PARAMETRIC ROLLING IN HEAD SEAS – AN AUSTRALIAN PERSPECTIVE

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ABSTRACT

The onset of parametric rolling in head seas has been known to cause serious safety issues for ships, particularly containerships. The aim of this work was to investigate the prediction of the occurrence of parametric roll and the factors which influence it.

The threshold boundaries, for the inception of parametric roll for a typical containership were established using the Mathieu equation. A series of model experiments was then conducted to validate the theoretical predictions for the inception of parametric roll and investigate the influence of wave height, wave length and GM on the inception of parametric roll.

For all the GM values tested reasonable agreement was found between the numerical predictions and the experimental results. A reduction in wave height was found to reduce the range of encounter frequencies for which parametric roll will occur. Parametric roll was found to occur for a range of wavelengths provided that the encounter wave period was in the critical range.

KEY WORDS: Parametric roll, containerships, head seas, model experiments

INTRODUCTION

When a ship is sailing in head and bow quartering seas it may encounter significant heave and pitch motions. In such circumstances significant roll motions would not generally be expected. However, if certain conditions are satisfied, a resonant roll motion can be established and grow to unacceptable levels for the safety of the ship, its cargo and crew.

'Auto parametric roll resonance', or 'parametric roll', is a large amplitude roll resonance, which can occur in following, stern quartering, head and bow quartering seas. Parametric roll in head and bow quartering seas does not generally pose substantial risk of capsize. However, it can result in conditions conducive to cargo shift, damage and subsequent consequences as well as making living and working conditions difficult for the crew.

The International Maritime Organisation (IMO) issued a circular in 1995 (IMO 1995) giving guidance to mariners on the avoidance of parametric roll in following and quartering seas. The IMO is currently reviewing this code with the aim of improving the quality of its guidance, particularly for the occurrence of parametric roll in head seas.

The theoretical conditions required for parametric rolling to occur have been validated by model tests (Dallinga et al. (1998), Luth and Dallinga (1998) and France et al. (2003)). More recent work has been conducted by Brunswig et al. (2006), Taguchi et al. (2006) and Hashimoto et al. (2006).

Many of these previous studies on this phenomenon have involved post-Panamax containerships, which are larger than those currently operating in Australian ports. An initial investigation was conducted at the Australian Maritime College (AMC), in collaboration with the Australian Maritime Safety Authority (AMSA) and focused on a series of free running tests with varying speed, wave height and wave frequency (Xia et al. (2006)). The current study by AMC and AMSA was initiated to verify whether the phenomenon also applies to smaller containerships and to provide input to guidance material being developed by IMO for the assistance of mariners.

The first aim of this work was to predict the occurrence of parametric roll for a container vessel operating in head seas. This was done using the Mathieu Equation, as utilised successfully by a number of authors previously (Francescutto (2000), France et al. (2003)). This allowed threshold boundaries to be predicted for the zone of instability where parametric roll may be expected to occur.

A series of model experiments was then conducted in the Australian Maritime College's towing tank to investigate the influences of wave conditions, ship speed and GM on the parametric roll behaviour of this containership. The experiments were conducted on the P&O Nedlloyd Hoorn since this represents a typical containership.

A number of aims were established for the experimental program:

- Validate the theoretical predictions for the inception of parametric roll.
- Investigate the influence of wave height and wave length on the inception of parametric roll.
- Establish the effect of GM on parametric roll behaviour.

THEORETICAL PREDICTIONS

The following equation describes the motion of a ship rolling in a head sea (Francescutto (2000), Francescutto and Bulian (2002), France (2003)):

$$I'\ddot{\phi} + D(\dot{\phi},\phi) + R(\phi,t) = 0 \qquad [1]$$

where I' is the virtual moment of inertia, D is the damping, R is the restoring force, ϕ the instantaneous roll angle and t is time. Note that there is no explicit forcing term due to the wave. With the inception of parametric roll, equation 1 may be linearised giving:

$$I'\ddot{\phi} + M\dot{\phi} + \Delta\overline{\mathrm{GM}}(t)\phi = 0 \, . \qquad [2]$$

If the transverse metacentric height is assumed to vary with amplitude $\delta\overline{\mathrm{GM}}$ about the average value of $\overline{\mathrm{GM}}$ the following is obtained:

$$\ddot{\phi} + 2\mu\dot{\phi} + \omega_\phi^2\left[1 + \frac{\delta\overline{\mathrm{GM}}}{\overline{\mathrm{GM}}^*}\cos(\omega_e t + \varepsilon)\right]\phi = 0 \, . \qquad [3]$$

This is an equation of the Mathieu type where μ is the roll damping, ω_e the encounter wave frequency and ω_ϕ the natural roll frequency. The equation may be transformed into the following form by neglecting the phase, ε, and changing the independent variable $\omega_e t = 2t'$:

$$\ddot{\phi} + 2\mu^*\dot{\phi} + 4\frac{\omega_\phi^2}{\omega_e^2}\left[1 + \frac{\delta\overline{\mathrm{GM}}}{\overline{\mathrm{GM}}^*}\cos(2t')\right]\phi = 0 \qquad [4]$$

with $\mu^* = \dfrac{2\mu}{\omega_e}$. If the damping is then cancelled by a linear transformation:

$$\ddot{\phi} + \left[4\frac{\omega_\phi^2\left(1-(\mu^*)^2\right)}{\omega_e^2} + 4\frac{\omega_\phi^2}{\omega_e^2}\frac{\delta\overline{\mathrm{GM}}}{\overline{\mathrm{GM}}^*}\cos(2t')\right]\phi = 0 \qquad [5]$$

The change in natural roll frequency due to damping is represented by $\omega_\phi^2\left(1-(\mu^*)^2\right)$. It is assumed that the damped natural frequency is equal to the undamped natural frequency so that the following linear differential equation, with periodic coefficients may be defined as:

$$\ddot{\phi} + 4\frac{\omega_\phi^2}{\omega_e^2}\left[1 + \frac{\delta\overline{\mathrm{GM}}}{\overline{\mathrm{GM}}^*}\cos(2t')\right]\phi = 0 \qquad [6]$$

The threshold for instability of the upright condition which will promote parametric roll may be obtained by solving this linear Mathieu equation. The threshold values for excitation of parametric rolling according to $\dfrac{\delta\overline{\mathrm{GM}}}{\overline{\mathrm{GM}}^*}$ may be found, for n integers:

$$\omega_e \approx \frac{2}{n}\omega_\phi \, . \qquad [7]$$

The regions of instability corresponding to n = 1, 2 and 3, with no damping, are shown in Figure 1. For ships operating in head seas it is the region corresponding to n = 1 which is of importance.

If damping is present the minimum value of the instability changes according to:

$$\frac{\delta\overline{\mathrm{GM}}}{\overline{\mathrm{GM}}^*} \approx \frac{1}{\mu^n} \, . \qquad [8]$$

The boundaries of the first instability region, n = 1, with linear damping may be found from:

$$\frac{\delta\overline{\mathrm{GM}}}{\overline{\mathrm{GM}}^*} = \sqrt{\left(2 - \frac{\omega_e^2}{2\omega_\phi^2}\right)^2 + \frac{\omega_e^4}{\omega_\phi^4}\left(\frac{4}{\omega_e^2}\right)^2\left(1-(\mu^*)^2\right)} \qquad [9]$$

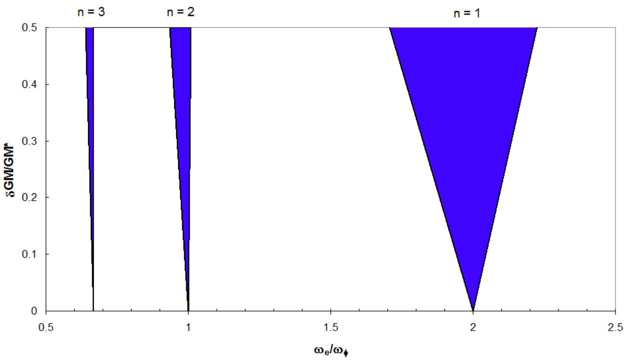

Fig. 1 Threshold boundaries of the first three instability zones for the linear undamped Mathieu equation.

TOWING TANK EXPERIMENTS

Model Details

The P&O Nedlloyd Hoorn is a twin-propeller container ship which was launched in 1978. A 1:100 scale model of this vessel was utilised in the towing tank experiments. The vessel and model particulars are shown in Table 1 with an image of the model shown in Figure 2.

The model was ballasted to the design displacement, with the mass units located to obtain the required distribution for the roll and pitch radii of gyration. A roll frame was used to measure and set the roll radius of gyration whilst the bifilar method was used to measure and set the pitch radius of gyration.

The static roll period was obtained from tests free floating in water. An inclining experiment was also conducted to obtain the KG of the model.

Fig. 2 Model of P&O Nedlloyd Hoorn

Table 1 Vessel and Model Particulars

	Full Scale Vessel	Model (Scale 1:100)
LBP	247 m	2470 mm
B	32 m	320 mm
Draught	12 m	120 mm
Δ	64000 tonnes	62.4 kg
L/B	7.72	7.72
B/T	2.67	2.67
C_b	0.69	0.69
k_{yy}/L_{pp}	0.24	0.24
k_{xx}/B	0.328	0.328

Experimental Configuration

The experiments were conducted in the Australian Maritime College's towing tank which is 100 m long, 3.55 m wide, and has a water depth of 1.5 m. A powered carriage was used to tow the model and waves were generated by a computer-controlled single-flap paddle wave maker positioned at one end of the tank.

In order to maximise the freedom of movement of the model, while being towed, it was attached to the carriage fore and aft with thin wire traces connected to elastic shockcord; a method previously utilised successfully by Burcher (1990), Francescutto (2000) and Neves et al. (2003). A small hole was drilled through the bow of the model on the waterline and two 0.75 mm wire cables were led out to pulley blocks positioned on a beam 2 m in front of the model. The cables were then led back to the carriage and connected to 5 mm elastic shockcord, which in turn was fastened to the carriage. A similar system was used aft, although more freedom was allowed through the use of thinner, more flexible, elastic shockcord. This towing system minimised constraint in heave, pitch and roll and also allowed partial freedom in surge, sway and yaw.

The excitation of the model was conducted by removing a small mass (500 g which was not part of the model's original ballast) fitted amidships at the deck edge. This was equivalent to an initial excitation of 6.5 degrees of roll.

The motions of the model were measured using a Crossbow IMU300CC sensor. This is a six-axis measurement system designed to measure linear acceleration along three orthogonal axes and rotation rates around three orthogonal axes. It uses three accelerometers and three angular rate sensors to make a complete measurement of the dynamics of the model. The sensor was fitted at the centre of gravity of the model and data logged on the carriage computer (using Crossbow software – Gyroview) via an RS-232 serial link.

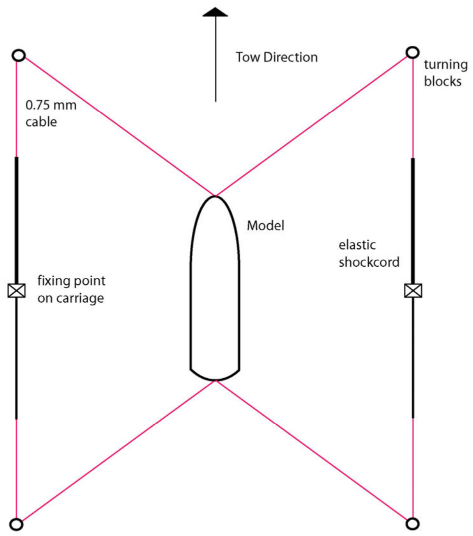

Fig. 3 Plan view schematic of towing configuration

The incident wave height was measured with a resistance wave probe fixed approximately 5 m in front of the wave maker.

Test Conditions

The tests were carried out in regular waves for a variety of wavelengths and wave heights, as shown in Table 2.

Table 2 Summary of Test Conditions

GM (full scale)	Natural Roll Period T_ϕ (full scale)	Wavelength Ratio λ/L	Wave Height (full scale)
0.69 m	23.2 s	0.9	3.0 m, 6.0 m & 8.0 m
		1.0	3.0 m, 5.0 m, 6.0 m & 7.5 m
		1.1	3.0 m, 6.0 m, 6.25 m & 9.0 m
1.1 m	25.8 s	0.8	3.0 m, 6.0 m & 9.0 m
		1.0	3.0 m, 6.0 m & 9.0 m
		1.1	3.0 m, 6.0 m & 9.0 m
1.6 m	20.6 s	0.8	6.0 m & 9.0 m
		1.0	3.0 m, 6.0 m & 9.0 m
		1.1	3.0 m, 6.0 m & 9.0 m
2.1 m	17.9 s	0.8	9.0 m
		1.0	9.0 m

Test Procedure

The wave maker was started and the incident wave train measured to ensure that the correct wavelength and wave height were created. The carriage was then started when the wave front was approximately 10 m in front of the model. This allowed the small amount of periodic surge, which was observed after the carriage acceleration was complete, to recede before the model encountered the waves. The six degrees of motion experienced by the model were logged for a period of approximately 90 seconds (for the complete test run) at 200 Hz. When the motion of the model was deemed to be in a steady state condition, it was excited by removing the mass. When the data collection was completed the wave generation was terminated and the carriage stopped.

RESULTS AND DISCUSSION

The roll angle time history for each run conducted in waves was examined and placed into one of two categories: parametric roll; no parametric roll, after the initial excitation the roll motion decayed. Examples of the raw data illustrating these two categories are shown in Figures 5 and 6.

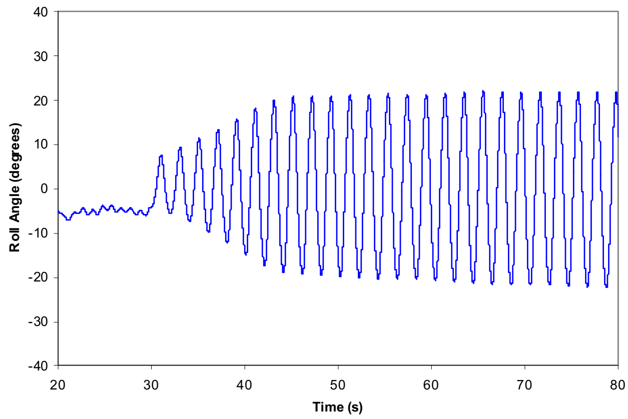

Fig. 5 Raw roll angle data showing parametric roll

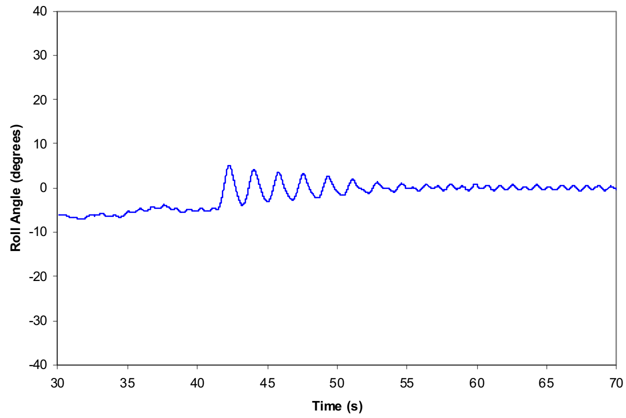

Fig. 6 Raw roll angle data showing no parametric roll

The results for each test run were then plotted in conjunction with the theoretical threshold curves, for the various wavelength to ship length ratios (λ/L) investigated, see Figures 7 to 10. The theoretical undamped threshold curves are denoted by the blue lines (compare with n = 1 instability zone in Figure 1); theoretical damped threshold curves are denoted by the red lines; whilst the test results are the symbols (filled indicating presence of parametric roll; empty indicating no parametric roll). The X–axis is $\left(\frac{\omega_e}{\omega_\phi}\right)^2$, where ω_e is encounter frequency and ω_ϕ is the natural roll frequency; $\left(\frac{\omega_e}{\omega_\phi}\right)^2$ is dependent on the encounter frequency, or vessel speed since for a single condition the wave frequency is constant. The Y-axis is $\frac{\delta\overline{GM}}{\overline{GM}^*}$, where $\delta\overline{GM}$ is the amplitude of transverse metacentric height variation about the average value of $\overline{GM}^*$; it is dependent on wave height with an increase in wave height resulting in a larger $\frac{\delta\overline{GM}}{\overline{GM}^*}$ value. The $\frac{\delta\overline{GM}}{\overline{GM}^*}$ values were found for each wave condition tested using the hydrostatic analysis software Hydromax Pro produced by Formation Design Systems.

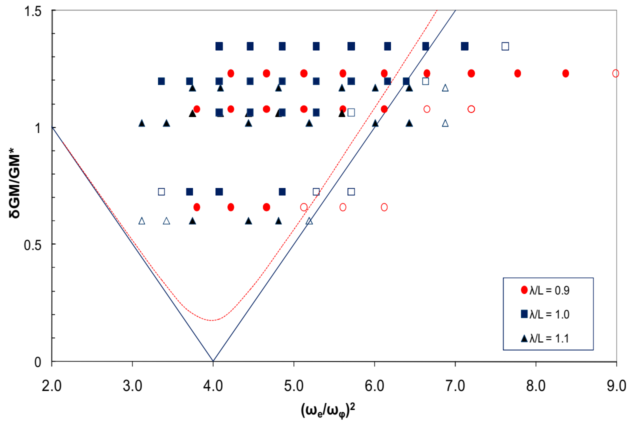

Fig. 7 Threshold boundaries for parametric roll, comparison of experimental and theoretical results, GM = 0.69 m.

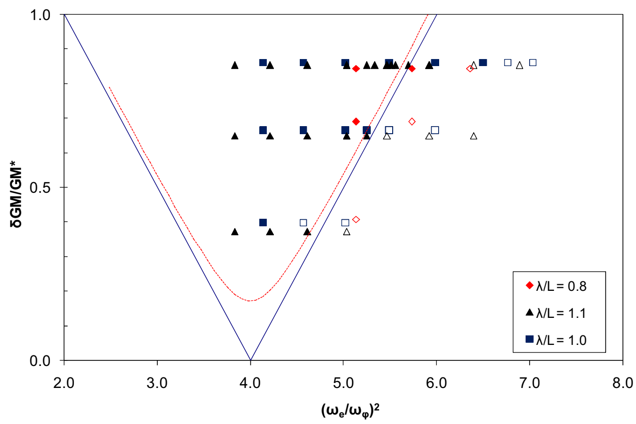

Fig. 8 Threshold boundaries for parametric roll, comparison of experimental and theoretical results, GM = 1.1 m.

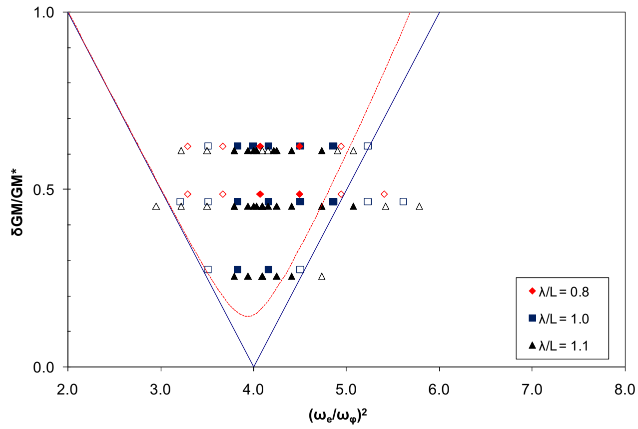

Fig. 9 Threshold boundaries for parametric roll, comparison of experimental and theoretical results, GM = 1.6 m.

Figures 7 to 10 indicate that a reduction in wave height results in a reduction of the range of encounter frequency for which parametric roll will occur. Generally for each condition tested, an increase in speed, thus increasing the encounter frequency, past the numerically determined threshold boundary resulted in the non-occurrence of parametric roll.

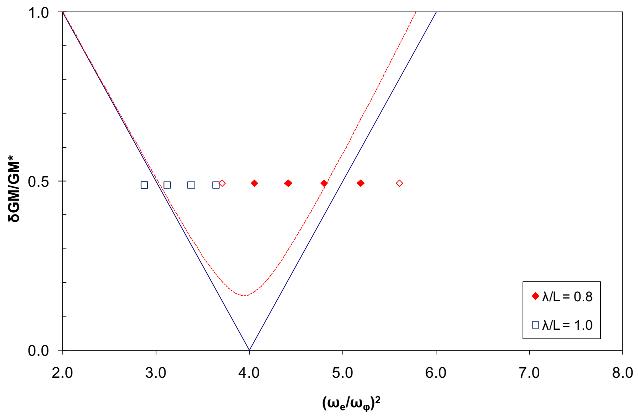

Fig. 10 Threshold boundaries for parametric roll, comparison of experimental and theoretical results, GM = 2.1 m.

For all the GM values tested reasonable agreement was found between the numerical predictions and experimental results, particularly at the higher $(\omega_e/\omega_\phi)^2$ boundary for parametric roll occurrence. However correlation was inferior for $(\omega_e/\omega_\phi)^2$ values less than 3.8; parametric roll did not occur in this region although the Mathieu Equation predicted that it would. In general the results suggest that the Mathieu Equation is an appropriate method for predicting the onset of parametric roll.

It should be noted that as the GM is increased the natural roll period reduces. This has the effect of also increasing the vessel speed required for parametric roll to be predicted to occur at, since $\left(\frac{\omega_e}{\omega_\phi}\right)^2$ will reduce with increasing ω_ϕ. As the vessel speed increases the roll damping also increases which significantly reduces the theoretical damped threshold curves. All these factors therefore tend to reduce the likelihood of parametric roll occurring with increased GM values.

CONCLUSIONS

The threshold boundaries, for the inception of parametric roll for a typical containership, the P&O Nedlloyd Hoorn, were established using a mathematical model based on the Mathieu equation. In addition a series of model experiments was conducted in the Australian Maritime College's towing tank to investigate the influences of wave conditions, ship speed and GM on the parametric roll behaviour of this containership.

The comparison between the theoretical and experimental results, of the threshold boundaries, was found to be reasonable for all GMs tested.

It is important to note that as the GM is increased the natural roll period reduces. This has the effect of also increasing the vessel speed required for parametric roll to be predicted to occur at, since $\left(\frac{\omega_e}{\omega_\phi}\right)^2$ will reduce with increasing ω_ϕ. As the vessel speed increases the roll damping also increases which significantly reduces the theoretical damped threshold curves. All these factors therefore tend to reduce the likelihood of parametric roll occurring with increased GM values.

The correspondence between experimental and theoretical results is, in the authors' view, sufficiently strong for the Mathieu equation to be used as the basis of computing ship-specific guidance information for masters in deciding appropriate navigational measures to avoid or evade bow/head seas parametric rolling in service.

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Fig. 11 Model of P&O Nedlloyd Hoorn experiencing severe roll motions during experimental testing, full scale GM =1.1m, full scale H_w = 9m, λ/L = 1.1