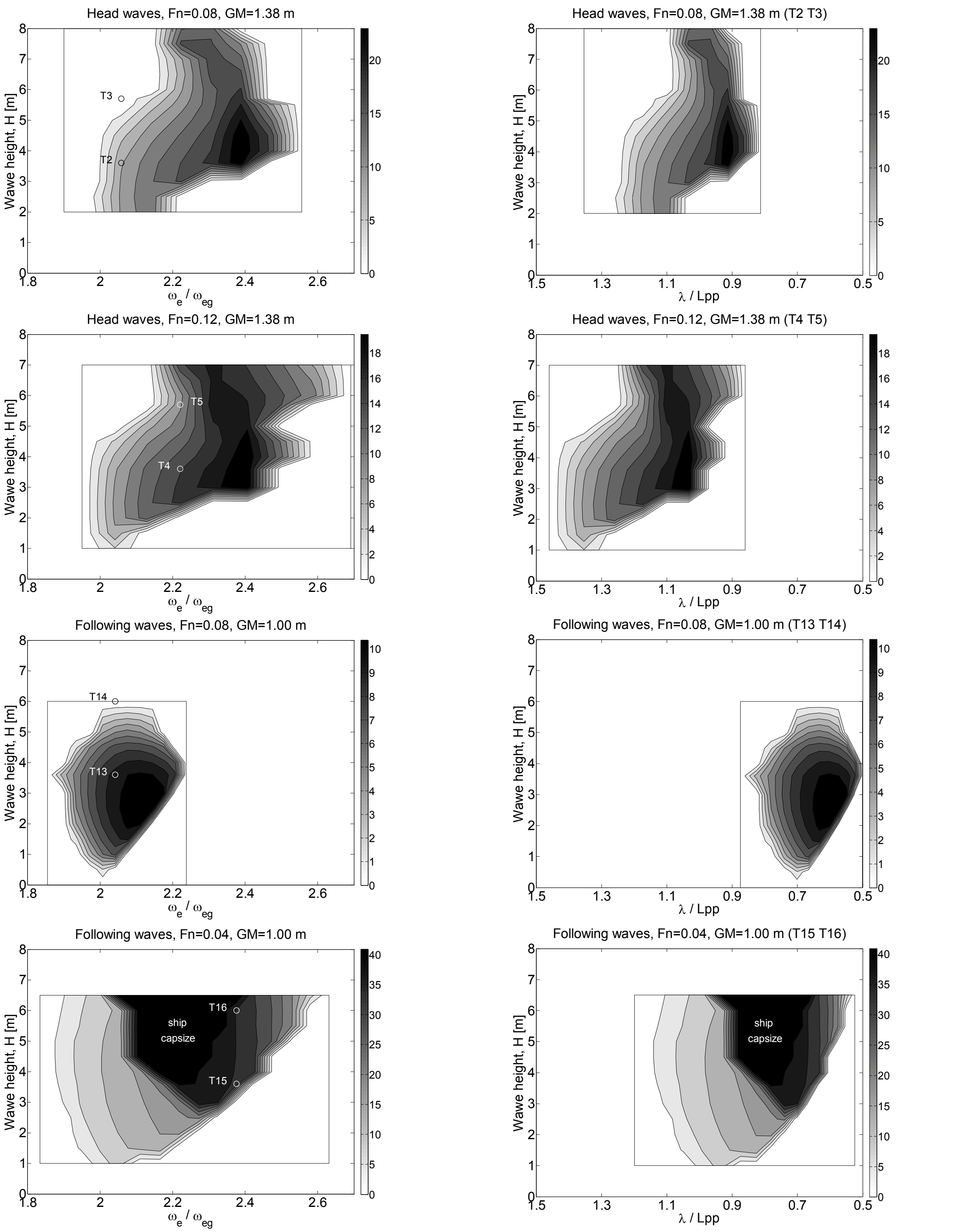

Figure 1 Results from the parametric study. Grey scale represents roll amplitude. The four upper plots: head waves. The four lower plots: following waves. Left: encounter frequency on abscissa. Right: wave length on abscissa. The range of parameter variation is represented by the inner boxes. The test cases of the benchmark study are marked with circles.

Bulian, G., Francescutto, A., (2008) Theoretical Prediction and Experimental Verification of Multiple Steady States for Parametric Roll. Proc. 10th Int. Ship Stability Workshop, Daejeon, Korea

Hua, J., Palmquist, M., (1995) A Description of SMS – A Computer Code for Ship Motion Simulation. KTH, TRITA-FKT, Report 9502, ISSN 1103-270X, Stockholm, Sweden

Hua, J., Palmquist, M., and Lindgren, G. (2006) An "Analysis of the Parametric Roll Events Measured Onboard the PCTC AIDA". Proc. of the 9th Int. Conf. on Stability of Ships and Ocean Vehicles (STAB 2006), Rio de Janeiro, Brazil

Neves, M. A .S., Rodriguez, C. A., and Vivanco, J.E.M. (2009) "On the limits of stability of ships rolling in head sea". Proc. IMechE: J. of Eng. for the Maritime Environment Vol. 223 Part M

Paulling, J.R., (2006) Parametric Rolling of Ships – Then and Now. Proc. of the 9th Int. Conf. on Stability of Ships and Ocean Vehicles (STAB 2006), Rio de Janeiro, Brazil.

Schreuder, M. (2005) Time simulation of the behaviour of damaged ships in waves. Shipping and Marine Technology. Chalmers University of Technology. Licentiate Thesis, Gothenburg, Sweden.

Spanos, D., and A. Papanikolaou (2009) SAFEDOR International Benchmark Study on Numerical Simulation Methods for the Prediction of Parametric Rolling of Ships in Waves. NTUA-SDL Report Rev 1.0.

Spanos, D., and A. Papanikolaou (2009a) "Benchmark Study on Numerical Simulation Methods for the Prediction of Parametric Roll of Ships in Waves". Proc. 10th Intl. Conf. on Stability of Ships and Ocean Vehicles (STAB 2009), St Petersburg, Russia

Umeda, N., Hashimoto, H., Stern, F., Nakamura S., Sadat Hosseini. S. H., Matsuda, A. and P. Carrica (2008) "Comparison Study on Numerical Prediction Techniques for Parametric Roll". Proc. of the 27th Symp.on Naval Hydrodynamics, Seoul, Korea.