Evaluation of the Cargo Loss of a Large Container Vessel due to Parametric Roll

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ABSTRACT

A Panmax Container vessel experienced the loss of several containers in when sailing westbound in the pacific. During the time of the cargo loss, the vessel was traveling in stern quartering seas and was rolling moderately. Suddenly, the roll was more violent and some containers were fallen over board. The analysis has shown that this situation could be associated to a parametric roll situation in the 1:1 resonance. This was later confirmed by a study where a detailed motion simulation in rough has been carried out.

KEY WORDS

Parametric Rolling, Cargo Loss, Motion Simulation.

INTRODUCTION

Parametric rolling as the source of cargo losses of ships, especially large Container vessels, has become a significant problem, and the APL CHINA case has demonstrated the vulnerability of these types of vessel in heavy weather. However, parametric rolling as such is not a new phenomenon, it is actually known for many years and has its main source in the alteration of the righting levers in crest and trough situations. Since some years, the problem is associated with container vessels and due to the incidents recorded, it is mainly considered as a problem that occurs in head sea scenarios. This is due to the fact that most of the container losses happened in such scenarios, where the vessels had significant initial GM- values, which resulted in large accelerations and consequently a cargo loss if the roll amplitudes become significant.

These events have drawn the attention away from the fact that also in stern quartering seas, parametric rolling can occur, which always leads to large rolling angles, in worst cases even to a capsize, but not necessarily to large accelerations due to the fact that the GM- values which make these scenarios possible are moderate or low. As a matter of fact, two critical situations do occur in stern quartering seas, namely the 2:1 resonance situation at lower speeds (2 pitch cycles per one roll cycle), which often leads to extremely violent roll (in this situation, the roll damping is also very low) or the 1:1 resonance at larger speeds which can lead to large rolling amplitudes if the significant wave length and height do lead to sufficiently large righting lever alterations. These two scenarios may occur in following or stern quartering seas, whereas in head seas, only the 2:1 scenario may occur.

Especially on the Pacific Route, ships are very often operated in following sea scenarios. This is due to the fact that weather routing is better possible on these routes as e.g. on the Atlantic route due to the fact that the weather conditions are more stable on this route. This is shown in Fig. 1, where the course distribution is presented for the North Pacific Route.

![Figure 1: Routing and course distribution on the Pacific Route from full scale observations (by courtesy of DNV).](image-url)
It is obvious that the dominant scenario is the stern quartering and following sea scenario on this route. Operating vessels in these scenarios may lead to parametric roll problems, which can be more critical than in head seas due to the fact that the stability of the vessel is generally lower and large roll angles occur very suddenly, without any indication for the crew that they are sailing close to a critical stern quartering scenario (see Fig. 6 below). According to our experience with model tests, a ship may be operated for a long time in such a scenario without any violent rolling and suddenly, if a group of waves (2 or 3) fits well to the response of the vessel, large roll angles are suddenly excited that can lead to a capsize. If a container vessel experiences a cargo loss in such a situation, this results in a shift of the natural response period to smaller values and the vessel is immediately out of resonance.

In the present case study, a Panmax Container vessel was travelling in the North Pacific, experiencing wind forces abt. BF 7-8 from NW to SW directions. The wavy scenario has been caused by a low pressure in a closest distance of abt 800 nm to the vessel. At the (night) time the incident happened, the vessel was steering about 100 Degree at approximately 21 knots speed with wind and waves mainly abaft beam (theoretical calculations performed by our department during the case study have determined a significant wave height of abt. 6.50 - 7.00 m and a significant period of abt. 9 - 10.5 s). The rolling motion was considered to be not violent by the crew with an average rolling angle about 15 degree. Suddenly, the vessel was rolling heavily and a noise was heard. Later, it was found that a significant number of containers had been fallen overboard and some damage at the vessel was noted.

**SHIP DATA AND LOADING CONDITION**

The vessel is a Panmax Container Vessel with the following main dimensions: Length over all: abt 260 m, Length between perpendiculars: abt 240.00 m, Moulded breadth: 32.24 m, Design draft: abt 11.00 m, Depth to freeboard deck: abt 19 m. The following figure shows the body plan of the vessel:

The vessel's loading condition derived from the loading instrument was such that the initial GMc-value was abt. 0.85 m with the trim slightly positive down by head. Fig. 5 shows the stillwater righting lever curve together with the relevant trough/crest curves (see below). It can clearly be noted that the stillwater righting lever curve can be characterized by moderate initial GM and good additional form stability.
BEHAVIOUR OF THE SHIP IN ROUGH WEATHER

Introduction to the relevant phenomena
Whenever a ship sails in rough weather, it is well known that she is endangered mostly in head or following seas due to stability alterations. This principle is explained by Fig. 4, where the three most important scenarios are plotted. For the stability analysis of ships which determines the stability limiting curves, the stillwater condition is used. However, when a ship sails in either following or head seas, the waves travel along the ship and situations occur when either a wave crest is roughly at L/2 (crest condition) or a trough (trough condition). As typical ship designs are characterized by a significant flare at both ends, this results in the fact that the stability of the ship is reduced in the crest condition (when the ends of the ship have reduced waterline area) and on the other hand increased in the trough condition (when the waterline area is increased). The amount of stability reduction or increase depends on the specific hull form, and it is well known that some ship designs are extremely sensitive in this respect. Typically, a wave of roughly ship length results in the largest stability alterations, but some ship designs are also sensitive to waves that are shorter than ship length. In beam seas, even at zero speed (dead ship condition), a ship is typically very safe due to the fact that most of the energy exposed to the ship by the sea is dissipated by the drifting motion. Only in a beam sea resonance, which can occur at excessive values of initial GM, a ship might be endangered in a beam sea situation, too.

The alterations of righting levers in following or head seas is illustrated by Fig. 5, where the righting levers of the vessel have been computed for the stillwater condition (light blue, the crest condition where the wave crest is at L/2 (green) and for the trough condition (wave crest 0.5 times wavelength in front of L/2, red). It can clearly be seen that for the crest condition, the stability is significantly reduced, whereas for the trough condition, the stability is significantly improved. The reduction/improvement mainly depends on wave length and wave height. Fig. 5, left, shows the situation for the most critical wave, which roughly equals LbP, where the stability reduction is most significant. For the wave of 150 m length, which has been selected as a probable wave for the cargo loss scenario, the stability reduction is less pronounced. If a ship has a natural rolling frequency $\omega_R$ which may be expressed by the formula

$$\omega_R = \sqrt{\frac{gGM}{i}}$$

[1]

where $g$ is the gravity constant, GM is the initial metacentric height and $i$ the roll radius of gyration and if she is sailing in a condition where the encounter frequency between ship and waves meets the ship's natural rolling frequency $\omega_E$ which is...
given by the formula

\[ \omega_e = \omega - \frac{\omega^2}{g} v_s \cos \nu \]  

where \( \omega \) is the frequency of the waves, \( \nu \) is the angle between ships course and the wave propagation direction and \( v_s \), the ship speed, then the energy from the waves is transferred into the ship at its own natural frequency which can result in extremely large rolling angles due to the so called 1:1 resonance (1 pitch cycle per roll cycle). For a given wave length, this 1:2 resonance can occur at several combinations of speed and course. This phenomenon is generally known as parametric rolling and has its main source in the righting lever alterations between crest and trough. Furthermore, the 1:2 resonance (2 pitch cycles per roll cycle), is known as much more dangerous than the 1:1 resonance. This 1:2 resonance typically occurs in following seas at low speeds and low GM-values, where the 1:1 resonance can occur in following seas at low GM-values and higher speeds. At high GM-values, a 1:2 resonance can occur in head seas at slow or moderate speeds. If the righting lever alterations are above a critical value or if the crest stability is below a critical value, extremely large roll motions can occur at or close to a critical resonance.

In following seas, the mechanisms that lead to large amplitude roll are more complex than in head seas, due to the following reasons: The a.m. formula for the natural roll response frequency is derived from the stillwater GM. As a matter of fact, GM alters significantly between crest and trough condition which means that the natural roll period becomes dependent on the actual position of the vessel on the wave. In following seas, the vessel stays long enough on the crest (differently to the head sea scenarios) where the ship is very weak (GM may become negative at the crest for many ships) that the natural response frequency follows more or less the encounter frequency. This results in the fact that in stern quartering seas, no clearly defined resonance spots occur can be seen but a more broad banded area of large roll angles (e.g. Fig. 7). Further it is to be kept well in mind that the a.m. formula for the natural roll response frequency is only valid for small roll angles. Depending on the question whether the ship has positive or negative form stability, the natural response frequency may significantly decrease or increase with larger roll angles.

Simulation method for large amplitude roll

Ship motion simulations are currently carried out using the program 'Rolls' originally developed by Kroeger (1987) and Petey (1988) at the Institut fuer Schiffbau, University of Hamburg. 'Rolls' simulates the motion of intact and damaged ships in time domain in all six degrees of freedom in regular waves and irregular long or short crested sea ways. For four motions, namely heave, pitch, sway and yaw, response amplitude operators (RAO) are used, calculated linearly by means of strip theory. The surge motion is simulated assuming a hydrostatic pressure distribution under the water surface for the determination of the surge-inducing wave forces. While the roll motion is simulated non-linearly using equation 3, where \( M_{\text{wind}}, M_{\text{sy}}, M_{\text{wave}} \) and \( M_{\text{tank}} \) are the roll moments due to wind, sway and yaw, waves and fluid in tanks and flooded compartments, respectively. \( M_d \) is the non-linear damping moment using damping coefficients following Blume (1979). \( \omega, \psi \) and \( \psi \) are the roll, pitch and yaw angles, respectively, while \( m \) is the mass of the ship and \( g \) the gravitational acceleration. The righting arm in the seaway \( h \) is determined for every time step using Grim's effective wave as modified by Soeding (1987). \( I_{xx} \) and \( I_{xz} \) are the moment of inertia about the longitudinal axis and the product of inertia, respectively, calculated for the actual mass distribution (light ship and cargo).

\[
\ddot{\psi} = M_{\text{Wind}} + M_{\text{sy}} + M_{\text{wave}} + M_{\text{Tank}} - M_d - m(\varphi - \dot{\psi}) h_S - I_{xx} \left[ \sin \dot{\psi} + \cos \dot{\psi} \right] - I_{xz} \left[ \sin \dot{\psi} + \cos \dot{\psi} \right]
\]  

Figure 6: Simulation of a capsize in stern quartering seas in a 2:1 resonance scenario by our simulation method. Note the sudden capsize after the vessel travelled for a while at small roll angles. This case could be validated by model tests.
ANALYSIS OF ROLL MOTIONS IN HEAVY WEATHER

As a next step, it was analyzed under which conditions the ship would reach a large roll angle, e.g. 25 Degree. This analysis was carried out for four different significant wave lengths, which were varied from 150 m (the wave length the vessel probably experienced) to 240 m, which is the significant wave length close to the one generating the largest righting lever alterations. Larger significant wave lengths were also chosen to cover swell effects that might have played a role in the scenario.

All calculations were carried out in irregular waves using a JONSWAP-Spectrum. The limiting significant wave height was determined in such a way that a large roll angle Degree could definitively be reached during the time of simulation, which was set to 10000 s or 2.8hrs. For each situation, 10 different simulations with varied random parameters and initial conditions have been performed. The calculation was stopped at a significant wave height of 12 m, so the 12 m limiting significant wave height might lead to large roll angles or to a smaller one. The results are plotted in Fig. 7 as polar diagrams. Each polar diagram represents the results for one significant wave length selected, the radial coordinate shows the different speeds selected, namely 8, 12, 14, 16, 18, 20 and 21 knots. The circumferential coordinate shows the encounter angles calculated, namely 0 Degree (following seas), 15, 30, 45, 60, 90 (beam seas), 120, 150 and 180 Degree (head seas). As the vessel was definitively travelling in stern quartering seas, the course grid between 0 and 90 degree was finer than for the other scenarios. The results show clearly that if a ship speed of abt. 21 knots is assumed, a large roll angle is reached at significant wave heights of approx. 6-7m, because the vessel is close to the 1:1 resonance. This does in principle hold for all wave lengths calculated. The 1:2 resonance occurs at very low speeds (abt. 6-8 kn) and is shifted to lower speeds with higher wave lengths. As the vessel was definitively far away from the 1:2 resonance, this case needs no further consideration. For the shorter wave lengths, a roll angle of 15 Degree occurs at speeds of 20-21 knots (18 at exactly following seas) at wave heights of 6-7m at encounter angles from zero (exactly following) to abt. 30 degree (stern quartering). For the larger significant wave lengths, this area becomes more pronounced although the resonance is shifted forward to lower critical speeds. This is due to the fact that the righting lever alterations become larger if the wave length increases. The fact that the resonance does not occur as a sharply pronounced spot has been discussed in the above sections. Concluded, it can be stated that rolling angles of 15 Degree can occur at a ship speed of abt. 21 knots at significant wave heights between 6 and 7 m at encounter angles between 0 and 30 Degree, whereas all other speed/course combinations (except slow speeds close to the 1:2 resonance) require larger significant wave heights up to 12 m or more.

STATISTICAL SEA STATE CONDITION OF THE AREA OF INTEREST

From long term observations, there is statistical material available about the sea state conditions in the area of interest. Using the published data by Soeding (2001) in Global Seaway Statistics for the region of interest (Point Nr. 117), the following dependency of wave heights an wave lengths can be determined by using a 98% quantil, which is a typical technical assumption (this means that 98% of all wave heights in this area are below the given limiting value):

The Tables state waves with height probability of : 98% within the class of waves given by the period.
The table shows clearly that for the wave length of 150 m, a wave height above 6.50 m is hardly possible, whereas for the longest wave length analyzed, this limiting wave height amounts to 9.70 m. For the wave length of 170 m, the limiting value is about 7.50 m. For the occurrence of the 15 Degree roll angle, the conclusion is obvious: As wave heights of more than 6.50 m at 150 m wave length are practically not possible in this area, the encounter angle must have been about 0 to maximum 45 Degree, because all other encounter angles lead to larger required significant wave heights which are practically not possible. If a wave length of 180 m is assumed, the same basic results are achieved. From the a. m. assumptions of the related wave heights and wave lengths, a 150-180m wave is the most probable assumption if a wind force between 7 Bft and 8 Bft is used as input. From this analysis, the following conclusions can be drawn: The possible wave heights in the area of interest clearly show that all other scenarios except a stern quartering scenario about 0-45 Degree encounter angle and a speed of about 21 knots will either not lead to a 15 Degree roll angle or are physically not possible. Furthermore, the scenarios that have been identified as relevant fit quite well to the speed, course and weather data that are available. The analysis has clearly shown that the roll excitation mechanism is clearly parametric roll in situation close to the 1:1 resonance.

**SUMMARY AND CONCLUSIONS**

Large Amplitude roll motion due to parametric excitation can also happen in stern quartering seas. Two possible resonance scenarios, the 2:1 and the 1:1 resonance may occur, depending on the speed and rough magnitude of initial GM. However, as the vessel stays long enough at crest and trough, the natural response frequency follows the excitation mechanism so that the resonance becomes more broad banded. For a Panamax container vessel that sailed in stern quartering seas, large roll amplitudes occurred close to the 1:1 resonance area. It could be clearly demonstrated by numerical simulations that the stern quartering 1:1 resonance scenario remained as the only possible scenario for the occurrence of large roll angles. These findings are of practical importance, as parametric rolling is mainly assigned to head sea scenarios where large accelerations do occur due to the large GM values. In stern quartering sea scenarios, the GM is significantly smaller which results in lower accelerations, but significantly larger roll angles which can lead to a capsize.

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