Assessment of Operational Risks of Parametric Roll

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ABSTRACT

In October 1998, a post-Panamax, C11 class containership encountered extreme weather and sustained extensive loss and damage to deck stowed containers. The motions of the vessel during this storm event were investigated through a series of model tests and numerical analysis. This confirmed that parametric roll was the most likely cause of the accident. The results of this study were presented in a technical paper in 2003 (France et al 2003).

One of the remaining questions of the study is the long-term probability (risk) of such an incident because several requirements must be satisfied for parametric roll to occur. These concern the loading condition, speed and wave height and period.

In our paper the results will be presented of a first-time attempt to quantify the operational risks of parametric roll for a large containership. The attempt is based on scenario simulations over a long period of time (5 years) in which many individual voyages are simulated on a given route. In the simulations a weather hind cast (waves and wind) is used to evaluate the sustained speed and ship behavior at every individual 2-hour time step. In the calculations the voluntary and involuntary speed loss are taken into account. The paper pays attention to the statistical aspects of the interpretation of the results.

Nomenclature

\( k_{xx} \) – Transverse radii of gyration (m)
RMS – Root mean square
\( T \) – Period (s)
\( T_p \) – Peak period (s)
\( H_s \) – Significant wave height (m)
\( V_{calm} \) – Calm water speed (knots)
\( \mu \) – Relative wave heading (deg)

Introduction

In late October 1998 a laden, post-Panamax, C11 class containership, eastbound from Kaohsiung to Seattle, was overtaken by a violent storm in the North Pacific Ocean. The encounter with the storm continued for some 12 hours, mostly at night, during which the master reduced speed and attempted to steer into increasingly higher seas off the vessel’s starboard bow. Ultimately, the seas became completely confused and violent.

Significant wave heights steadily increased from 10.9 m with a \( T_p \) of 13.5 s at the beginning of the storm to 13.4 m and 15.4 s at in the middle. The maximum \( H_s \) was 14.9 m with a \( T_p \) of 16.4 s.

More significant than the violence and magnitude of the seas, however, were reports by experienced engine and deck officers of unexpectedly extreme and violent ship motions during the worst of the storm. At times yaw angles of 20 deg port and starboard made course keeping almost impossible. Main engine overspeed trips and shaft vibrations together with pounding reflected significant pitch amplitudes. Port and starboard rolls as great as 35 deg to 40 deg were reported to have occurred simultaneously with the extreme pitching.

When the crew surveyed the vessel the following morning they found devastation of the cargo. Of the almost 1300 on-deck containers, one-third, with their cargoes, had been lost overboard. Another one-third, with their cargoes, were in various stages of damage.
and destruction. Containers and cargoes hung over both sides of the vessel.

The motions of the vessel during this storm event were investigated through a series of model tests and numerical analysis. This confirmed that parametric roll was the most likely cause of the accident. The results of this study were presented during SNAME’s 2001 annual meeting and reported in a technical paper (France et al 2003).

In that paper several recommendations for further research were made. Following that paper two major actions have being taken. The SNAME has established Ad Hoc panel no #13 “Investigation of Head-sea Parametric rolling and resulting Cargo security Loads”. The IMO subcommittee on “stability, loadlines and on fishing vessel safety” has been asked during the July 2002 meeting to consider head-sea parametric roll.

One of the remaining questions is the long-term probability (risk) of head seas parametric roll event associated with high roll angles. Several criteria have to be fulfilled before parametric roll can occur. Loading condition, speed and wave all are determining if parametric roll will occur. It is assumed that the probability that these conditions are right at the same time for parametric roll to occur is small. This is one of the reasons that not many ship designers and ship operators are concerned of the problem. Still, a big incident happened with a container vessel, so the probability is not zero. But how high is it and can we expect a similar incident in the near future?

Contents

In this paper a first time attempt is presented to quantify operational risks of parametric roll for a large containership. The attempt is based on scenario simulations over a long period of time (five years) in which many individual voyages are simulated on a given route. Each time step the probability of parametric roll is evaluated.

The probability of parametric roll is taken from a database if simulation results generated for a range of speeds, wave headings and wave conditions. Numerical tools are used to generate this database.

In the simulations a weather hind cast (waves and wind) is used to evaluate the sustained speed and ship behavior at every individual two-hour time step. In the calculations the voluntary and involuntary speed loss are taken into account.

Theory

The theory behind parametric roll has been studied and described by many persons. In the references several papers and articles are given related to the theory behind parametric roll (Kempf 1938, Graff and Heckscher 1941, Pauling 1959 and 1961, Oakley 1974, Dunwoody 1998, Dallinga et al 1998, Luth 1998). In this paper only the principles of parametric roll will be described. Some examples from model tests will be given.

In “normal” conditions the motions of a vessel are caused by direct wave excitation. Resonant conditions can occur when the combination of wave heading, wave period and vessel speed lead to an encounter wave period close to the natural period of the vessel. These resonant conditions can lead to high motions.

For the roll motion resonant roll conditions can occur in beam waves and stern quartering waves. In head waves roll motion caused by direct wave excitation are not possible. Nevertheless, under certain conditions of encounter frequency, a rolling motion can exist. The roll motion, once started, may grow to large amplitude limited by roll damping and, in extreme conditions, may result in danger to the ship or its contents. This phenomenon is referred to as “auto parametrically excited motion” which is usually shortened to “parametric motion”. The term describes a state of motion that results not from direct excitation by a time-varying external force or moment but from the periodic variation of certain numerical parameters of the oscillating system. For a ship in head or stern seas the uneven wave surface together with the pitch-heave motion of the ship results in a time-varying underwater hull geometry. This varying geometry, in turn, results in time-varying changes in the metacentric height, i.e., in the static roll stability. The variation of the static roll stability can cause instability if it occurs in the appropriate period. The instability can lead to roll when a small excitation, introduced by a rudder movement for example, causes the vessel to take a small roll angle to one side. The roll angles can become very large if the stability variation and the wave height are large.

From theory and as validated by model tests (Dallinga 1998, Luth 1998, France 2003), parametric roll occurs when the following requirements are satisfied:

1. The natural period of roll is equal to approximately twice the wave encounter period.
2. The wavelength is on the order of the ship length (between 0.8 and 2 times LBP).
3. The wave height exceeds a critical level.
4. The roll damping is low.
Typical Results from Model Tests

In the figures below time traces of model tests are given of the roll motion, pitch motion and wave height during a run in regular head waves.

Figure 2 Time Trace of Roll, Pitch and Wave Height during Regular Wave Test

Figure 2 shows that at the start of the test the model was pitching to angles of about 4 deg, with negligible roll response. A small excitation, likely introduced by a rudder movement, causes the vessel to take a small roll to one side. Quite unexpectedly, roll angles then increased from a few degrees to over 30 degrees in only five roll cycles. This behavior is parametric rolling. Once parametric roll was initiated, the model continued to roll violently. The pitch amplitude remains the same.

Figure 3 shows an expanded view of the roll and pitch response in regular waves. Positive pitch values mean the vessel is pitched down by the bow. It can be seen from Figure 3 that there are two pitch cycles for each roll cycle, and that the model is always pitched down by the bow at maximum roll. That is, when the model is at maximum starboard roll it is pitched down by the bow, when upright at zero heel it is pitched down by the stern, and when at maximum port roll it is pitched down by the bow again. Throughout the test program, this relationship between pitch and roll motions existed whenever parametric roll was induced.

Figure 3 Expanded View of Roll and Pitch Motions during Regular Wave Test

Most of the irregular wave and short-crested sea tests fulfilled the requirements for parametric roll, as well. In Figure 4 the roll and pitch motions and the wave height are shown for a test in irregular seas. The 2:1 ratio between roll period and pitch period is again apparent. When the model encounters a sequence of wave components of a certain period and height, parametric rolling is initiated if the conditions are right. As in regular waves, the roll quickly builds to large amplitudes. When the wave period changes or the wave height diminishes, the parametric roll response quickly dissipates.

Figure 4 Expanded view of Roll and Pitch Motions at Time of Largest Roll in Short Crested Sea Test

Numerical Analysis

Nonlinear, time domain seakeeping computer codes are able to predict the phenomenon of parametric roll. During the investigation of the previous mentioned incident (France et al 2003) two computer codes were successfully used to predict parametric roll. SAIC’s LAMP (Large Amplitude Motion Program, Lin and Salvesen, 1998, Lin and Yeu, 1990, 1993, Treakle 2000) and MARIN’s FREDYN computer code (Hooft, 1987, de Kat, 1989, 2002, McTaggart, 2000) were used to simulate ship motions for comparison with model test results.

FREDYN is a nonlinear, time domain ship motion simulation program developed by MARIN over the last 10 years for particular use in predicting motions of naval frigates. However, it has also been utilized for commercial vessel motion predictions.

FREDYN takes into account the external forces on the ship due to wind and waves, rudders, bilge keels and active stabilizer fins and the reaction forces of the ship due to the motions. The total Froude-Krylov exciting forces are calculated by integration of the hydrostatic and dynamic wave pressures up to
the instantaneous waterline, which makes the program nonlinear. Since FREDYN is a full 6 degrees of freedom model it includes the couplings between the individual modes of motion. Both nonlinearity of the excitation forces and coupling between the 6 motions is required to be able to predict parametric roll motion. The maneuvering model is based on frigate type ships; all other routines are independent of the ship type. Since maneuvering was not a major aspect in this investigation, the FREDYN model was applicable.

FREDYN models a ship as a free running vessel in waves, comparable to a free sailing model in a seakeeping basin. The heading of the vessel is controlled by an autopilot that reacts to the instantaneous motions of the ship. The initial speed is set to the desired value and the RPM of the motor is set such that the ship is propelled at the desired speed in calm water. Due to the waves, the speed and course of the ship change during the runs. However, different from MARIN’s seakeeping basin, FREDYN is capable of modeling only uni-directional long-crested waves.

Several studies (France 2003, Luth and Dallinga, 2000) have shown that although FREDYN is capable of predicting parametric roll, the prediction of roll amplitude is of limited accuracy. This is due to the difficulty to predict the non-linear (viscous) roll damping correctly and the fact that several important effects are not modeled by FREDYN—speed loss and speed variations—which likely account for this inaccuracy in amplitude.

Selection of Case

For the study presented in this paper the post-Panamax, C11 containership, which encountered the storm, as described in the introduction was used. It is a logical starting point because already FREDYN simulations and model tests were performed on the same vessel at MARIN.

**FREDYN Simulations**

The FREDYN computer program was used to generate a database containing the probability of parametric roll for a range of speeds and wave conditions. Before running all conditions FREDYN was compared to the results of model tests in order to estimate the accuracy of the program in the calculation of parametric roll for a wide range of wave conditions.

The same loading condition as used during the model tests was taken. Extra attention was paid to the roll angles and the roll damping, which is calculated with the Ikeda Himeno (1978) method. In the following three figures the roll decay as measured and as calculated by FREDYN is given for three different speeds.

**Roll Decay Tests Comparison**

In Figure 6 the roll decay results from model tests and FREDYN computations for zero knot speed are presented. To get the natural roll period correct and the roll damping the \( k_{xx} \) used in FREDYN was tuned. After that tuning the comparison between FREDYN and model tests was very good.

![Figure 6 Roll Decay at Zero Knots](image)

In Figure 7 and Figure 8 the same comparison is given for 5 knot and 10-knot speed. The results show that also for these speeds the “\( k_{xx} \) tuned” FREDYN results are very close to the model test results.

**Figure 5 C11 Hull Form C11 type case**

A rendering of the C11 hull form is presented in Figure 5. Typical of post-PANAMAX containerships, the C11 has extensive bow and stern flare. The ship’s natural roll period as used in this study was 25.7 seconds. This corresponds to the estimated value during the incident.
The rest of the FREDYN computations were performed with an altered $k_{xx}$ value. No other tuning parameters were used.

**Regular Wave Tests Comparison**

In Figure 9 the results of FREDYN computations for regular waves are compared to model tests ($H_s = 8 \text{ m}, T = 14.1 \text{ s}, \mu = 180 \text{ deg}$ and $V_{c\text{alm}} = 16 \text{ knot}$). The figure show time traces of the roll motion, pitch motion and wave amplitude. From the time trace of the waves one can see that the wave amplitude during the model tests is not completely constant. The results of this can be seen in the time trace of the pitch motion. There one can see that the maximum pitch amplitudes are also not constant. The time trace of FREDYN shows constant wave and thus pitch amplitudes.

The time traces of the roll motion shows that the FREDYN results are very close to the model tests results. Also the pitch amplitudes are very well predicted by FREDYN. This means that the prediction of the roll damping in FREDYN is very well for this case.

In Figure 10 the time trace of roll motion as predicted by FREDYN and measured during model tests is given for another wave condition ($H_s = 10 \text{ m}, T = 14.1 \text{ s}, \mu = 150 \text{ deg}$ and $V_{c\text{alm}} = 16 \text{ knot}$). The figure shows that also in that condition the comparison between FREDYN and model tests shows very good agreement.

**Irregular Wave Tests Comparison**

The last check on the accuracy of FREDYN is in irregular waves. In the table below the statistical results of measurements and calculations in irregular waves is given ($H_s = 13 \text{ m}, T_p = 15.1 \text{ s}, \mu = 180 \text{ deg}$ and $V_{c\text{alm}} = 16 \text{ knot}$).

<table>
<thead>
<tr>
<th></th>
<th>Model tests</th>
<th>FREDYN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_s$ [m]</td>
<td>13.2</td>
<td>12.96</td>
</tr>
<tr>
<td>RMS Roll [deg]</td>
<td>9.89</td>
<td>9.50</td>
</tr>
<tr>
<td>Max Roll [deg]</td>
<td>34.74</td>
<td>30.57</td>
</tr>
</tbody>
</table>
From the table it can be seen that also in irregular waves the FREDYN results are very close to the results of the model tests. The root mean square (RMS or standard deviation) of roll is within 4% and the mean of the maximum and minimum values within 8%. Also the pitch motion is very well predicted by FREDYN.

**Conclusion of Comparison FREDYN and Model Tests**

Results of roll decay, regular wave tests and irregular wave tests have been compared. After “tuning” of the $k_{xx}$ to get the natural roll period correct the FREDYN results showed good to very good agreement with the model tests. It is assumed that also in other wave conditions the FREDYN predictions will be good. Therefore it can be concluded that the FREDYN results can be used to predict the parametric roll behavior of the real vessel in arbitrary conditions.

**Probability of Parametric Roll Database Results of FREDYN Simulations**

In order to assess the operational risks of parametric roll the probability of parametric roll must be known for all wave conditions (relative wave heading, wave height, wave period and vessel speed), that the vessel might encounter during her normal operation.

For this purpose a large amount of FREDYN simulations were performed. The program was used for the earlier described case (C11 class containership with a natural roll period of 25.7 sec.) for a matrix of speeds, wave headings, wave periods and wave heights. The speed range used was from 2.5 knot to 20 knots with a 2.5 knot increment, three wave headings were used (120 deg, 150 deg and 180 deg), the wave periods ($T_p$) varied from 3.5 s to 17.5 sec with one second increment and the wave height range taken varied from $H_s = 0.5$ to $H_s = 14.5$ with one meter increment. By eliminating all unrealistic combinations of wave height and wave period the total amount of calculations could be reduced to 3165 simulations.

In order to encounter enough wave groups each simulation was performed for three hours real time. Three hours is also the mean duration of a sea state. Variation of the simulation duration and analysis of the results showed that a three-hour simulation time is enough in order to see if parametric roll occurs in a particular condition.

**Analysis of Results**

The results of each individual calculation is a three hour time trace of the motions, position of the vessel, speed etc. as presented in the earlier sections. The program gives also statistical results (RMS, minimum, maximum etc.), which however cannot be used to determine if the vessel suffered from parametric roll in that particular condition. The vessel could indeed be in parametric roll conditions only for a small period of time, which wouldn’t influence the statistical results but still a few large roll angles are sufficient to cause large damage to the vessel. So, to analyze the probability of parametric roll in each condition the individual time traces were used.

In order to see if parametric roll occurred in one simulation a special analysis was made on the results. For each time step the roll angle was compared to a threshold level. If two subsequent roll amplitudes (negative or positive) are higher than that threshold the group of roll angles is marked as parametric roll (see Figure 11). For each simulation the number of these groups was determined as well as the total duration of all groups in one simulation. The total group time is a good figure to evaluate the probability and seriousness of parametric roll events in a particular sea state. To determine the group time a threshold of 10 degrees roll amplitude was used.

![Figure 11 Determination of Group Time of Subsequent (Parametric) Roll Angles](image-url)

Several different criteria were tried to determine if in a sea state the vessel suffers from parametric roll. The first one was the number of groups with parametric roll per 3 hours simulations. It was expected that the number of groups would increase with the wave height. It turned out that above a certain wave height the number of groups decreases...
because the vessel is continually subject to parametric roll. Finally, the mean of 1/10th highest roll amplitudes was used to determine if in a sea state the vessel suffered from parametric roll. If that value was above 10 degrees the sea state was marked as one in which the vessel would have parametric roll.

Results of FREDYN Calculations

In the table below a sample of the FREDYN results is given. The table shows the mean of 1/10th highest roll amplitudes for a speed of 5 knots in head waves for a range of wave heights and wave peak periods.

<table>
<thead>
<tr>
<th>Hs (m)</th>
<th>8.5</th>
<th>9.5</th>
<th>10.5</th>
<th>11.5</th>
<th>12.5</th>
<th>13.5</th>
<th>14.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tp(s)</td>
<td>1.5</td>
<td>2.5</td>
<td>3.5</td>
<td>4.5</td>
<td>5.5</td>
<td>6.5</td>
<td>7.5</td>
</tr>
<tr>
<td>0.5</td>
<td>0.1</td>
<td>0.5</td>
<td>0.6</td>
<td>0.6</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
</tr>
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<td>1.5</td>
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<td>0.1</td>
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<td>0.1</td>
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<td>2.5</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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</tr>
<tr>
<td>3.5</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>4.5</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<td>5.5</td>
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<td>0.1</td>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 2 Mean of 1/10th highest Roll Amplitudes, Speed = 5 knots, Head Waves

In the figures below the mean of 1/10th highest roll amplitudes is plotted against the significant wave height for a few different conditions.

Figure 12 Mean of 1/10th highest roll amplitudes for different speeds, head waves, Tp = 13.5 s

Figure 13 Mean of 1/10th highest roll amplitudes for different wave periods, head waves, Speed = 5 knots

Table 3 Total time of Parametric Roll in 3 hour Simulation in minutes (Group Time), Speed = 5 knots, Head Waves

In the figures below the mean of 1/10th highest roll amplitudes is plotted against the significant wave height for a few different conditions.
First of all the figures clearly show that parametric roll is a phenomenon with is limited by a threshold wave height. The associated roll angles are immediately important. This effect is less in bow quartering waves (120 deg) than in head waves. The speed has a large influence on the occurrence of parametric roll. For high speeds parametric roll will only occur for very high wave heights. This is due to two effects. The speed influences the encounter wave period and the roll damping is higher for higher speeds. Also the wave period is important for parametric roll to occur. When the wave period is not close to half the natural roll period parametric roll will not occur.

Assessment of Operational Risks of Parametric Roll

In the previous section a database was presented containing information for which wave conditions, wave heading and speed the vessel will suffer from parametric roll. If that information is combined with information about the probability of these wave conditions and speeds on a particular route one can determine the operational risks of parametric roll on a route. In the following two sections two approaches will be described, the wave scatter diagram approach and the scenario simulation approach.

It must be noted that the database as presented in the previous section was determined for one loading condition only. The results show that the vessel is subject to parametric roll for that loading condition. The results also showed that the occurrence of parametric roll depends in the wave period, which depends on the natural roll period, and a threshold wave height. With a different loading condition with a lower natural roll period the wave periods in which the vessel is subject to parametric roll is also different. Situations occur in which the threshold wave height for which parametric roll could start do not exist (unrealistic steep waves) for the critical wave periods.

So, for other loading conditions the probability of parametric roll could be different and even zero depending on the GM and natural roll period. A container vessel will sail with a different loading condition on each trip. In this study we have only looked at one loading condition. The results as presented are therefore conservative. The probability of loading conditions in which the vessel is subject to parametric roll should also be taken into account.

Wave Scatter Diagrams Approach

A wave scatter diagram gives the probability of a certain combination of wave height and wave period for a given sea area or route. The wave scatter diagram however doesn’t give information on the relative wave direction and the speed that the vessel will sail. When combining the information of the wave scatter diagram with the parametric roll database a wave heading and vessel speed must be assumed. The probability of this wave heading and vessel speed is however not known.

In Table 4 the results of combining wave scatter diagrams with the parametric roll database are presented.
The wave scatter diagram gives the probability of each combination of $H_s$ and $T_p$ in thousands. The wave scatter diagram used is area 9 (North Atlantic) all directions from the Global Wave Statistics (Hogben 1986). The colors indicate the sea states for which parametric roll occurs for different speeds in head waves. From the table one can determine the probability of parametric roll by counting the number of occurrences of the sea states within the colored fields.

If one assumes that the vessel sails in head seas with a speed of 5 knots the probability of parametric roll is 7.3%. For 10 knots the probability is 0.7% and for 15 knots 0%. The same analysis was performed for all speeds and wave headings from the parametric roll database. The results are presented in Table 5.

If one assumes that the vessel sails in head seas with a speed of 5 knots the probability of parametric roll is 7.3%. For 10 knots the probability is 0.7% and for 15 knots 0%. The same analysis was performed for all speeds and wave headings from the parametric roll database. The results are presented in Table 5.

### Table 5 Probability of Parametric Roll (in %) for North Atlantic area for Different Combinations of Speed and Wave Heading

<table>
<thead>
<tr>
<th>Speed [knots]</th>
<th>Wave Heading [deg]</th>
<th>120</th>
<th>150</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>1.4</td>
<td>9.4</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>0.6</td>
<td>6.5</td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td>0.2</td>
<td>1.9</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>0</td>
<td>0.5</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>12.5</td>
<td>0</td>
<td>0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>15.0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>17.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>20.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

From the table the influence of wave heading and speed on the occurrence of parametric roll can again be seen. At a wave heading of 120 deg the probability of parametric roll is very small even at very low speeds. In bow quartering waves of 150 deg and head waves the probability of parametric roll can be significant for speeds smaller than ten knots.

The table clearly shows that the vessel with this loading condition would have a non-zero probability of a parametric roll event. The probability of the vessel sailing a certain wave heading and speed is however not known. With the statistical method, using wave scatter diagrams, it is difficult to assess those risks. The results of a statistical approach do not tell the effect of persistence of storms on the number of affected trips. Also the impact that operational measures (like a temporary reduction of speed) have on the number of occurrences of parametric roll cannot be difficult to evaluate correctly. The results of scenario simulations are simpler to use for that purpose. But the main advantage is that at each time step of the simulation the wave and wind conditions are known and the sustained speed.

### Scenario Simulation Approach

A practical way around the problems and limitations of a statistical approach is based on a deterministic step-wise simulation of a given “mission”. The use of hind cast data (from wind-wave models) as input for wind and waves solves the problem of accounting for the right coherence between wind and waves and the varying spectral characteristics of the waves. We used MARIN’s GULLIVER scenario simulation program for this purpose.

### Weather

The scenario simulations are based on hind cast data for North Atlantic from Jan 01, 1995 to Dec 31, 1999. The data were obtained from the European Center for Medium Range Weather Forecasts (ECMWF) in Reading in the UK.

The wind estimates are based on a mathematical model for the atmosphere; the data were correlated daily with meteorological station measurements. Wave spectrum data are then obtained after processing of the wind field with a wind-wave model.

The wind is available in terms of speed and direction (see Figure 16 for example). The wave data consist of significant wave height, mean period and direction of wind-sea and swell. The data are available on a grid of 1.5 deg x 1.5 deg in time steps of 6 hours.

![Figure 16 Example of ECMWF Data, Wind Speed on North Atlantic, January 10, 1999](image_url)

For each time step an irregular short crested sea is reconstructed from the above global parameters. A JONSWAP wave spectrum with variable spectral shape and directional spread was used according the Mitsuyatsu formulation.

### Route

Calculations were performed on one route between Southampton and New York. A northern trip was simulated in both westbound and eastbound directions. The route is the great circle from Southampton to New York. Because weather
information is missing for about 60 miles from the British coast, trips do not exactly start at Southampton but at co-ordinate: 50.16N / 3.65 W. The route is 2937 nautical miles long. Simulations were performed for the vessel going westbound and returning from New York (eastbound).

![Figure 17 Route Used for Scenario Simulations](image)

**Calculation Procedure**

An individual voyage consists of a fixed route, which consists of a number of waypoints. A voyage starts at the first waypoint at a pre-defined moment in time; it ends when the last waypoint has been reached. Time is increased with a fixed quantity (in this case 2 hours) at the end of each time step. At each time step the simulation:

- Interpolates the wind and waves at the ships position;
- Re-constructs the wave spectrum from the wind sea and swell parameters;
- Evaluates the involuntary speed loss due to wind drag and added resistance from waves;
- Calculates the progress at each time step.

To obtain reliable statistics a large number of trips is simulated. The present simulations account for a departure on every fourth day over a period of five years. A period of four days is regarded sufficient to obtain statistically independent results. It is assumed in the simulations that the vessel doesn’t reroute or change course.

**Analysis Procedure**

The results of the simulations are time traces of encountered wave conditions (wave height, wave period and wave direction) and the sustained speed on the route. Unlike the wave scatter diagram approach now the probability of a certain wave heading and sustained speed is known. At each time step the wave condition and sustained speed were used to look in the parametric roll database to see if the vessel is subject to parametric roll. The total numbers of parametric roll events were counted as well as the number of trips were one or more events occurred.

**Results of Scenario Simulations**

A total number of 456 trips eastbound and 456 westbound were simulated. In all the results presented in the tables it is assumed that the vessel is always sailing with the same loading condition.

In Figure 18 the time trace of the wave height for all simulations is given. The seasonal effects on the wave height can clearly be seen. The winter periods can be recognized from the periods with higher wave conditions. Very interesting is the fact that the summer seasons are not without relatively high wave conditions.

![Figure 18 Time Trace of Wave Height for all Simulations West Bound](image)

Figure 19 (frequency of occurrences of the wave height) and Figure 20 (probability of exceedance of a wave height) show statistical results of the analyzed wave height time trace.
Figure 19 and Figure 20 show that on this route high waves can occur. The probability of waves higher than 7.5 m is 1 % and the probability of waves higher than 10 m is 0.1 %.

Figure 21 shows the time trace of the sustained speed. Also there the seasonal effects can be seen. The maximum speed in calm water is 25 knots and the maximum speed loss due to wind and waves is about ten knots.

In Table 6 the results of the analysis of simulation results and the parametric roll database are given. The table gives for the west bound and east bound trips the number of trips and events where according to the parametric roll database the vessel would have a parametric roll event. The criterion is that the vessel is sailing in head or bow quartering waves and that the mean of the 1/10th highest roll amplitude is higher than 10 degrees. In the table also the percentage of trips and time steps with parametric roll events is given. The table also gives the number of trips and events with two successive roll angles (due to parametric roll) above 20 degrees and 30 degrees.

<table>
<thead>
<tr>
<th></th>
<th>West Bound Trips</th>
<th>East Bound trips</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1/10 &gt;= 10 deg</td>
<td>N= 3 % 0.66 N= 0.02</td>
<td>N=0 0.00 N=0 0.00</td>
</tr>
<tr>
<td>Successive Angles &gt;= 20 deg</td>
<td>N= 2 % 0.44 N=0 0.00</td>
<td>N=0 0.00 N=0 0.00</td>
</tr>
<tr>
<td>Successive Angles &gt;= 30 deg</td>
<td>N= 0 % 0.00 N=0 0.00</td>
<td>N=0 0.00 N=0 0.00</td>
</tr>
</tbody>
</table>

Table 6 Number of Trips and Time Steps with Parametric Roll Events. Max. Sustained Speed

From the table one can see that in approximate one percent of the trips west bound a parametric roll event occurs. The number of trips with parametric roll is three. In two of the trips the roll angles are higher than 20 degrees East bound no parametric roll events occur. The reason for the difference between the results for west bound and east bound route is the direction of the depressions on the North Atlantic. The depression travel from west to east and the main direction of the waves on the latitude used is in the same direction. A vessel going to the west will encounter more head and bow quartering waves than going from west to east. Thus the probability of parametric roll is higher going from east to west the other way.

In Figure 22 the maximum sustained speed (open blue points) for all the west bound trips is plotted against wave height. The scatter is due to the relative wave heading. In head seas the vessel will loose speed and in following waves and stern quartering waves the speed will not be affected much.
From the figures it can be seen that if one only takes into account involuntary speed loss (due to wind and waves) that the vessel is sailing at very high speeds in high waves (between 12.5 and 15 knots in waves above ten meter). At these high speeds the vessel the probability that the vessel suffers from bow flare slamming and green water is high. It is assumed that a captain would reduce speed in these high sea states.

To see the influence of voluntary speed loss on the probability of parametric roll a simple scenario was assumed. The scenario (red dots in Figure 22) assumes that the speed is reduced to 7.5 knot when the waves are higher than $H_s = 8$ m but lower than $H_s = 12$ m and further reduced to 5 knots in waves above $H_s = 12$ m. The results of using this scenario together with the results of the analysis of simulation and the parametric roll database are given in Table 7.

<table>
<thead>
<tr>
<th></th>
<th>Trips</th>
<th>Steps</th>
<th>Trips</th>
<th>Steps</th>
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</thead>
<tbody>
<tr>
<td><strong>West Bound Trips</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1/10 &gt;= 10 deg</td>
<td>22</td>
<td>104</td>
<td>4.82</td>
<td>0.38</td>
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<tr>
<td>Successive Angles &gt;= 20 deg</td>
<td>21</td>
<td>88</td>
<td>4.61</td>
<td>0.32</td>
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<tr>
<td>Successive Angles &gt;= 30 deg</td>
<td>2</td>
<td>5</td>
<td>0.44</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>East Bound trips</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1/10 &gt;= 10 deg</td>
<td>3</td>
<td>5</td>
<td>0.66</td>
<td>0.02</td>
</tr>
<tr>
<td>Successive Angles &gt;= 20 deg</td>
<td>3</td>
<td>5</td>
<td>0.66</td>
<td>0.02</td>
</tr>
<tr>
<td>Successive Angles &gt;= 30 deg</td>
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<td>0</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 7 Number of Trips and Time Steps with Parametric Roll Events. Voluntary Speed Loss

From Table 7 one can see that when voluntary speed loss is taken into account in nearly 5% of the trips parametric roll occurs, with nearly 5% events with roll angles higher than 20 degrees (west bound).

The reason that the percentage for parametric roll with roll angles lower than 20 degrees and the percentage with roll angle higher than 20 degrees is small is due to the fact that parametric roll is a threshold phenomenon. If parametric roll occurs the associated roll angles have immediately large amplitudes. East bound the risk is less than 1%.

It is clear that voluntary speed loss and course changes will influence the risk of parametric roll events. The measures to reduce “normal” ship motions, vertical and transversal accelerations, slamming or green water can put the vessel into situation were it is subject to parametric roll. If one assumes that the vessel would have a zero speed in all wave conditions were parametric roll could occur but where the sustained speed is to high for parametric roll one can determine the “theoretical” maximum number of parametric roll events. These results are presented in Table 8.

<table>
<thead>
<tr>
<th></th>
<th>Trips</th>
<th>Steps</th>
<th>Trips</th>
<th>Steps</th>
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</thead>
<tbody>
<tr>
<td><strong>West Bound Trips</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1/10 &gt;= 10 deg</td>
<td>92</td>
<td>692</td>
<td>20.18</td>
<td>2.50</td>
</tr>
<tr>
<td>Successive Angles &gt;= 20 deg</td>
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<td>609</td>
<td>19.30</td>
<td>2.20</td>
</tr>
<tr>
<td>Successive Angles &gt;= 30 deg</td>
<td>7</td>
<td>22</td>
<td>1.54</td>
<td>0.08</td>
</tr>
<tr>
<td><strong>East Bound trips</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1/10 &gt;= 10 deg</td>
<td>11</td>
<td>35</td>
<td>2.41</td>
<td>0.13</td>
</tr>
<tr>
<td>Successive Angles &gt;= 20 deg</td>
<td>10</td>
<td>34</td>
<td>2.19</td>
<td>0.12</td>
</tr>
<tr>
<td>Successive Angles &gt;= 30 deg</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 8 Maximum Number of Trips and Time Steps with Parametric Roll Events. Zero Speed

From the table one can see that the percentage of maximum number of trips where sea conditions are encountered in which the vessel would suffer from parametric roll is 20% (from which just over 19% with roll angles higher than 20 degrees). East bound the values are much lower (2%).

The results show that the potential risk of parametric roll is significant. But, if the vessel can maintain speed and avoid head seas and bow quartering seas when the waves are high the risk drops significantly. However, even than the risk is not zero. This means that if loading conditions with a high natural roll period cannot be avoided the vessel is to use weather routing to avoid wave heights above a certain threshold value. Or, avoid certain loading conditions when the vessel cannot re-route.

For ship designers this means that they should design vessels that can maintain high speeds in rough weather. So enough power to avoid involuntary speed loss and such a design that voluntary speed loss is not needed (no bow flare slamming, green water etc.).
Conclusions

In this paper a first time attempt to quantify the operational risks of parametric roll for a large container vessel is presented. The used vessel is a C11 class post-panamax container vessel. It can be assumed that vessels in the same class will behave in the same way.

For the study the information from weather statistics from wave scatter diagrams and scenario simulations is coupled with a parametric roll database. This database gives the probability of parametric roll for a given vessel speed, wave heading, wave height and wave period. The database was determined by using a very large number of non-linear seakeeping simulations using MARIN’s FREDYN program.

Before running all simulations the results of FREDYN were compared to model tests results. The comparison of roll decay tests, regular waves tests and irregular wave test showed that after the tuning of the transverse radii of gyration $k_x$, the results of the simulation were very close to the results of the model tests.

In this paper only one loading condition was used. It is known that the vessel is subject to parametric roll for that loading condition. Normally a container vessel sails in a variety of different loading conditions, some for which parametric roll could occur but also some for which it never will. This means that the results presented in this paper should be regarded as conservative.

Using a wave scatter diagram it was determined that the probability of parametric roll at low speeds (2.5 knot) in head waves and bow quartering waves of 150 deg at low speeds is 9%. At 5 knot speed it is 6% and with higher speeds the probability drops significantly. The probability of the vessel sailing a certain wave heading and speed is however not known when one uses a wave scatter diagram. Voyage simulations are needed to quantify those risks.

Voyage simulations of a container vessel on an imaginary route from Southampton to New York were performed. For the weather on the route a five-year hind cast database from ECMWF was used. The database contains information on the wind, wind driven seas and swell for each time step. Each time step during the simulation the actual weather is used to determine the speed loss due to wind and waves. A total number of 456 trips west bound and 456 trips east bound were simulated.

Using voyage simulations it was determined that the maximum theoretical number of trips were wave conditions are encountered which can cause parametric roll is 20% when going west bound. East bound the probability is much lower due to the fact that the average encountered wave direction not head or bow quartering waves.

Using a maximum sustained speed scenario it was determined that the probability of encountering parametric roll is less than 1% going west bound and zero going east bound. The maximum sustained speed scenario however doesn’t account for voluntary speed loss. It is assumed that a captain would reduce speed to avoid bow flare slamming, green water or high motions in certain conditions.

Assuming a simple speed reduction scenario it was determined that the probability of encountering parametric roll is then 4.8% going west and less than 1% east bound. When there is parametric roll the probability that the roll angles are above 20 degrees is more or less the same 4.6%.

In all the simulations performed it was assumed that the vessel would sail with the same loading condition, wouldn’t reroute or change heading. These can off course influence the results presented. Rerouting would reduce in most of the cases the probabilities but change of heading might raise the probabilities if the captain decides to heave into the waves.

The results showed that the occurrence of parametric roll depends in the wave period, which depends on the natural roll period, and a threshold wave height. With a different loading condition with a lower natural roll period the wave periods in which the vessel is subject to parametric roll is also different. Situations occur in which the threshold wave height for which parametric roll could start do not exist (unrealistic steep waves) for the critical wave periods. So, for another loading conditions the probability of parametric roll could be different and even zero depending on the GM and natural roll period.

The results presented in this paper show that the current fleet of C11 type container vessel have a non negligible risk of encountering condition in which parametric roll can occur. The ship operators should be aware of this risk and take measures to reduce it. Avoid loading conditions with a high natural roll period or if that is not possible use weather routing to avoid high waves.

For ship designers this means that they should design vessels that can maintain high speeds in rough weather. So enough power to avoid involuntary speed loss and such a design that voluntary speed loss is not needed (no bow flare slamming, green water etc.).
References


