Automatic loading and unloading of inland container barges

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Abstract

This paper concentrates on the future design of inland barge service centres: focusing primarily on automatic loading and unloading of containers. Over the past decade transport of containers by inland barges in Rotterdam has increased consistently: They presently carry more than 35% of the hinterland transport of containers in Rotterdam which is expected to increase to 50% in the near future. Currently manually operated cranes process the loading and unloading of inland shipping. To allow the operation to be carried out automatically, the motions of crane and ship need to be tuned with the utmost precision: the accuracy of placing the container and the movement of the ship due to external conditions will decide whether or not automation is a feasible option. In order to gain insight into the viability of automatic loading and unloading of containers a study is carried out on the movement of different berthed inland vessels under normal conditions. Current technology has been taken as a basis for crane performance in terms of movement and precision. Use is made of a computer model called SHIP-MOORINGS developed by Alkyon Hydraulic Consultancy & Research, Marknesse, The Netherlands, designed to simulate the dynamic behaviour of berthed vessels taking into account all six modes. The number of variables determining the movement of a vessel at berth is large: It is impossible to develop a universal berth and harbour configuration representative for all conditions. Hence this study is aimed to determine the characteristic movements of a typical inland vessel under normal circumstances. This is carried out by executing computations with systematic variation of parameters. The paper presents the results of these computations and draws conclusions with respect to the feasibility of automatic loading and unloading of inland vessels.
1. Introduction

The paper will describe the key factors, which influence the process of loading and unloading. These can be divided into margins, external forces, berth configuration and stability characteristics of the vessel. This is translated into a mathematical model. The model will then be used to test the movement of the vessel under various inputs. Results will be compared with the acceptable margins from which conclusions will be drawn (see Figure 1).

Figure 1: Overview of the analysis process

2. Analysis of acceptable margins

Four variables play an important role in automatic loading and unloading. The first variable is incorporated in the ships design (a) and aims to compensate the various displacements due to the:
(b) crane in placing the container;
(c) movement of the ship;
(d) error in determining the ships exact location in relation to the crane.
In the new generation vessels (a) is represented by so called cell guides as shown in Figure 2 together with b, c and d.

All variables are stochastic: The calculations shown will be carried out with deterministical, significant values having 13.5 percent chance of being exceeded. It is not the objective to establish the true downtime of the vessel: instead the study aims to provide insight in the practicability of automatic loading and unloading.

Assuming containers will not be jammed between cell guides due to the rotation of the vessel the following conditions are stated (basic assumption is that these represent a worst case scenario in terms of phases of different modes, see Paragraph 4.3).

First, if the vessel does not move and the exact location of the ship is known, automatic loading and unloading is possible if the amplitude of the movement due to the crane in placing the container (b) is smaller than the marginal amplitude allowed by the cell guides (a).

\[ b < a. \] (1)

Secondly, if the vessel does move (due to external forces) and the average position of the ship needs to be determined with the use of measuring equipment then...
automatic loading and unloading is possible only if the sum of the displacement of the container \((b)\), the amplitude of the ships movement \((c)\) and the inaccuracy in determining the position of the vessel \((d)\) is smaller than the marginal amplitude allowed by the cell guides \((a)\).

\[ b + c + d < a. \]  

Thirdly, if the above two requirements are not fulfilled then automatic loading and unloading is only possible if the crane follows the movement of the vessel. In that case one needs to satisfy the conditions as stated in Equation 1. In addition one needs to take into consideration the error inherent to the ‘following’ system.

In order to gain an understanding into acceptable horizontal margins these conditions are quantified based on current technology. Assuming that the cell guides are capable of compensating a maximum amplitude of 7 cm (Wanders [1]) and that the crane has a maximum error of 3 cm (NELCON [2]) means that requirements for automatic loading and unloading for Condition 1 \((b < a)\) are satisfied \((3 \text{ cm} < 7 \text{ cm})\). More interesting is Condition 2 as it involves the movement of the vessel. Assuming the position of the vessel can be determined within 1 cm (TUD [3]) means that the vessel may not move in excess of 3 cm \((c < a-b-d, \text{ in this case } c < 7-3-1)\) in the horizontal plane. In case of a ‘following’ mechanism the crane must have the required capacity in terms of acceleration and velocity in order to ‘follow’ the movement of the vessel.

3. Possible solutions to automatic loading and unloading

Solutions contributing to overcoming the difficulties of automatic loading and unloading can be split into three main approaches:

- Limiting the movement of the vessel by:
  - limiting the forces on the vessel (for example by constructing breakwaters);
  - mooring the vessel in such a way that it moves within the required boundaries (for example by using mooring lines);
  - designing the ship in such a way that forces have less effect upon its movement (for example by changing the block coefficient).
- Making use of a crane mechanism capable of following the movement of the vessel;
- A combination of the above.

4. System determining the movement of the ship

4.1. Introduction

The response of the vessel is determined by multiplying the spectrum of external forces \((m^2/s)\) with the spectrum of the transfer function \((m/m)\). The transfer function is
the ratio between the displacement of the waves and the displacement of the vessel. The shape of the spectrum of external forces depends upon the size and characteristics of wind and waves whereas the shape of the spectrum of the transfer function depends on the stability characteristics of the vessel, which is also influenced by the berth configuration. The components, which determine the movement of the vessel, can be split into three:

- the vessel;
- waves, wind and current;
- and berth configuration.

These components will be briefly mentioned below.

4.2. Inland water vessels

The European fleet of inland barges is large and diverse. The load capacity varies from 250 to 4600 tons. Lengths range from 38 metres to almost 135 metres. A length of 110 metres and a breadth of 11.4 metres, which is characteristic for a Rhineship, were until recently the maximum dimensions allowed for a vessel on the Rhine. Latest generation inland water vessels are even larger, capable of carrying up to 600 containers. One of these is the so called Jowi with a length of 134.20 metres and a breadth of 16.84 metres, not only designed to carry just containers but also developed to be suitable for automatic loading and unloading. This is evident due to its high stability and its ingenious configuration of cell guides (see Figure 2).

4.3. Stability

In terms of movement a vessel will have six modes. This can be split into three rotations and three translations. The resultant horizontal and vertical displacement depends on the difference in phase angle between every mode. This means that modes opposite to each other can both enhance and reduce the resultant horizontal and vertical movements of the vessel. It was mentioned previously, that stability plays an important role in keeping the vessel within the required margins. A measure of the stability of the vessel is the meta-centric height. The meta-centre (GM) is the point around which the vessel turns when brought out of balance. The meta-centric height is the distance between the meta-centre and the centre of gravity; hence the stability is dependent upon the shape of the vessel and centre of gravity of the ship plus the load. The distance between the two centres will decrease if the centre of gravity of the cargo is positioned high above the centre of gravity of the empty vessel: In general a voluminous load will lead to a decrease in stability hence a fully loaded container vessel will be less stable than the same vessel loaded with heavy bulk cargo which has
its centre of gravity below the centre of gravity of the empty vessel. A loaded and an unloaded vessel should therefore be regarded as different vessels and be analysed separately. Movement caused by loading and unloading is assumed to be negligible compared to the movements caused by wind and waves. For details regarding movement caused by loading and unloading see (Wijnolst et al, [4]).

4.4. External forces

Beside natural causes an important source of wave generation is that of passing ships. Depending on the shape and size of the vessel, its speed, the dimensions of the waterway and the position of the vessel in the waterway, vessels are capable of generating critical waves in sheltered waters (Groenveld [5] and MRHE [6].)

The influence of natural and civil structures upon waves, wind and current at a berthing side is unique for every harbour: waves travelling from deep water to the shore and eventually arriving at the quay, where the inland vessel is being loaded and unloaded, are subject to many physical processes such as shoaling, reflection, refraction and diffraction.

Wind is an important dynamic natural force to take into consideration not only because it generates an entire wave spectrum but can also influence movement of crane and vessel directly.

Under normal circumstances, current will have little or no effect on the movement of berthed vessels. However, in rare cases of sites being exposed to large currents such as in a river or estuary, currents can present problems.

4.5. Berth configuration

Berth configuration is split into three elements defined as quay, mooring lines and fenders. The type of quay and its location within the harbour may have an important effect on the occurrence of waves at berth: on the one hand reflection determines the total energy of the wave, on the other hand quays can function directly as a shelter.

Mooring lines and fenders are the link between quay and ship and ensure the ship remains in place at berth. The combination of mooring lines and fenders has influence on the movement of the vessel and is therefore of importance during loading and unloading. This influence is not only determined by the configuration, but also by stiffness of lines and fender. As long as pre-stress is maintained, meaning the ropes will not slacken, the combined stiffness of the parallel configuration is the sum of the stiffness of the fender and the stiffness of the ropes.

5. Mathematical model

At this stage the system composed of the vessel, external forces and berth configuration is translated to a mathematical model. In doing this use is made of
Newton's second law,

\[ \sum_{j=1}^{6} M_{kj} \ddot{x}_j = F^e_k, \quad k = 1, \ldots, 6. \] (3)

\( M_{kj} \) is representative for the inertia matrix of the vessel, \( \ddot{x}_j \) is representative for the acceleration vector and \( F^e_k \) is representative for all the forces acting upon the vessel. These forces can be wave forces, wind forces, current forces, hydrodynamic reaction forces (as a result of the movement of the vessel), hydrostatic restoring forces, mooring line forces, fender forces and forces as result of viscosity.

Due to the properties of the berth configuration the behaviour of the vessel is not linearly related to its displacement, velocity and acceleration. This means that the superposition principle is no longer valid and one is forced to revert to the direct solution of the equations of motion as function of time. In order to achieve this use is made of the formulation given by Cummins (1962). The conversion of equations in the frequency domain to those in the time domain is described by (Oortmerssen [7] and Journee and Massie [8]). Based on these equations the ship's motions have been computed using a computer simulation program called SHIP-MOORINGS. This program is developed by Alkyon Hydraulic Consultancy & Research, Marknesse, The Netherlands, to analyse moored objects subject to external forces such as due to wind, waves, current and interaction effects with passing ships.

6. Input

In order to analyse and compare the various parameters having influence upon the movement of the vessel a standard berth configuration is introduced as well as standard external conditions. Herein use is made of the Rhineship. The Jowi is simulated to make a comparison of the influence of vessel size and stability. The mooring line and fender configuration is based upon that used under normal circumstances by the Jowi. This means the vessel will have one bowline, one stern line and a single spring at the back of the vessel (see Figure 6). The line characteristics are comparable to tensioned steel. The fenders are wooden dolphins (Bridgestone Corporation [9] and PIANC [10]), placed at an equal distance of 40 metres.

In order to simplify the analysis the vessel is berthed in a so-called 'barge service centre.' This is a U-shaped berth based on the design of (Wijnolst et al, [4]). The finger piers are designed as quays on piles and therefore have no influence upon the external forces such as wind, waves and current. Only the quay facing the bow of the vessel will have a close face, such as to reflect the incoming waves. Figure 3 and Figure 4 explain the berth configuration. The depth is constant throughout the berth area and fixed at 6.0 meters.
Figure 3: Simplification of U-shaped berth in a barge service centre

Figure 4: Cross-section A-A pier configuration

External conditions are based upon measurements carried out at the Sloehaven near Vlissingen in The Netherlands, at Ramsgate in the United Kingdom and at the Maasvlakte in Rotterdam in The Netherlands.

The waves are characterised in terms of a Jonswap spectrum. This is a spectrum meant to describe a growing sea. For the standard conditions the peak factor gamma \( \gamma \) is set at 3.30. The spectrum is further characterised by a significant wave height and a peak period established at 0.2 metres and 4 seconds respectively. For comparison with the standard external conditions the height is varied between 0.1 and 0.5 metres. The wave period is varied between 3 and 8 seconds. Simulations are conducted over a period of 1000 seconds meaning that in case of testing a wave period of 8 seconds a minimum of 125 waves are used. Tests described by the International Towing Tank Conference [11] state a minimum of 50 waves for reliable results. For the standard configuration waves travel at right angles in relation to the length of the vessel (90° or
270°, see Figure 5): from experimental analyses this is found to be the most unfavourable angle in terms of the movement of the vessel (see Figure 6: influence angle of wave attack). The influence of second order wave forces is not taken into account in the analyses.

![Figure 5: Angle of wave attack](image)

Wind is determined by the correlation between wave period and wind speed and is simulated as a static force. The effect of wind on the vessel is determined by its shape and stability (Marine Forum, International Oil Companies [12]). Other parameters having influence upon the movement of the vessel are angle of wave attack, wave reflection (from the quay), and mooring line tension, configuration, material and stiffness. Also fender material and configuration is tested. The analyses are based upon varying one parameter and keeping others constant (standard configuration). In all cases at least three different values of the parameter are tested in order to establish a meaningful relation.

7. Results

7.1. Introduction

In this paragraph the most significant results will be presented and discussed. It is repeated that the analysis focuses only on the horizontal movement of the vessel. Movements are given for the centre of gravity of the vessel, unless mentioned otherwise. The movement of the vessel will be determined by the correlation between wind and wave spectrum (m²/s) and the transfer function (see Chapter 4).

7.2. Stability characteristics vessel

Under the influence of identical conditions, with waves coming in at right angles, the loaded Jowi moves considerably less than the Rhineship. This is especially true for roll and can be explained by the difference in characteristic period for roll. This significant difference in response is a direct consequence of the difference in meta-centric height and hence the difference in stability (see Table 1.)

The natural frequency will increase as a result of a stiff mooring configuration.
Therefore one can conclude that the natural period of both Rhineship and Jowi in loaded and moored condition tend towards the wave period (4 seconds.) The opposite can be said about the vessels in unloaded condition (see Table 1.)

The ratio between depth and breadth of the vessel determines the effect of damping by waves and hence the shape of the transfer function (see Figure 6) (Journee and Massie [8].) Significant damping will result in a lower peak of the transfer function resulting in a smaller response.

![Wave Damping](image)

Figure 6: Wave damping as a function of the ratio between breadth and draught

<table>
<thead>
<tr>
<th>Ratio of breadth v. draught B/T</th>
<th>Rhineship loaded</th>
<th>Rhineship unloaded</th>
<th>Jowi loaded</th>
<th>Jowi unloaded</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>5.5</td>
<td>2.5</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>9.5</td>
<td>3.0</td>
<td>5.0</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>5.3</td>
<td>6.15</td>
<td>7.01</td>
<td>26.10</td>
<td></td>
</tr>
<tr>
<td>2.58</td>
<td>1.93</td>
<td>0.94</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>0.94</td>
<td>0.92</td>
<td>0.84</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Natural periods, ratio breadth and draft, GM value and the resulting roll amplitude

The combination of the natural frequency in relation to the wave spectrum and the effect of damping will determine the resultant movement of the vessel.

Having established the movement at the centre of gravity (cog.) means that the rotations need to be translated to a horizontal movement at the top of the cell guide (see Table 2 and Table 3).

<table>
<thead>
<tr>
<th></th>
<th>Double roll amplitude (°)</th>
<th>Resulting horizontal movement (y-direction) at a height of 7 metres above cog. (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhineship loaded</td>
<td>1.93</td>
<td>0.24</td>
</tr>
<tr>
<td>Rhineship unloaded</td>
<td>0.94</td>
<td>0.12</td>
</tr>
<tr>
<td>Jowi loaded</td>
<td>0.92</td>
<td>0.11</td>
</tr>
<tr>
<td>Jowi unloaded</td>
<td>0.84</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 2 Effect of roll upon the horizontal movement
The effect of yaw and surge are relatively insignificant due to the waves coming in at right angle. The fact that there is any kind of movement in these is due to the asymmetrical mooring line configuration.

The movement induced by sway is largely depended upon the draught of the vessel: for shallower draught the vessel will be less sensitive to movement:

<table>
<thead>
<tr>
<th></th>
<th>Significant value of double sway amplitude (y-direction) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhineship loaded</td>
<td>0.15</td>
</tr>
<tr>
<td>Rhineship unloaded</td>
<td>0.14</td>
</tr>
<tr>
<td>Jowi loaded</td>
<td>0.17</td>
</tr>
<tr>
<td>Jowi unloaded</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 5: Effect of sway on the horizontal movement of the vessel

So far the results present horizontal movement as a result of the individual modes (pitch and heave are not relevant for horizontal movements and are therefore not mentioned). In reality the resultant horizontal movement will be determined by the combination of the various modes depending upon the difference in phase angle between them. This means that opposite modes can both enhance and reduce the resultant horizontal and vertical movements. In Table 6 the resultant horizontal movement represents the sum of the modes: in this case the phase angle of roll and sway are such that they result in a maximum horizontal movement.

<table>
<thead>
<tr>
<th></th>
<th>Resulting horizontal movement (y-direction) at a height of 7 metres above cog. (m) as a result of roll and sway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhineship loaded</td>
<td>0.39</td>
</tr>
<tr>
<td>Rhineship unloaded</td>
<td>0.26</td>
</tr>
<tr>
<td>Jowi loaded</td>
<td>0.28</td>
</tr>
<tr>
<td>Jowi unloaded</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 6: Resulting horizontal movement at top of the cell guides

7.3. External forces

The wave induced motions increase for all modes as the direction of the waves rotate from 0° to 90° to the longitudinal axis of the vessel. This is due to the fact that the natural period of the vessel is moving towards the period range of incoming waves. For waves approaching the vessel at right angles (90° or 270°) the mooring lines show loads, which are beyond the recommended values. For waves outside the 70° to 110° sector, barges are not very sensitive to movement. Figure 6 is a graphic representation of the results.
Figure 6: Effect of varying angle of wave attack on sway, surge, roll and yaw

As the wave height increases so does the response of the vessel: the area under the wave spectrum will increase which, as long as it overlaps with the transfer function, has a direct influence on the response spectrum (see Chapter 4).

For an increase in wave period the wave spectrum will move to the right in relation to the transfer function. Whenever this leads to an increase in overlap between spectrum and transfer function (period of the wave tends to the natural period of the vessel), there will be an increase in the response.

The effect of wave reflection depends upon the change in phase angle as a result of reflection. This depends on the type of boundary. The boundary also determines the reflected wave amplitude expressed in terms of the reflection coefficient (Dock and Harbour Authority [13]).

A static wind force has little effect on the movement of the vessel: this is a result of the limited wind area of the vessel.

7.4. Berth configuration

An increase in line tension has little effect upon the movement of the vessel: as long as the pretension is within the linear region of the spring characteristic there will be no effect on the natural frequency of the vessel or the transfer function. The limited influence upon the movement of the vessel is caused by the significant mass of the vessel in relation to the size of the springs (mooring lines).

Use of 3 or 4 mooring lines instead of 2 has a critical influence upon the horizontal movement of the vessel. This is especially true for surge and yaw.

An increase in stiffness has a direct effect on the natural frequency of the vessel: using synthetic mooring lines leads to a significant increase in sway for loaded and
unloaded conditions. Roll increases especially as a result of the unfavourable influence upon the transfer function in relation to the wave spectrum. Increasing the tension in the stainless steel mooring lines has little effect on the horizontal movement of the vessel as long as the lines do not slacken. An explanation for the limited effect is that it has almost no influence on the transfer function and hence upon the response spectrum. An increase in stiffness merely results in very large forces in the mooring lines and fenders. An increase in stiffness reaches a point beyond which a further increase has little effect.

Spreading the fenders vertically on the quay has a slight influence on the rolling movement of the vessel: this is a result of an increase of the moment working against the movement of the vessel.

8. Conclusions

With respect to automatic loading and unloading these conclusions will assume the most adverse correlation between the phases of the modes.

Waves between 70 and 110 degrees produce the most significant horizontal movements as result of roll and sway. Even very low waves from these directions can prevent automatic loading and unloading: waves with a height of 0.2 metres produce horizontal movements which by far exceed the horizontal limit of 3 cm (as stated in Chapter 2). In case waves between 70 and 110 degrees are eliminated then automatic loading and unloading is a possibility for a significant wave height up to 0.3 metres from remaining directions.

Use of synthetic mooring lines is not useful to combat the movement caused by roll and sway.

Pre-tensioned stainless steel wires are effective in reducing the horizontal movement of the vessel.

Using 4 mooring lines is an effective measure to restrict the horizontal movement caused by surge, sway and yaw.

9. Recommendations

The sensitivity of fender characteristics, shape of the wave spectrum and the effect of dynamic wind on the movement of the vessel should be studied and interpreted in further detail.

For all harbours it is recommended that the physical influence of civil and natural structures such as breakwaters, quays, beaches and harbour geometry should be incorporated within the mathematical model. Quantitative figures in terms of the movement of the vessel should be generated and interpreted as part of the analysis.

For automatic loading and unloading it is recommended to carry out research into the possibility of the crane ‘following’ the movement of the vessel.

In the development of a mechanism suitable to achieve automatic loading and unloading it is recommended to carry out an extensive cost analysis.
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