Philipp Russell

Theoretical Investigations on the Container Loss of a Small Panamax Container Vessel in Heavy Sea

TUHH
Technische Universität Hamburg-Harburg
First Examiner: Prof. Dr.-Ing. Stefan Krüger
Second Examiner: Dipl.-Ing. Nicolas Rox
Declaration of Authorship

I hereby declare and confirm that this thesis and the work presented in it have been generated by me as the result of my own original research. I did not make use of any other sources than those stated in the bibliography.

Signature                                        Place, Date

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<th>Meaning</th>
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<tr>
<td>$A_{BK}$</td>
<td>[m²]</td>
<td>Total bilge keel area</td>
</tr>
<tr>
<td>$a_{t,max}$</td>
<td>[m/s²]</td>
<td>Maximum transversal acceleration</td>
</tr>
<tr>
<td>$B$</td>
<td>[m]</td>
<td>Breadth of the ship</td>
</tr>
<tr>
<td>$BM$</td>
<td>[m]</td>
<td>Distance between the center of buoyancy and the metacentre</td>
</tr>
<tr>
<td>$D$</td>
<td>[m]</td>
<td>Depth to freeboard deck</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>[t]</td>
<td>Displacement of the ship</td>
</tr>
<tr>
<td>$g$</td>
<td>[m/s²]</td>
<td>Gravitational acceleration of 9.81 m/s²</td>
</tr>
<tr>
<td>$GM$</td>
<td>[m]</td>
<td>Metacentric height</td>
</tr>
<tr>
<td>$h$</td>
<td>[m]</td>
<td>Hydrostatic righting lever; equivalent to GZ</td>
</tr>
<tr>
<td>$H_{1/3}$</td>
<td>[m]</td>
<td>Significant wave height; the arithmetical average height (trough to crest) of the largest third of the waves</td>
</tr>
<tr>
<td>$i$</td>
<td>[m]</td>
<td>Gyration or roll radius; often expressed in factors of $B$</td>
</tr>
<tr>
<td>$I_{fs}$</td>
<td>[m⁴]</td>
<td>Transversal moment of inertia of the free surface in partly filled tanks</td>
</tr>
<tr>
<td>$I_{WL}$</td>
<td>[m⁴]</td>
<td>Transversal moment of inertia of the water-plane area</td>
</tr>
<tr>
<td>$k$</td>
<td>[1/m]</td>
<td>Wave number</td>
</tr>
<tr>
<td>$KB$</td>
<td>[m]</td>
<td>Vertical center of buoyancy</td>
</tr>
<tr>
<td>$KG$</td>
<td>[m]</td>
<td>Vertical center of gravity</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>[m]</td>
<td>Wave length</td>
</tr>
<tr>
<td>$L_{oa}$</td>
<td>[m]</td>
<td>Length over all</td>
</tr>
<tr>
<td>$L_{pp}$</td>
<td>[m]</td>
<td>Length between perpendiculars</td>
</tr>
<tr>
<td>$\mu$</td>
<td>[°]</td>
<td>Encountering angle</td>
</tr>
<tr>
<td>$\omega$</td>
<td>[rad/s]</td>
<td>Circular frequency of the waves</td>
</tr>
<tr>
<td>$\omega_c$</td>
<td>[rad/s]</td>
<td>Frequency of encounter</td>
</tr>
<tr>
<td>$\omega_R$</td>
<td>[rad/s]</td>
<td>Natural frequency of the rolling ship</td>
</tr>
<tr>
<td>$\pi$</td>
<td>[-]</td>
<td>Mathematical constant of 3.14159...</td>
</tr>
<tr>
<td>$\rho_{fs}$</td>
<td>[t/m³]</td>
<td>Density of the fluid in partly filled tanks</td>
</tr>
<tr>
<td>$S_\xi$</td>
<td>[m²/s]</td>
<td>Specific wave energy density per area</td>
</tr>
<tr>
<td>$T_D$</td>
<td>[m]</td>
<td>Design draught</td>
</tr>
<tr>
<td>$T_M$</td>
<td>[m]</td>
<td>Mean draught</td>
</tr>
<tr>
<td>$T_e$</td>
<td>[s]</td>
<td>Period of encounter</td>
</tr>
<tr>
<td>$T_R$</td>
<td>[s]</td>
<td>Roll period</td>
</tr>
<tr>
<td>$T_s$</td>
<td>[s]</td>
<td>Significant period; the period corresponding with the circular frequency in the spectrum’s center of gravity</td>
</tr>
<tr>
<td>$\nabla$</td>
<td>[m³]</td>
<td>Displaced volume of the ship</td>
</tr>
<tr>
<td>$w$</td>
<td>[m]</td>
<td>Cross-curves of stability</td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
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<tbody>
<tr>
<td>a.B.</td>
<td>above baseline</td>
</tr>
<tr>
<td>a.m.</td>
<td>ante meridiem; before midday</td>
</tr>
<tr>
<td>E4</td>
<td>Calculation method database for the use in ship design</td>
</tr>
<tr>
<td>e.g.</td>
<td>example given</td>
</tr>
<tr>
<td>i.e.</td>
<td>id est; that is</td>
</tr>
<tr>
<td>ISSC</td>
<td>International Ship Structure Congress</td>
</tr>
<tr>
<td>JONSWAP</td>
<td>JOint North Sea WAve Project</td>
</tr>
<tr>
<td>kn</td>
<td>knots; nautical unit of speed; (1 \text{ kn} = 0.5144 \text{ m/s} = 1.852 \text{ km/h} = 1.151 \text{ mph})</td>
</tr>
<tr>
<td>LCG</td>
<td>Longitudinal Centre of Gravity</td>
</tr>
<tr>
<td>LSW</td>
<td>Light Ship Weight</td>
</tr>
<tr>
<td>MAIB</td>
<td>Marine Accident Investigation Branch</td>
</tr>
<tr>
<td>RAO</td>
<td>Response Amplitude Operator</td>
</tr>
<tr>
<td>TCG</td>
<td>Transversal Centre of Gravity</td>
</tr>
<tr>
<td>TEU</td>
<td>Twenty foot Equivalent Unit</td>
</tr>
<tr>
<td>TUHH</td>
<td>Technische Universität Hamburg-Harburg; Hamburg University of Technology</td>
</tr>
<tr>
<td>USA</td>
<td>United States of America</td>
</tr>
<tr>
<td>VCG</td>
<td>Vertical Centre of Gravity; equivalent to KG</td>
</tr>
</tbody>
</table>
1. Introduction

Ever since containers have been established as a means of cargo transport in standardized units, the use of ships to facilitate an unbroken transportation chain was of primary concern. These container vessels are known to be faster than other types such as tankers or bulk carriers. Consequently their lines are sharpened, though the need for maximized payload still remains, leading to significant bow flares. Because adherence to schedules is vital to customers of the shipping companies, the advantage of high speed is taken whenever deemed necessary. Especially in heavy seas the combination of large bow flares and high speeds is regarded as critical. This is due to extensive slamming loads and associated pitch movements. Therefore in these situations a speed reduction below a certain limit is required. The result is a decrease in roll damping and thus higher rolling angles, depending on the ship’s stability and loading condition respectively. The roll accelerations arising from this circumstance may lead to the loss of containers overboard or even fatalities among the crew. In the past predominantly ships within the ballast condition and according high stability have been involved in accidents [1] [2]. The transversal accelerations on the bridge in those situations led to the loss of lives. In contrast the accident to be covered in this thesis comprises just the loss of containers. Nowadays, about 10,000 containers per year are lost overboard due to heavy weather in combination with insufficient cargo securing, causing environmental and economic damage [3].

The vessel to be further examined was sailing under British flag at the time of the accident, hence the MAIB investigated it by default [4]. Since detailed data on the ship’s seakeeping behaviour and occurred accelerations was missing, a final cause of the cargo loss could not be determined. For this reason the Institute of Ship Design and Ship Safety at the Hamburg University of Technology was assigned to deliver the required information, which shall be provided in this thesis.

1.1. Summary of the accident

The accident in question took place on a sea passage of the ship from Le Havre in France to Newark in the USA on 27 January 2006 at 50° 15’ N 034° 02’ W. That means it happened during Winter in the middle of the North Atlantic Ocean, an area and a season generally known for their harsh environmental conditions. The departure was planned for 24 January, the arrival for 31 January. Having left Europe, the vessel’s master received weather information on a couple of low pressure systems to be encountered during the original passage straight through the Atlantic. Therefore he decided to take a northern route, increasing the average speed to maintain the intended schedule. Being supported by westbound winds, the ship made good time and the journey went well till the morning of 27 January, when the weather had deteriorated due to a depression over Newfoundland.

Beginning at 9 a.m. ship’s time, the speed had been reduced from 22 knots to about 5 knots to counteract pitching. The vessel faced head seas from about 140 to 145 degrees\(^1\) on the port bow with the swell’s period being estimated by the crew to 11 seconds, i.e. wavelengths just below the ship’s length. In the afternoon the master decided to turn the ship directly into the direction of the swell, since he was concerned about the possibility of what he took for “parametric rolling”\(^2\).

\(^{1}\)0 degree being following seas from astern.
\(^{2}\)See also section 2.1 for theoretical background on this issue.
1.2. Objectives

Because the roll motions were deemed to be too high, the chief officer was ordered to take ballast water on board 45 minutes previous to the accident. This action raised the GM to 1.13 metres and thereby improved the ship’s hydrostatic stability. Shortly before the container loss the vessel was struck by a series of waves larger than average approaching from both port and starboard, accompanied by an increase in wind to Beaufort 12. Thus rolling angles of roughly 25 to 30 degrees in five rolls were caused, the last one being effected by a steep wave of 10 to 12 metres.

Following these events the containers in bay 34 in front of the bridge toppled over, leading to the loss of 27 forty foot containers into the sea, 28 forty foot containers to stay collapsed on board and only 9 forty foot containers remaining upright. An assessment of the affected bay revealed extensive damage caused by compression forces to the containers, the cargo securing systems and a pedestal.

1.2. Objectives

The investigation report shows clearly that the motion of the ship and the corresponding forces resulted in the collapse and loss of the containers, so this can be regarded as an elementary fact. Verified information on relevant environmental factors, e.g. the wave period, the exact height of the larger waves as well as the occurred rolling angles, are missing however and need to be scrutinised thoroughly. In addition calculations involving dynamic parameters, for instance accelerations, have not been executed yet and shall for this reason be conducted in the thesis.

As mentioned before, container ships are susceptible to pitching as a consequence of their hull form. Furthermore the widening of the frames both in the bow and in the stern region can create problems concerning the roll motion, which is explained later on. The operation of such vessels in the ballast condition, being an outcome of the world economic crisis and thus less transported cargo, has lead to accidents due to the high stability and thereby short roll periods. These cases were surveyed by the Institute of Ship Design and Ship Safety at the TUHH in several publications [1] [2] [5].

On that account the purpose of this thesis is to examine the seakeeping behaviour of the ship and it’s influence on the accident, while drawing comparisons to the other events.

This will be done by providing some basic theory and commenting the process of data input. Subsequently calculations will be performed and their results presented. Finally the thesis will come to a conclusion reflecting the task.
2. Theory

2.1. Roll resonance

The investigation report analyses the danger of so-called “parametric rolling” during the accident, including some explanation of the phenomenon. It is a common misconception that this occurs just at specific ratios of the ship’s natural period and the wave period. In the context of oscillations in general, the term “parametric” indicates transient parameters like the natural frequency or the damping. Applied to the rolling oscillations of a vessel, the natural frequency is calculated as in equation (2.1), assuming rolling angles in the linear interval of the righting lever curve and stillwater [6].

\[ \omega_R = \frac{\sqrt{g \cdot GM}}{i} \quad \text{[rad/s]} \quad (2.1) \]

GM with no heel consists of three components, which are displayed in equation (2.2), whereas \( i \) depends on the mass distribution of light ship and deadweight.

\[ GM_0 = \frac{I_{WL}}{\nabla} + KB - KG \quad \text{[m]} \quad (2.2) \]

While KG is constant and depending on the loading condition, the other two terms in this equation are functions of the immersed hull. The first expression, called BM, is nearly proportional to the breadth squared, KB to the draught of the ship [7].

If KB and BM are varying now due to a wavy surface, GM also changes, resulting in a decrease of the natural frequency as well as “softening” of the ship, because a higher heeling angle can be reached using the same amount of energy. Therefore GM oscillates around the stillwater GM depending on the current water surface. Thus the ship’s natural frequency, which is as mentioned regulated by the actual GM, becomes a **transient parameter**. Consequently the **ship is rolling parametric all the time** on account of stillwater conditions being purely academical, although the effect can be more or less significant. What has to be determined individually for each considered situation is whether the roll motions are governed by parametric or external excitation. Mathematically speaking parametric influences are represented by the left-handed side of the associated differential equations, while external ones constitute the inhomogeneity on the right-handed side [8].

Concluding this section, it is noted, that instead of the often incorrectly used term “parametric rolling” the expression “roll resonance” shall be the replacement in the following. In addition the susceptibility of container vessels to this aspect due to their flared frames is pointed out.

2.2. Natural seaway

To conduct seakeeping calculations, a proper model of the natural seaway is required. The energy of a single long crested deep water wave can be described by using a potential theoretical approach. Being affected by inconstant wind, natural seaways are always composed of scattered directions and frequencies, so it has to be superposed by many different waves. Therefore the

---

1.varying with the time
2.3. Simulation within E4

Energy of the waves is measured in a first step by determining their amplitudes during empirical measurements and afterwards standardised by means of circular frequency differences. The resulting correspondence between the circular frequency and the specific energy density per area is called a spectrum, which is approaching zero at low and very high frequencies and has a typical peak between these extrema. In a second step this spectrum is dispersed around a main encountering angle employing a cos\(^2\)-function thereby forming a wind sea spectrum.

Commonly known wind sea spectra are the Pierson-Moskowitz spectrum and the JONSWAP spectrum, which is a Pierson-Moskowitz spectrum modified by experimentally gained data. To create either one of these spectra two parameters are needed: the significant wave height and the significant period. Having got this input, the Pierson-Moskowitz spectrum can be expressed as in (2.3), the form being recommended by the ISSC in 1964 [9].

\[
S_\zeta(\omega) = 173 \frac{H_s^2}{T_{\text{s}}^{4}} \frac{1}{\omega^5} \exp(-692 \frac{T_{\text{s}}^{-4}}{\omega^4}) \quad [m^2s] \quad (2.3)
\]

Real Seaways comprise partly wind sea, i.e. waves with a phase velocity lesser than or equal to the wind speed, and partly swell, which are waves with a phase velocity larger than the wind speed. These two combined are called sea state. Therefore it can be necessary to utilize other spectra with two peaks instead of one. Particularly in heavy seas with a lot of wind as is the case in this accident the wind sea part is dominant, hence a JONSWAP spectrum with a cos\(^2\)-function dispersing it around the encountering angle is applied here.

2.3. Simulation within E4

All calculations in this thesis are performed using the software E4, which is available at the Institute of Ship Design and Ship Safety. E4 is a collection of numerous computation methods for the ship design process, including a method called E4ROLLS to investigate the seakeeping behaviour of a ship. Being originally developed by SÖDING in consequence of the E.L.M.A. TRES accident [10], it has later been enhanced by KRÖGER [11] and during further research at the Hamburg University of Technology, resulting in the actual version used for this thesis. The following description is based upon ROX [5], KLUWE [12] and SÖDING [13]. E4 is able to simulate all six degrees of freedom of a ship in the time domain, which are as follows:

- **Surge** The translational motion along the longitudinal axis of the ship.
- **Sway** The translational motion along the transversal axis of the ship.
- **Heave** The translational motion along the vertical axis of the ship.
- **Roll** The rotatory motion around the longitudinal axis of the ship.
- **Pitch** The rotatory motion around the transversal axis of the ship.
- **Yaw** The rotatory motion around the vertical axis of the ship.

Of these the sway, heave, pitch and yaw motion are calculated via a linear approach, while the surge and the roll motion are simulated in a non-linear way. For the linear motions RAOs are calculated using a strip method, that means slicing the ship into a specific number of frame discs representing the hull form, determining their responses to the seaway individually and then assembling them together again. This has to be done for every speed of interest.

The ship’s displacement is taken into account for the RAO determination by means of a cuboid with a moment of mass inertia equivalent to that of the ship. This depends on the lightship weight distribution and loading condition definition. In the process links of the linear motions to the
non-linear ones are respected. Nevertheless the linkage has it’s limits, for example the danger of broaching\(^2\) is not covered and the ship’s reactions in beam seas are overestimated, the reason for that being the linearisation of the sway and yaw motions.

Considering the roll motion non-linear is vital, as linearisation of the roll motion would mean using a straight line with the initial GM being it’s gradient to constitute the righting lever curve. Due to the particular high amplitudes reached by the rolling ship, such an approach is not to be allowed. Therefore equation (2.4) is applied to compute the roll motions [12].

\[
\ddot{\varphi} = \frac{\Theta_{xz} \left[ \left( \dot{\psi} + \psi \dot{\varphi} \right)^2 \cos(\varphi) - \left( \ddot{\vartheta} + \dot{\vartheta} \dot{\varphi} \right)^2 \sin(\varphi) \right] - d_L \dot{\varphi} - d_Q \dot{\varphi} |\dot{\varphi}| - m \left( g - \ddot{\zeta} \right) h_s}{\Theta_{xx} - \Theta_{xz} \left( \psi \sin(\varphi) + \vartheta \cos(\varphi) \right)} + \frac{M_{\text{Tank}} + M_{\text{Sway and Yaw}} + M_{\text{Exciting Wave}} + M_{\text{Wind}}}{\Theta_{xx} - \Theta_{xz} \left( \psi \sin(\varphi) + \vartheta \cos(\varphi) \right)} \left[ \text{rad} \right] \left[ \frac{\text{m}}{\text{s}^2} \right] \tag{2.4}
\]

In there denotes:

- \( \varphi \) the angle indicating roll motions,
- \( \vartheta \) the angle indicating pitch motions,
- \( \psi \) the angle indicating yaw motions and
- \( \zeta \) the earth-fixed coordinate indicating heave motions.

- \( \dot{\varphi}, \ddot{\varphi}, \dddot{\varphi}, \dot{\psi} \) and \( \ddot{\zeta} \) their corresponding angular velocities and accelerations.

- \( m \) the mass of the ship without the added hydrodynamic mass for the heave motion.

- \( g \) the constant gravitational acceleration of 9.81 m/s\(^2\).

- \( h_s \) the righting lever of the equivalent wave as per concept of GRIM [8].

- \( \Theta_{xx} \) the moment of mass inertia around the longitudinal axis and \( \Theta_{xz} \) the product of mass inertia in the xz-plane, both referred to the ship’s centre of gravity.

- \( d_L \) the linear and \( d_Q \) the quadratic roll damping coefficient according to BLUME [14].

- \( M_{\text{Tank}}, M_{\text{Sway and Yaw}}, M_{\text{Exciting Wave}} \) and \( M_{\text{Wind}} \) the roll moments affecting the ship because of free surface effects, sway and yaw motions as well as waves and wind.

Also the surge motions are determined non-linear based on the equation (2.5) below [12].

\[
\ddot{\xi} = - \left[ \frac{2 R(v_0)}{v_0 m^*} \dot{\xi} + \frac{R(v_0)}{v_0^2 m^*} \dot{\xi}^2 + \frac{\Delta R}{m^*} \right] \left[ \frac{\text{m}}{\text{s}^2} \right] \tag{2.5}
\]

In there denotes:

- \( \xi \) the coordinate indicating surge motion.

- \( \dot{\xi} \) the velocity and \( \ddot{\xi} \) the acceleration in the longitudinal direction.

- \( R \) the speed-dependent resistance of the ship in stillwater.

- \( \Delta R \) the resistance added because of the motion in waves.

- \( v_0 \) the mean forward speed of the ship.

- \( m^* \) the ship’s mass together with added hydrodynamic mass.

Finally it can be stated, that the method E4ROLLS delivers results comparatively fast. This is due to the joint effort of the precalculated righting levers in waves according to GRIM, the likewise precalculated RAOs and BLUME’s roll damping coefficients. In the scope of other investigations the method has proven to model the seakeeping behaviour of ships accurately [1] [2].

\(^2\)The sudden turn of a vessel broadside to the waves, often leading to capsizing.
3. Preparation

3.1. Ship data

To survey the accident of the ship in question, the Institute of Ship Design and Ship Safety is provided with the following material:

- The official investigation report of the Marine Accident Investigation Branch [4].
- The lines of the ship shown in figure 3.1.
- The daily printouts of the on-board loading computer from 24 January to 27 January 2006.

Based on these documents a hydrostatic model is generated in E4. The ship’s main dimensions are given in table 3.1.

![Figure 3.1.: Lines plan of the vessel](image)

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{oa}$</td>
<td>210.11</td>
<td>m</td>
</tr>
<tr>
<td>$L_{pp}$</td>
<td>197.10</td>
<td>m</td>
</tr>
<tr>
<td>B</td>
<td>32.20</td>
<td>m</td>
</tr>
<tr>
<td>$T_D$</td>
<td>11.00</td>
<td>m</td>
</tr>
<tr>
<td>D</td>
<td>19.40</td>
<td>m</td>
</tr>
<tr>
<td>Containers</td>
<td>2902</td>
<td>TEU</td>
</tr>
<tr>
<td>Service speed</td>
<td>23.5</td>
<td>kn</td>
</tr>
</tbody>
</table>

Table 3.1.: Main dimensions

The bilge keel dimensions, which are important for the roll damping, are taken from drawings of a sister ship available at the Institute of Ship Design and Ship Safety and shown in table 3.2.

![Table 3.2.: Bilge keel dimensions](image)

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>59.66</td>
<td>m</td>
</tr>
<tr>
<td>Height</td>
<td>370.00</td>
<td>mm</td>
</tr>
<tr>
<td>$A_{BK}$</td>
<td>44.15</td>
<td>$m^2$</td>
</tr>
</tbody>
</table>

Table 3.2.: Bilge keel dimensions

3.2. Model validation

To determine the quality of the hydrostatic model displayed in figure 3.2 and thus the quality of the results, the cross-curves of stability in E4 are compared to those derived from the loading
3.2. Model validation

Because in the loading computer printouts only righting levers are given, the cross-curves are calculated from equation (3.1) [7].

\[ w(\varphi) = h(\varphi) + VCG \cdot \sin(\varphi) + TCG \cdot \cos(\varphi) \quad [\text{m}] \quad (3.1) \]

<table>
<thead>
<tr>
<th>Cross-curve of stability</th>
<th>Actual (E4) [m]</th>
<th>Target (Loading Computer) [m]</th>
<th>Relative Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>w (5°)</td>
<td>1.317</td>
<td>1.322</td>
<td>-0.4 %</td>
</tr>
<tr>
<td>w (10°)</td>
<td>2.636</td>
<td>2.632</td>
<td>0.2 %</td>
</tr>
<tr>
<td>w (15°)</td>
<td>3.961</td>
<td>3.948</td>
<td>0.3 %</td>
</tr>
<tr>
<td>w (20°)</td>
<td>5.293</td>
<td>5.277</td>
<td>0.3 %</td>
</tr>
<tr>
<td>w (30°)</td>
<td>7.946</td>
<td>7.913</td>
<td>0.4 %</td>
</tr>
<tr>
<td>w (40°)</td>
<td>10.187</td>
<td>10.160</td>
<td>0.3 %</td>
</tr>
<tr>
<td>w (50°)</td>
<td>11.765</td>
<td>11.762</td>
<td>0.0 %</td>
</tr>
<tr>
<td>w (60°)</td>
<td>12.632</td>
<td>12.645</td>
<td>-0.1 %</td>
</tr>
<tr>
<td>w (70°)</td>
<td>12.948</td>
<td>12.998</td>
<td>-0.4 %</td>
</tr>
</tbody>
</table>

Table 3.3.: Comparison of the cross-curves

Table 3.3 contrasts the values in E4 with the values of the loading computer. The E4 cross-curves are calculated with free trim because they appear to be closer to the target cross-curves than fixed trim cross-curves. Remaining differences can be explained by the non-modelled rudder, propeller and other appendages as well as by not included structural details, which may work as buoyancy bodies at higher heeling angles. In addition the hydrostatic accuracy, controlled by the number of frames used to describe the hull form, may differ from the loading computer. Due to the only slight differences the quality of the model is good.

Figure 3.2.: Hydrostatic model used for the calculations
3.3. Loading condition

An evaluation of the loading computer printouts leads to the loading condition shown in table 3.4. Because some information are missing, the weight data of the LSW and of the stores is estimated\(^1\). The cargo’s centre of gravity is then adjusted to reach the total vertical centre of gravity and the floating position given in table 3.5.

<table>
<thead>
<tr>
<th>Item</th>
<th>Weight [t]</th>
<th>LCG [m]</th>
<th>TCG [m]</th>
<th>VCG [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Ship</td>
<td>12400</td>
<td>92.000</td>
<td>0.000</td>
<td>12.500</td>
</tr>
<tr>
<td>Stores</td>
<td>111</td>
<td>40.000</td>
<td>0.000</td>
<td>4.000</td>
</tr>
<tr>
<td>Cargo</td>
<td>22214</td>
<td>91.747</td>
<td>0.125</td>
<td>16.812</td>
</tr>
<tr>
<td>Ballast</td>
<td>4032</td>
<td>113.330</td>
<td>-1.820</td>
<td>7.580</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>3262</td>
<td>89.380</td>
<td>1.320</td>
<td>5.300</td>
</tr>
<tr>
<td>Diesel Oil</td>
<td>103</td>
<td>30.420</td>
<td>7.080</td>
<td>9.100</td>
</tr>
<tr>
<td>Lube Oil</td>
<td>111</td>
<td>30.080</td>
<td>-1.940</td>
<td>6.390</td>
</tr>
<tr>
<td>Fresh Water</td>
<td>254</td>
<td>28.420</td>
<td>-1.010</td>
<td>7.770</td>
</tr>
<tr>
<td>Totals</td>
<td>42487</td>
<td>92.864</td>
<td>0.000</td>
<td>13.660</td>
</tr>
</tbody>
</table>

Table 3.4.: Loading condition during the accident

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_M</td>
<td>11.06</td>
<td>m</td>
</tr>
<tr>
<td>Trim (positive forward)</td>
<td>-1.23</td>
<td>m</td>
</tr>
<tr>
<td>Heel</td>
<td>0.00</td>
<td>[^\textdegree]</td>
</tr>
</tbody>
</table>

Table 3.5.: Floating position as given by the loading computer

Furthermore the extension of the particular masses is defined to determine the moment of mass inertia and thereby the gyration radius of the ship. The associated righting lever curve is displayed in figure 3.3. Due to the slight difference between the real ship and the calculation model

\[ \text{ACCIDENT} \quad \text{port side} \]

\[ \text{Righting lever [m]} \]

\[ \text{Heeling angle [deg]} \]

Figure 3.3.: Righting lever curve of the loading condition during the accident

\(^1\text{Values not given by the loading computer are marked in grey and italics in table 3.4.}\)
the GM differs. It is 1.306 metres in E4 versus 1.17 metres in the loading computer. Both values comply with the corrected GM in consideration of the free surface correction dGM because of partly filled tanks. If the ship heels, the fluid's centre of gravity in these tanks shifts, decreasing the hydrostatic stability according to equation (3.2) [7], in this case by 0.13 metres.

\[
GM_{\text{corrected}} = GM_{\text{solid}} - dGM \\
dGM = \sum_i \rho_{fs,i} \cdot I_{fs,i} / \Delta \quad [m] \tag{3.2}
\]

Free surfaces however also increase the roll damping due to the sloshing fluid. In matters of the ship’s motions in waves the two effects are deemed to compensate one another. Consequently E4 uses the solid GM of 1.436 metres to perform the seakeeping calculations.

### 3.4. Environmental conditions

According to the weather charts in the annex of the official investigation report the accident happened under the conditions shown in table 3.6. A significant wave period to use as an input for the creation of a wave spectrum, explained in section 2.2, is missing though. The most probable period has therefore to be determined in the scope of the thesis. For this purpose non-linear simulations will be performed based on the given data for several periods to isolate the most dangerous one. It is decided to execute the calculations without the consideration of wind, since the vessel in accident is encountered almost head-on. Therefore the wind has not much impact on the side lateral area and thereby the roll motion.

Besides of that the statement, that the waves hitting the vessel shortly before the accident were larger than average, is just an estimation of the crew. The same goes for the occurred rolling angles of 25 to 30 degrees, making the significance of both information questionable.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significant wave height $H_{1/3}$</td>
<td>5.4</td>
<td>[m]</td>
</tr>
<tr>
<td>Wave encountering angle $\mu$</td>
<td>150.0</td>
<td>[°]</td>
</tr>
<tr>
<td>Wind speed</td>
<td>68.0</td>
<td>[kn]</td>
</tr>
<tr>
<td>Wind encountering angle</td>
<td>170.0</td>
<td>[°]</td>
</tr>
</tbody>
</table>

Table 3.6.: Weather data as given by the investigation report

for the creation of a wave spectrum, explained in section 2.2, is missing though. The most probable period has therefore to be determined in the scope of the thesis. For this purpose non-linear simulations will be performed based on the given data for several periods to isolate the most dangerous one. It is decided to execute the calculations without the consideration of wind, since the vessel in accident is encountered almost head-on. Therefore the wind has not much impact on the side lateral area and thereby the roll motion.

Besides of that the statement, that the waves hitting the vessel shortly before the accident were larger than average, is just an estimation of the crew. The same goes for the occurred rolling angles of 25 to 30 degrees, making the significance of both information questionable.

### 3.5. Possible causes of the accident

The accident to be surveyed provides a clue in the form of lost or damaged containers subsequent to a series of rolls. Based on this fact it can be stated that the seakeeping behaviour of the vessel had influence on the cargo loss, though it is yet unclear to what extent. This is because the investigation report mentions structural failure of the lashing equipment and of the containers themselves, possibly due to overweight and heavy over light containers. Considering only seakeeping, either roll resonance or external excitation of the ship could have been the predominant factor causing the accident, as demonstrated in section 2.1. Noteworthy in this context is the ballasting operation shortly before the accident, raising the GM substantially by means of over a thousand tons of ballast water. To clarify if such ballasting was permissible in that situation or if it set the crucial precondition for the following occurrence, this loading condition shall be examined as well in the thesis. Moreover the ballast arrival condition shall be investigated to achieve a similar loading condition as in the other accidents [1] [2], so that the seakeeping behaviours of the vessels can be compared to one another.
4. Calculation

4.1. RAO determination

As explained before, the linearly calculated Response Amplitude Operators are required as an input for the non-linear simulation. Figure 4.1 displays the frames used for the strip theory. Where the hull form changes significantly, such as in the bow and stern region, the ship is approximated by more frames than in other areas. Furthermore the extensions of the cuboid with the same moment of mass inertia as the loaded ship are shown. The side lateral area is needed to control if these extensions are reasonable.

![Model for the RAO calculation](image)

Based on this, a dry roll radius of 0.40 B and a wet one including added hydrodynamic masses of 0.44 B is calculated. This is an appropriate value for this ship type and loading condition. The stillwater natural roll period yields to 23.55 seconds, which is valid up to a rolling angle of about 10 degrees due to the righting lever curve in figure 3.3. The RAOs themselves are computed for an interval of wavelengths between two times the ship’s breadth and 250 times the ship’s draught to provide a response of the vessel to almost every possible natural wave. For speeds higher than 15 knots the shorter wave lengths have to be excluded because the RAOs for the surge, sway and yaw motions reach inapplicable high values.
Figure 4.2.: Linear RAOS for a speed of 5 knots and the accident loading condition

Exemplary RAOS for the speed of 5 knots during the accident are plotted in figure 4.2 against the wave period. The ship’s responses are standardised to become non-dimensional, the translational ones by the wave amplitude, the rotational ones by the wave slope. Each line within the graphs signifies one of seven encountering angles between 0 and 180 degrees. Clearly recognisable is a resonance around 23.55 seconds, which represents as mentioned the stillwater natural roll period. Furthermore the qualitative difference between surge, heave and pitch motions on the one hand and sway, roll and yaw motions on the other hand is remarkable. This is a consequence of the ship being symmetric, so that both groups of motions can be calculated separately.
4.2. Non-linear simulation and period identification

Because the investigation report does not deliver a significant period to start with, preliminary calculations are needed to determine the most dangerous one. For this purpose polar diagrams resulting from the non-linear simulations are employed. Polar diagrams provide a clear overview of the ship’s seakeeping behaviour. Their radial coordinate corresponds to the ship’s speed, while their circumferential coordinate represents the encountering angle between ship and seaway\(^1\). Within this grid the wave heights to fulfil specific pre-set criteria are given. For each period of interest a new polar diagram is needed, using the input of a spectrum. To eliminate statistical influences, each polar diagram is based upon five different seaways of the same spectrum.

As a reference point for the period identification the criterion of a maximum occurred rolling angle is chosen. Due to the estimations of the crew in the MAIB report [4] this is set to 30 degrees while starting at a wave length of \( L_{pp} \) meaning a wave period of 11.24 seconds. Because these are rather long waves to be found in nature, the further investigation is concentrated on wave lengths between 100 and 172 metres and hence wave periods between 8 and 10.5 seconds.

Calculating with periods of 11.24 and 10.5 seconds results in the polar diagram shown in figure 4.3.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{polar_diagram}
\caption{Polar diagram up to 9 knots for a maximum rolling angle of 30 degrees and wave periods of 10.5 and 11.24 seconds}
\end{figure}

The interval is 1 knot in radial and 10 degrees in circumferential direction, the wave heights range from 6 to 14 metres. This first examination and comparison confirms two presumptions: firstly the wave heights required to reach such high rolling angles as stated in the report are extraordinary at a wave length of \( L_{pp} \). Secondly the susceptibility of the ship to roll motions is heightened in shorter and consequently steeper waves. Both of the facts are plausible bearing in mind that the wave slope is used to standardise the related RAO.

Based on this, polar diagrams are generated for the shorter wave periods ranging from 8 to 10 seconds and displayed in the figures 4.4, 4.5 and 4.6. Figure 4.4 clearly demonstrates the decreasing effect of waves below periods of 8 seconds or wave length of 100 metres. Waves this short break sooner than the longer ones because the chance to reach a critical ratio of height to length increases for shorter waves. Accordingly the most dangerous period has to be between 8 and 10.5 seconds.

\(^1\)0 degrees being following seas, 90 degrees being beam seas and 180 degrees being head seas.
4.2. Non-linear simulation and period identification

Figure 4.4.: Polar diagram up to 9 knots for a maximum rolling angle of 30 degrees and wave periods of 8 and 8.5 seconds

Comparing the right side of figure 4.4 with figures 4.5 and 4.6 excludes 8.5 seconds as the most probable period as well. If the remaining polar diagrams 4.5 and 4.6 are contrasted to one another, it is evident, that wave periods of 9, 9.5 and 10 seconds are more critical than the other ones. Of these a period of 9.5 seconds seems to be the most dangerous one because the respective polar diagram shows the lowest wave heights required to reach a rolling angle of 30 degrees even at higher speeds.

Figure 4.5.: Polar diagram up to 9 knots for a maximum rolling angle of 30 degrees and wave periods of 9 and 9.5 seconds

Therefore the significant wave period during the accident for all further considerations is set to 9.5 seconds. It has to be stated that this does not have to be the actual wave period encountered on 27 January 2006 in the North Atlantic Ocean. Having no other data at hand and judging by the simulations performed, it is nevertheless a valid assumption.
4.3. Righting lever alterations and roll resonance

To evaluate the possibility of roll resonance due to parametric excitation, the righting lever alterations occurring in waves are regarded in a first step. This is done using the most critical wave length, which is the length between the perpendiculars of the ship, and the significant wave height during the accident. By this means it can be examined if the preconditions for a roll resonance are met, i.e. if the differences between the crest and trough situation are high enough to cause a serious roll motion at all.

![Figure 4.6: Polar diagram up to 9 knots for a maximum rolling angle of 30 degrees and wave periods of 9.5 and 10 seconds](image)

Figure 4.7.: Righting lever alterations at a wavelength of $L_{pp}$ and a wave height of $H_{1/3}$

The results of this calculation displayed in figure 4.7 show, that on the one hand the crest...
4.3. Righting lever alterations and roll resonance

situation is not as severe to move the initial GM into a negative region. On the other hand however the differences are not as negligible as it was the case during the other accidents.

Therefore the critical speeds for a roll resonance are determined in a second step. For the encountering frequency between ship and waves equation (4.1) is valid [15].

$$\omega_e = \omega - kv \cos(\mu) \quad \left[ \text{rad s}^{-1} \right]$$

(4.1)

With

$$\omega_e = \frac{2\pi}{T_e}, \quad \omega = \frac{2\pi}{T_s}, \quad k = \frac{2\pi}{\lambda}, \quad \lambda = \frac{g T_s^2}{2\pi}$$

and the condition

$$T_R = 2 T_e$$

for the 2:1 resonance this yields equation (4.2) for the critical speed.

$$v_{crit} = \left( 1 - \frac{2 T_s}{T_R} \right) \frac{g T_s}{2\pi \cos(\mu)} \quad [\text{kn}]$$

(4.2)

Using this relation, an encountering angle $\mu$ of 150° and the ship’s stillwater roll period $T_R$ of 23.55 seconds, calculated with the solid GM and the wet gyration radius, the critical speeds in table 4.1 are found.

<table>
<thead>
<tr>
<th>Wave period $T_s$ [s]</th>
<th>Wave length $\lambda$ [m]</th>
<th>Wave Speed $c$ [kn]</th>
<th>Critical Speed $v_{crit}$ [kn]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0</td>
<td>99.9</td>
<td>24.3</td>
<td>-9.0</td>
</tr>
<tr>
<td>8.5</td>
<td>112.8</td>
<td>25.8</td>
<td>-8.3</td>
</tr>
<tr>
<td>9.0</td>
<td>126.5</td>
<td>27.3</td>
<td>-7.4</td>
</tr>
<tr>
<td>9.5</td>
<td>140.9</td>
<td>28.8</td>
<td>-6.4</td>
</tr>
<tr>
<td>10.0</td>
<td>156.1</td>
<td>30.4</td>
<td>-5.3</td>
</tr>
<tr>
<td>10.5</td>
<td>172.1</td>
<td>31.9</td>
<td>-4.0</td>
</tr>
<tr>
<td>11.0</td>
<td>188.9</td>
<td>33.4</td>
<td>-2.5</td>
</tr>
</tbody>
</table>

Table 4.1: Critical speeds for a 2:1 roll resonance using the stillwater roll period

Because these are valid for stillwater conditions only, which are quite the opposite of conditions providing parametric excitation, another calculation is done using the sea roll period as per concept of KRÜGER and KLUWE [16]. Their basic idea to get a better approximation of the ship’s natural roll period is to replace the initial stillwater GM with an effective GM in waves. For this purpose an auxiliary righting lever curve consisting of the average between the crest and the trough righting lever curve is constructed\(^2\). The effective GM is then developed as the gradient of the straight line, which encloses the same area as the auxiliary curve up to an angle of 40 degrees. Using this GM, the sea roll period of the vessel yields to 20 seconds for this loading condition. The results of the calculation with this period are shown in table 4.2.

\(^2\)This is the magenta-coloured one in figure 4.7.
4.3. Righting lever alterations and roll resonance

<table>
<thead>
<tr>
<th>Wave period $T_s$ [s]</th>
<th>Wave length $\lambda$ [m]</th>
<th>Wave Speed $c$ [kn]</th>
<th>Critical Speed $v_{crit}$ [kn]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0</td>
<td>99.9</td>
<td>24.3</td>
<td>-5.6</td>
</tr>
<tr>
<td>8.5</td>
<td>112.8</td>
<td>25.8</td>
<td>-4.5</td>
</tr>
<tr>
<td>9.0</td>
<td>126.5</td>
<td>27.3</td>
<td>-3.2</td>
</tr>
<tr>
<td>9.5</td>
<td>140.9</td>
<td>28.8</td>
<td>-1.7</td>
</tr>
<tr>
<td>10.0</td>
<td>156.1</td>
<td>30.4</td>
<td>0.0</td>
</tr>
<tr>
<td>10.5</td>
<td>172.1</td>
<td>31.9</td>
<td>1.8</td>
</tr>
<tr>
<td>11.0</td>
<td>188.9</td>
<td>33.4</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Table 4.2.: Critical speeds for a 2:1 roll resonance using the sea roll period

Both critical speeds for the most dangerous period of 9.5 seconds isolated in section 4.2 are negative, meaning that a roll resonance at this speeds would only occur if the waves encountered the vessel from astern with an angle of $30^\circ$. This is due to the high roll periods resulting from the loading condition. Furthermore the righting lever alterations and thereby the parametric excitations are even lower when using a wave period of 9.5 seconds, that means a wave length of 140.9 metres, as is to be seen in figure 4.8.

![Graph showing righting lever alterations](image_url)

Figure 4.8.: Righting lever alterations at a wavelength of 140.9 metres and a wave height of $H_{1/3}$
5. Results

5.1. Accident loading condition

The polar diagrams used in section 4.2 are limited to lower speeds and encountering angles between 90 and 180 degrees because they are only used to isolate the significant wave period. To get a better understanding of the vessel’s seakeeping behaviour in general, the polar diagrams are extended to higher speeds and the full encountering angle range. Figure 5.1 does this for the most dangerous period of 9.5 seconds and compares wave heights required to reach maximum rolling angles of 25 and 30 degrees, which were estimated by the crew. Again the interval is 1 knot in radial and 10 degrees in circumferential direction. The wave height scale is also the same, so the 5.4 metres present during the accident are violet in there.

![Polar diagram up to 18 knots for a wave period of 9.5 seconds and maximum rolling angles of 25 and 30 degrees](image)

Figure 5.1.: Polar diagram up to 18 knots for a wave period of 9.5 seconds and maximum rolling angles of 25 and 30 degrees

Obvious is the roll resonance in following seas having it’s origin around the critical speed calculated in table 4.2 with the effective GM in waves. Also the wave heights required to reach a rolling angle of 25 degrees are generally smaller than those to reach 30 degrees. Even so it is important to note, that above a speed of about 10 knots the danger of high rolling angles is reduced drastically. This is due to the increased roll damping at higher speeds, which are however impracticable in head seas because of high slamming loads on the bow structure. The
accident conditions are defined by an encountering angle of 150 degrees and the ship's speed of approximately 5 knots. So the wave heights needed to induce such rolling angles as stated in the report are well above the significant wave height of 5.4 metres. This matches the statement of the ship's master about a series of waves larger than average. Nevertheless the possibility of temporary decreased speed as a consequence of wave forces has to be taken into account. By this means the ship could have been brought into a more vulnerable situation closer to the centre of the polar diagram, where even small wave heights are dangerous.

At first view it remains unclear whether parametric excitation or direct seaway moments caused the high roll amplitudes. But if figure 5.2 is included in the considerations, the answer is provided displaying the required wave heights for even higher rolling angles of 35 and 40 degrees.

Figure 5.2.: Polar diagram up to 18 knots for a wave period of 9.5 seconds and maximum rolling angles of 35 and 40 degrees

According to this the dangerous region of parametric influence is definitely located in following seas. This agrees with the thoughts in section 4.3: the righting lever alterations are formed in such a way, that the resonance has to be met rather exactly in order to result in severe roll motions. This was not the case during the accident, as it happened in head seas at a speed of 5 knots.

Therefore the following results are gathered:

- The governing factor of the roll motions is external excitation by the seaway and not roll resonance due to parametric excitation.

- The significant wave height of 5.4 metres during the accident is not sufficient enough to cause a rolling angle of 25 to 30 degrees.

- The required significant wave heights to reach such high rolling angles reside in the area above 8 metres.
5.2. Situation before the ballasting operation

The first two results are valid regardless of the period assumption because comparative calculations with other periods show a similar qualitative behaviour. The third result is of quantified nature and thus valid for a wave period of 9.5 seconds only.

5.2. Situation before the ballasting operation

About 45 minutes before the accident the ship was ballasted with 1104 tonnes of ballast water to improve the hydrostatic stability. While the GM was increased by this operation, the natural roll period was decreased in the same step, forcing the ship closer to a 2:1 roll resonance. So the situation before the ballasting operation is examined as well and compared to the accident loading condition. This is achieved by taking out the additional ballast water and adjusting the centre of gravity in such a way, that the floating position of the day before is reached\(^1\). Figure 5.3 displays the difference between both loading conditions for the most dangerous period and the same rolling angle criterion.

The effect of the backwards shifted centre of the 2:1 resonance in the situation before the ballasting operation is clearly to be seen on the left side. Consequently the ship is much more in danger in following seas before ballasting than after ballasting. This did not affect the vessel on the days before the accident because the speed exceeded 20 knots and the waves were considerably smaller than on 27 January.

On the other hand this means that loading the ballast water had the opposite effect by deteriorating the situation in head seas. Thereby the preconditions for the accident have been met.

\(^1\)Loading computer data is given only once a day.
5.2. Situation before the ballasting operation

So the ship has a higher GM with the extra ballast water and is thus considered safer from a nautical standpoint, but in fact the seakeeping behaviour in the seaway encountered is worse than before. This is in general not predictable as polar diagrams do not exist on a bridge to evaluate possible dangerous situations.

The comparison with other wave periods shows not the same characteristics in all cases. Especially at higher periods there is an improved seakeeping behaviour in head and following seas after ballasting, as figure 5.4 demonstrates exemplary for a wave period of 10.5 seconds.

![Figure 5.4: Polar diagram comparing the situations before and after ballasting for a wave period of 10.5 seconds and a maximum rolling angle of 30 degrees](image)

Worth mentioning is the fact that the loading condition before ballasting is close to the design state with just enough ballast water to fulfil statutory requirements in terms of intact stability and longitudinal strength. This raises the question if the design seakeeping behaviour should be the one on the left side of figures 5.3 and 5.4 because this particular aspect is not specified by mandatory regulations.

In conclusion this section delivers the following results:

- The 2:1 roll resonance in following seas is *shifted further forward* by taking ballast water on board.
- The situation in head seas *deteriorates* after the ballasting operation.
- The additional ballast water therefore *definitely contributed* to the accident.

The first result is valid for any wave period because it is a consequence of the modified roll period. The second and the third result however are dependent on the significant wave period, which is just estimated to 9.5 seconds in the absence of reliable input.
5.3. Seakeeping behaviour in the ballast arrival condition

The accidents surveyed recently by the Institute of Ship Design and Ship Safety happened in the ballast arrival condition [1] [2], so the seakeeping behaviour of this vessel under the same circumstances is to be examined in the following. Because this loading condition is totally different from the other ones, all cargo and most of the consumables\(^2\) are removed from the calculation model. For proper propulsion and tolerable slamming loads both the bow and the stern have to be immersed sufficiently, so the fore and aft peak ballast tank are filled with sea water. At the same time the longitudinal bending moment in the hull has to stay within permissible limits. Therefore midship ballast tanks have to be used as well. Based upon the tanks listed in the loading computer, a viable filling plan complying with the aforementioned boundary conditions is developed. The resulting mass and centre of gravity of the ballast water is then entered into E4.

Due to the position of the ballast tanks in the double bottom and the amount of cargo removed the centre of gravity shifts to a lot lower position. This results in a much higher solid GM of 6.04 metres, a smaller wet gyration radius of 0.4 B and thus a much shorter natural roll period of 10.61 seconds. The righting lever alterations for this loading condition in figure 5.5 show only slight differences between the situations on a wave crest and in a wave trough.

![Figure 5.5.: Righting lever alterations in the ballast arrival condition](image)

This is because the draught in the ballast arrival condition is smaller than the design draught, so the water-plane area varies not that much as before. As a consequence remarkable parametric excitation is not an issue. Furthermore a 2:1 roll resonance would require wave periods about half the ship’s roll period, resulting in wavelengths below 50 metres, which are rather rare and break soon. Finally the sea roll period is the same as the stillwater period, which is plausible given the fact that the ship does not possess additional form stability in this loading condition.

For the reasons stated before, the seakeeping behaviour is very different from that during the accident, as figure 5.6 demonstrates. There is no recognisable spot of resonance in the ballast

\(^2\)Fuel, freshwater, etc.
arrival condition, but instead beam seas appear to be much more dangerous than before. Due to the negligible parametric excitation this is a result of direct seaway moments. Nevertheless it has to be kept in mind, that the calculation method overestimates the ship’s reactions in beam seas. Even in this loading condition the increased roll damping above a certain speed is obvious, though the associated value is depending much more on the encountering angle here than in the accident loading condition.

Figure 5.6.: Polar diagram comparing the situations during the accident and in the ballast arrival condition for a wave period of 9.5 seconds and a maximum rolling angle of 35 degrees

The qualitative behaviour in the ballast arrival condition is comparable with that of the CCNI GUAYAS, the FRISIA LISSABON and the CHICAGO EXPRESS, which are the ships in the other cases surveyed [1] [2]. Of these the first two are about the same in terms of main dimensions, but the last one is of postpanamax size. If the associated investigation reports are reviewed, it can be found that the ship examined in this thesis is more susceptible to beam seas than the FRISIA LISSABON and the CHICAGO EXPRESS but not as much as the CCNI GUAYAS. Judging by table 5.1, this does not concur with the corresponding GM values because other factors, for instance the hull form or the floating position, influence the seakeeping behaviour as well.

<table>
<thead>
<tr>
<th>Ship</th>
<th>$L_{pp}$ [m]</th>
<th>$B$ [m]</th>
<th>$GM_{corrected}$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRISIA LISSABON</td>
<td>195.40</td>
<td>29.80</td>
<td>4.56</td>
</tr>
<tr>
<td>CCNI GUAYAS</td>
<td>195.40</td>
<td>29.80</td>
<td>5.63</td>
</tr>
<tr>
<td>Ship examined here</td>
<td>197.10</td>
<td>32.20</td>
<td>5.85</td>
</tr>
<tr>
<td>CHICAGO EXPRESS</td>
<td>319.00</td>
<td>42.80</td>
<td>7.71</td>
</tr>
</tbody>
</table>

Table 5.1.: Comparison of the ships in the ballast arrival condition
5.4. Accelerations affecting the containers

Another problem linked with this specific loading condition are the high transversal accelerations due to the short roll period. These become worse the farther a position is away from the roll axis and have thereby led to heavy injuries or even fatalities on the bridge during the other accidents. So the transversal accelerations on the bridge for an endangered speed and encountering angle derived from figure 5.6 are calculated in a single simulation and plotted in figure 5.7.

![Graph showing transversal accelerations](image)

Figure 5.7.: Transversal accelerations on the bridge in the ballast arrival condition

It is to be seen that the accelerations exceed 1g, which is a value reached during the other accidents as well. Considering the average width of a modern bridge, this poses a serious threat to the well-being and the lives of the crew.

Based on the investigations the following is found:

- The parametric excitations become insignificant in the ballast arrival condition.
- The ship becomes rather endangered in beam and bow quartering seas than in head and following seas.
- The accelerations on the bridge in this loading condition exceed 1g.

Therefore it is clear that this ship can be pushed into the same failure mode as any of the other vessels if given enough GM. This is in agreement with the results found by ROX for the operation of container ships in the ballast condition [5].

5.4. Accelerations affecting the containers

The accident in question caused the loss of 27 containers and damage to the remaining ones in bay 34 in front of the deckhouse. On that account the accelerations acting during the upward
motion shortly before the collapse are of interest. To determine these, separate simulations are performed for a speed of 5 knots and an encountering angle of 150 degrees. The wave period stays at 9.5 seconds, while the significant wave height is varied.

According to section 5.1 the significant wave heights required to reach rolling angles of 25 to 30 degrees exceed 8 metres. This concurs with the master’s statement in the report, which mentions a “steep sided swell wave, estimated to be between 10m to 12m in height” [4]. Therefore significant wave heights ranging from 9 to 12 metres are used in the following to ensure sufficiently high roll amplitudes. The correspondence between significant wave height and maximum rolling angle is shown in table 5.2 for the mentioned accident situation.

<table>
<thead>
<tr>
<th>$H_{1/3}$ [m]</th>
<th>Maximum rolling angle [$^\circ$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>24.20</td>
</tr>
<tr>
<td>10</td>
<td>28.93</td>
</tr>
<tr>
<td>11</td>
<td>34.64</td>
</tr>
<tr>
<td>12</td>
<td>35.53</td>
</tr>
</tbody>
</table>

Table 5.2.: Relation between the significant wave height and the maximum rolling angle

As can be seen in there, the interval of 25 to 30 degrees is well covered by the simulations. It has to be kept in mind however, that seaways with these extreme significant wave heights are rather rare in nature and only employed here to achieve the desired rolling angles artificially. In addition these values are about twice as high as during the actual accident.

The evidence found by the MAIB investigation suggests that the collapse was caused by the containers in row 07, which then led to a “domino effect” toppling the rest of the containers. Therefore the examination is concentrated on the containers in this row, being the third one counting from the outboard starboard side. All accelerations given are affecting the containers in their centre of gravity, which is assumed at half their length, at half their width and at 40 per cent of their height.

Figure 5.8.: Transversal accelerations affecting the lowest container in row 07 at a significant wave height of 9 metres
5.4. Accelerations affecting the containers

The histogram in figure 5.8 displays the transversal accelerations against their number of occurrences for the lowest container in row 07 at a significant wave height of 9 metres and provides associated statistical data. It is important to note that these accelerations include the gravitational acceleration $g$, which has a component in the $y$-direction by the sine of the rolling angle. As is to be seen, the maximum transversal acceleration is $4.3 \text{ m/s}^2$ and does rarely occur. Because all equipment is in general designed for transversal accelerations of $0.5g$, the waves higher than 9 metres seem to be more likely.

Figure 5.9.: Transversal accelerations affecting the lowest container in row 07 at a significant wave height of 10 metres

If figure 5.9 is inspected closely, it reveals a maximum acceleration of $5.2 \text{ m/s}^2$ for a significant wave height of 10 metres, which is a considerable increase compared to the situation in figure 5.8. The values here are scattered more than before, resulting in a more frequent occurrence of the higher accelerations. Furthermore, the linkage between the maximum rolling angle and the maximum transversal acceleration can be seen.

This is again confirmed by figures 5.10 and 5.11 for significant wave heights of 11 and 12 metres. Interesting is the fact, that the increase in maximum rolling angle and thereby in maximum transversal accelerations is not as severe from 11 to 12 metres as it is from 9 to 10 or 10 to 11 metres. Obviously the roll damping limits the roll amplitude to be reached. Nevertheless, a significant wave height of 12 metres is the most dangerous one examined with accelerations up to $6.2 \text{ m/s}^2$ and the highest average value.
5.4. Accelerations affecting the containers

Figure 5.10.: Transversal accelerations affecting the lowest container in row 07 at a significant wave height of 11 metres

Figure 5.11.: Transversal accelerations affecting the lowest container in row 07 at a significant wave height of 12 metres
As a result of these calculations the maximum transversal accelerations for the different significant wave heights are shown in table 5.3. Acceleration histograms for the higher positioned containers in row 07 can be found in appendix A. In addition the assumed vertical centres of gravity and the mass of the containers given by the investigation report are displayed.

<table>
<thead>
<tr>
<th>Container</th>
<th>VCG a.B. [m]</th>
<th>Mass [t]</th>
<th>$a_{t,max}$ [m/s²] at $H_{1/3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Tier 82)</td>
<td>22.56</td>
<td>17.3</td>
<td>4.3</td>
</tr>
<tr>
<td>2 (Tier 84)</td>
<td>25.45</td>
<td>27.8</td>
<td>4.4</td>
</tr>
<tr>
<td>3 (Tier 86)</td>
<td>28.35</td>
<td>17.6</td>
<td>4.4</td>
</tr>
<tr>
<td>4 (Tier 88)</td>
<td>31.25</td>
<td>19.1</td>
<td>4.5</td>
</tr>
<tr>
<td>5 (Tier 90)</td>
<td>34.14</td>
<td>16.0</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Table 5.3.: Transversal accelerations acting on the different containers in row 07 at varying significant wave heights

Apparently there are some heavy containers stored over lighter ones, the second one being of extraordinary weight, which is discussed further in the MAIB report [4]. The accelerations increase in the higher tiers, where the distance to the roll axis is greater. The effect of heightened waves however outreaches that of a heightened position.

Judging by this examination, the following results are gathered:

- The transversal accelerations on all containers can exceed 0.5g.
- The achievement of such high values is very rare.
- The required significant wave heights for this are 10 metres and more.

Again all quantitative findings are limited to a wave period of 9.5 seconds at a speed of 5 knots and an encountering angle of 150 degrees. But as this is the most critical period, the calculations are conservative. The accelerations are thus regarded to be transferable to slightly differing speeds and encountering angles. Because the actual wave heights during the accident are just estimates, a final evaluation can not be performed. Regardless it can be stated that the possibility of accelerations above 0.5g acting on the containers exists if the waves are high enough. As a consequence of that containers or lashing equipment could have been subject to failure, but assessing that is not the task in the scope of this thesis.
6. Conclusion

Regarding the information gained in the chapter before, it is to be said that this particular vessel faces problems with direct excitation by the seaway in head seas at slow speeds. If parametric excitation is an issue, it is in following seas at higher draughts only, where the variation of the water-plane area in waves is great enough. The extension of the mentioned problems however is dependent on the actual loading condition and the encountered wave period.

Comparison with the other accidents [1] [2] shows that this particular one is of a different nature. This is because it happened in a loading condition with a lot of payload, hence the GM was considerably lower than in a ballast condition. Consequently the natural roll period was higher resulting in lower transversal accelerations. Nevertheless it is possible to achieve the same failure mode as in the other cases, if this ship is operated in the ballast condition. Under that circumstances the effects of parametric excitation become negligible and the transversal accelerations on the bridge exceed 1g.

Another problem, which is constant throughout all loading conditions, is that of decreased roll damping at lower speeds. There are three basic approaches to counteract this: the first one is obviously to increase the speed. This would however require bow structures sturdy enough to endure speeds of at least 10 knots. The second one is to construct larger bilge keels, which are currently limited by the steel industry to profiles of 430 millimetres in height. A quite impressive comparison for a bilge keel of 1.5 times the original height used on this ship can be found in appendix B. The third approach is the use of free surface effects as a means of roll damping. This one is indeed linked with several problems. On the one hand the decrease of the hydrostatic stability could come into conflict with mandatory requirements, which makes the approach not feasible for loading conditions with an already low GM. On the other hand the handling of free surfaces requires at least a basic understanding of hydrostatics on the part of the crew as well as loading computers regarding the actual tank limitations. How the aforementioned has affected another accident, has recently been surveyed by the Institute of Ship Design and Ship Safety [17]. In that context it became apparent that ballast tanks on modern container ships are not capable of providing sufficient roll damping moments. This is due to their position in double bottom or double hull, so that the free surface is either not great enough or only effective up to small rolling angles.

Based upon the results it is recommended to employ physically accurate calculation methods for the seakeeping behaviour during the ship design process. This recommendation is underlined by the fact that this accident, in contrast to the other cases surveyed, happened in a loading condition close to the design state. Furthermore it is obvious that statutory limitations regarding the seakeeping behaviour of ships are needed. With respect to the ballasting operation, which has been proven to deteriorate the situation and enable the accident, it has to be stated that the GM alone is not a sufficient measure of the safety of a vessel, especially in heavy seas. Therefore polar diagrams for designated loading conditions should be handed to the crew in addition to stability booklets, so that possible dangerous situations can be evaluated and accidents thereby prevented.
A. Accelerations on the containers in row 07

A.1. Accelerations affecting the container in row 07 and tier 84

Figure A.1.: Transversal accelerations affecting the container in row 07 and tier 84 at a significant wave height of 9 metres

Figure A.2.: Transversal accelerations affecting the container in row 07 and tier 84 at a significant wave height of 10 metres
A.1. Accelerations affecting the container in row 07 and tier 84

Figure A.3.: Transversal accelerations affecting the container in row 07 and tier 84 at a significant wave height of 11 metres

Figure A.4.: Transversal accelerations affecting the container in row 07 and tier 84 at a significant wave height of 12 metres
A.2. Accelerations affecting the container in row 07 and tier 86

Figure A.5.: Transversal accelerations affecting the container in row 07 and tier 86 at a significant wave height of 9 metres

Figure A.6.: Transversal accelerations affecting the container in row 07 and tier 86 at a significant wave height of 10 metres
A.2. Accelerations affecting the container in row 07 and tier 86

Figure A.7.: Transversal accelerations affecting the container in row 07 and tier 86 at a significant wave height of 11 metres

Figure A.8.: Transversal accelerations affecting the container in row 07 and tier 86 at a significant wave height of 12 metres
### A.3. Accelerations affecting the container in row 07 and tier 88

- **Figure A.9.** Transversal accelerations affecting the container in row 07 and tier 88 at a significant wave height of 9 metres

- **Figure A.10.** Transversal accelerations affecting the container in row 07 and tier 88 at a significant wave height of 10 metres
A.3. Accelerations affecting the container in row 07 and tier 88

Figure A.11.: Transversal accelerations affecting the container in row 07 and tier 88 at a significant wave height of 11 metres

Figure A.12.: Transversal accelerations affecting the container in row 07 and tier 88 at a significant wave height of 12 metres
A.4. Accelerations affecting the container in row 07 and tier 90

![Graph](image1)

Figure A.13.: Transversal accelerations affecting the container in row 07 and tier 90 at a significant wave height of 9 metres

![Graph](image2)

Figure A.14.: Transversal accelerations affecting the container in row 07 and tier 90 at a significant wave height of 10 metres
A.4. Accelerations affecting the container in row 07 and tier 90

Figure A.15.: Transversal accelerations affecting the container in row 07 and tier 90 at a significant wave height of 11 metres

Figure A.16.: Transversal accelerations affecting the container in row 07 and tier 90 at a significant wave height of 12 metres
B. Seakeeping behaviour using a larger bilge keel

Figure B.1.: Polar diagram for a wave period of 9.5 seconds and a maximum rolling angle of 30 degrees with bilge keel heights of 370 mm and 560 mm
Bibliography


