MOTION CRITERIA FOR THE EFFICIENT (UN)LOADING OF CONTAINER VESSELS

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Abstract
Designers of maritime container terminals often experience difficulties in defining an acceptable degree of moored ship motions at the terminal to allow efficient (un)loading of container vessels. PIANC has published criteria for the principal movements of certain types of moored ships in harbours in relation to (un)loading efficiency (PIANC, 1995). However, it is not specified whether these criteria represent average, significant or maximum motions, they are indicated as “peak-peak” motions. It is believed that the specified criteria for container vessels are not strict enough. A number of different motion criteria are presently in use to determine the mooring of container vessels with 100% efficiency of (un)loading operations. As a result, a new PIANC Working Group 52 has been established in 2006 to produce new guidelines by 2011.

The paper provides an overview of the issues at stake. Surge is the principal motion of interest for (un)loading efficiency, due to the slow motion of the ship-to-shore crane in the direction along the quay. Loading efficiencies have been computed using an extensive series of numerical simulation of the motions of a moored container vessel, as function of container placing tolerances. The (un)loading efficiency is computed using a surge motion time-series analysis where the exceedance of the container placing tolerance criteria is considered to be delay time. Results are presented for a container placing tolerance of 0.1, 0.2 m and 0.3 m and a simultaneous surge motion velocity criterion of 0.05 m/s, for a range of (low-frequency) peak periods of a typical surge motion spectrum of a moored container vessel.

For a terminal design engineer, both the maximum allowable significant ship motions as illustrated here and the allowable frequency of exceedance {or annual (un)loading downtime} need to be considered. This depends on the local wave climate and the intensity of use of the terminal.

Keywords: container vessels, motions, (un)loading, efficiency
1. Introduction

Maritime container terminals have become increasingly important for import and export of various kinds of goods. Most container terminals have to operate on very strict time schedules. Downtime of the terminals, when loading and unloading is not possible or interrupted, usually has serious operational and financial consequences for the port or terminal. Prediction of the downtime of container terminals due to wave conditions forms an important part of port design and port operational studies. For example, there is usually a direct relationship between the length of a protecting breakwater and the wave conditions at the quay. Furthermore, long-wave action at the quay can be related to the basin and port layout.

The relationship between moored ship motion and container loading rates has been investigated as part of a research project by the Hydraulics Research Station in 1978 (Slinn, 1979). Prototype measurements were made at the Port of Tilbury and additional investigations were made in a small-scale physical model. During 2001, two MSc students from the Delft University of Technology made additional investigations at container terminals at the ports of Rotterdam and Flushing (Goedhart, 2002 and Maréchal, 2002, respectively). Goedhart also compiled a simulation program to investigate the relationship between the motions of the moored container vessel and the (un)loading rate.

PIANC has published a report on “Criteria for Movements of Moored Ships in Harbours – A Practical Guide” (PIANC, 1995). This was (part of) the result of the work undertaken by PIANC Working Group 24 (WG24). However, it is not specified in this PIANC report whether the criteria represent average, significant or maximum ship motions, while it is also believed that the motion criteria for container vessels are not strict enough. A number of different motion criteria are presently in use to determine the mooring of large container vessels for 100% efficiency of (un)loading operations. To establish clear guidelines for the maximum motions of moored container vessels, PIANC has formed Working Group 52 (WG52) in 2006 with the task to produce appropriate criteria for maximum allowable ship motions for the efficient (un)loading of moored container ships. The first author of this paper was a corresponding member of WG24 and is presently a member of WG52, which intends to complete its work by 2011.
It appeared to be very difficult for WG52 to obtain information, through questionnaires and interviews, on the relationship between moored container vessel motions and (un)loading efficiency at various container terminals in the world. It was therefore considered that simulator studies or a direct numerical approach could provide results to be used as a basis to formulate such criteria, as has been attempted earlier by Goedhart (2002). This paper provides the background to such an approach, using various motion criteria. Typical relationships between the surge motion of the moored ship and the (un)loading efficiency are presented.

2. Overview of Some Recommended Criteria

A number of moored ship motion criteria are being used to determine the (un)loading of large container vessels with (near) 100% efficiency. Generally, the motions are accepted to be maximum (rather than significant) amplitudes, that is, maximum deviations in either direction from the average position for each principal ship motion. The maximum sway motion amplitudes are in a direction away from the fender line which is the sway reference position.

Table 1 below shows a number of the recommended criteria. In this table, the criteria from Jensen et al (1990) are derived from moored ship research in the Nordic countries. It is noted that the frequency of exceedance of these movements should be less than 2% (7 days per year). In the table, Smitz refers to the original contribution of Mr Herbert Smitz to WG24, used as an internal document by WG24. The criteria of Smitz, as summarised in Table 9.7 of his contribution, are based on an extensive list of international references of the 1980’s.

The criteria from D’Hondt (1999) in Table 1 are the most restrictive and are based on the cell and pin tolerances of containers. D’Hondt specifies a maximum combined angle for roll and pitch of 0.45 degrees. The criteria from Moes are based on the other criteria in the table and physical and numerical modelling at the CSIR for contract projects. These criteria take into consideration the placing tolerances of containers, the avoidance of crane movements along the quay (for surge) and the much longer periods of horizontal motion (surge, sway and yaw) of a moored container vessel relative to the vertical motions (heave, roll and pitch).
Furthermore, modern ship-to-shore cranes can adjust spreader rotations, so that the rotational criteria (for roll, pitch and yaw) can be relaxed relative to those of D’Hondt.

Table 1: Maximum amplitudes of container vessels motion for 100% (un)loading efficiency

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Surge</td>
<td>0,5 m</td>
<td>0,5 m</td>
<td>0,5 m</td>
<td>0,24 m</td>
<td>0,3 m</td>
</tr>
<tr>
<td>Sway</td>
<td>0,4 m</td>
<td>0,3 m</td>
<td>0,6 m*)</td>
<td>0,22 m</td>
<td>0,3 m</td>
</tr>
<tr>
<td>Heave</td>
<td>0,45 m</td>
<td>0,3 m</td>
<td>0,4 m</td>
<td>0,20 m</td>
<td>0,3 m</td>
</tr>
<tr>
<td>Roll</td>
<td>1,5 deg</td>
<td>1 deg</td>
<td>1,5 deg</td>
<td>0,24 deg</td>
<td>0,5 deg</td>
</tr>
<tr>
<td>Pitch</td>
<td>0,75 deg</td>
<td>-</td>
<td>0,5 deg</td>
<td>0,4 deg</td>
<td>0,5 deg</td>
</tr>
<tr>
<td>Yaw</td>
<td>0,25 deg</td>
<td>-</td>
<td>0,5 deg</td>
<td>0,1 deg</td>
<td>0,5 deg</td>
</tr>
</tbody>
</table>

*) Although derived from Smitz, the PIANC criterion for sway is double the value of Smitz. This is probably due to an amplitude-to-range conversion error. The value of Smitz is more acceptable, defining sway motion away from the fender line.

3. Container (Un)loading

Containers are usually loaded and unloaded on container vessels by means of ship-to-shore gantry cranes, as illustrated in Photo 1. The containers are stacked in/on the ship in piles often using cell guides for under-deck storage, and are kept stable by means of an interlocking twist-lock pin system on the corners of the containers (see Photo 1, right side).

Photo 1: Unloading of container with a ship-to-shore crane spreader, showing twist-lock pin (photos courtesy of Dr M de Jong, Deltas)
During ship loading, the crane operator positions the container to be loaded above the cell guides or base containers and lowers it into position. The movement of the ship in response to waves, currents or wind, or by the wind on the transported containers, complicates this procedure. This holds specifically for the surge motion of the moored vessel, since the crane operator works from a stationary crane for each row of containers. The other five principal ship motions can be accommodated more easily by the crane operator by adjusting the spreader location and orientation. In the case of large surge motions, the crane operator is left with a finite time frame in which it is possible to place the container into position. If the ship has moved outside the reach of the spreader or the container, the operator has to wait until the vessel has moved back into this space frame, which means delay time. The duration of this time delay directly influences the efficiency of the terminal. This process is simulated in a numerical procedure, as explained in the following section.

4. Modelling Loading Productivity under Surge Motion

The most critical motion of a moored container vessel in response to waves is the surge motion, which is defined as the horizontal translation of the ship parallel to the quay. The surge motion usually occurs at a relatively low frequency, close to the natural surge frequency of the moored container vessel, which is usually between 40 s and 80 s, depending on actual ship displacement and the mooring stiffness. Because the surge motion is the largest factor influencing container loading, the modelling has been restricted to surge motion as a first approach. The numerical procedures could later be extended to include other principal ship motions such as sway, yaw or roll.

4.1 Surge spectrum

To compose a realistic surge motion of a vessel, an energy spectrum of the movements at different frequencies is needed. If a measured spectrum or a spectrum from a numerical ship motion model is available, this can be used directly. If no surge spectrum is available a spectrum can be generated using a theoretical surge spectrum. In this case, a Matlab procedure generateSurgeSpectrum has been used, which takes as arguments the peak period of the spectrum, the significant surge motion range (which is twice the significant amplitude) and the frequency limits where energy exists, as specified by the user. The spectrum is generated by fitting third order polynomials between the frequency limits and the peak frequency. The gradients of the energy spectrum at the frequency limits and the peak
frequency are set to zero. The spectral density of the spectrum is then iteratively adjusted to obtain the desired significant surge motion.

An example of a spectrum generated with the generateSurgeSpectrum function is shown in Figure 1 (blue spline line). The frequency limits were chosen as 0.005 Hz and 0.05 Hz with a peak period of $T_p = 60$ s. The spectral density was adjusted to obtain a significant surge motion range of 2.0 m. These conditions are considered typical for extreme surge motion of a container vessel. It is also possible to generate spectra that fit other distributions. One such distribution that was implemented is the Pierson-Moskowitch distribution (as used by Goedhart, 2002). The function generateSurgeSpectrumPM was used to generate a Pierson-Moskowitch spectrum with a peak period of $T_p = 60$ s and a significant surge motion range of 2.0 m.

The generated Pierson-Moskowitch spectrum is also shown in Figure 1 (red line) for a peak frequency of 0.0167 Hz ($T_p = 60$ s) and a significant surge motion range of 2 m. The shape of the Pierson-Moskowitch spectrum is fixed, while the shape of the spline-generated spectrum can be varied by adjusting the frequency limits. The spline-generated surge spectra are henceforth used in the simulations as it provides more flexibility in simulating measured spectra.

![Figure 1: Surge spectra generated by Pierson-Moskowitch and spline-generated functions](image-url)
4.2 Time-series generation

The numerical simulation of container loading will be done in the time domain. It is therefore necessary to generate a surge motion time series that fits the energy spectrum. This is done using the random-phase/amplitude model.

With the random-phase/amplitude model the spectrum is divided into a number of discrete frequency bands. A sinusoidal signal is constructed with a random frequency sample from one of the frequency bands. The amplitude of the sinusoidal signal is computed from the moment of the energy spectrum in a particular frequency band. A random phase angle is then generated for the sinusoidal signal. This process is followed for all of the frequency bands. The computed signals are then added to form the irregular time series of surge motions.

The Matlab function computePhaseAmp takes a spectrum in discrete form and computes the amplitudes and random phase angles corresponding to the discrete frequencies sampled from the spectrum. These components are used by the functions evalTimeSeries and evalVelSeries of the simulation program to compute the irregular surge motion and surge velocity at specified time steps.

4.3 Simulation of container loading

The simulation of a crane operator loading containers on a moving container vessel is implemented in the simulateLoading function. This function requires the following as input parameters:

- Significant surge motion
- Peak period of surge motion
- Frequency limits of the spectrum
- Time it takes to load a container
- Operational constraint in surge motion
- Operational constraint in velocity of the motion

The output of the function is the percentage time delay and the consequent efficiency of the terminal for the specified conditions. The efficiency is defined as the ratio of the number of containers loaded within the simulated time period over the amount of containers that could be loaded if there was no movement of the vessel.
To simulate container loading, a spectrum is generated according to specified conditions. From the spectrum a time series of surge motions is generated. The simulation is then started at time zero of the surge time series. The specified loading time is added to the current time of the simulation. The surge motion and the velocity of the surge motion are evaluated at the current loading time. If the velocity and the surge motion are both within the operational constraints as specified, a container is loaded. If either the surge motion or the surge motion velocity falls outside the specified operational constraints, the container cannot be loaded. In this case the simulation time is increased by a small time step and the surge motion and velocity is re-evaluated for the new time. This is repeated until the surge motion and velocity are both within the operational constraints and the container is recorded as loaded. There is no further time delay taken into account between reaching the loading condition and the actual loading, which may be an un-conservative assumption. The whole process repeats itself until the end of the specified simulation time.

Figures 2(a) and 2(b) show plots of a section of a generated surge motion time series and the surge velocity time series respectively. In both cases the chosen operational constraints are also indicated on the graph, which are a surge motion amplitude of 0.3 m and a surge velocity amplitude of 0.05 m/s.

Figure 2: (a) Section of a surge motion time series (solid line) with operational motion constraint at 0.3 m from average position (horizontal black dashed lines) (b) Corresponding surge velocity time series (solid line) with an operational velocity constraint at 0.05 m/s (horizontal black dashed lines)
A base loading rate of 30 units/movements per hour (one unit per 120 s) has been chosen. The red vertically dashed lines on these figures indicate the times when a container would have been loaded, but either the motion or velocity operational constraint was not met. The subsequent blue dashed line indicates the first opportunity in time after it was possible to load a container.

4.4 Statistical analysis

The surge motion time series is generated from the energy spectrum by discrete sampling. The random phase angles for the wave components are generated from a uniform distribution. Therefore, in order to obtain consistent results for simulation runs from different conditions, a number of time series of sufficient length should be generated, analysed and averaged.

The function generateGraphs simulates container loading for a 20 hour time series repeatedly. The simulation ends when the computed average productivity differs less than a specified tolerance from the previously computed average productivity. This simulation process is repeated with varying surge motion conditions.

Graphs of the simulation results for a range of surge peak periods are shown in Figure 3 for a surge motion amplitude criterion for container placement of 0.1 m, in Figure 4 for a surge motion amplitude criterion of 0.2 m and in Figure 5 for a surge motion amplitude criterion of 0.3 m, all three with an associated surge velocity criterion of 0.05 m/s. The trends in container loading efficiency, according to varying significant surge motion amplitudes and peak periods, can clearly be seen. A comparison of the three figures also shows the increase in efficiency for an acceptable higher motion criterion, for the same significant surge motion amplitude or implicitly for the same wave, current or wind conditions.

The results of the simulations are dependent on the shape of the surge motion spectrum and the motion limit criteria. Spectra with a broader range of energy would give substantially different results than spectra with a narrow range of energy. This should be kept in mind when modelling loading efficiency and the ship motion spectrum should be verified against measurements if possible. There may also be a difference between container loading and unloading, especially when spreader flaps are used.
Figure 3: Container loading efficiency curves for a range of surge peak periods, for a surge amplitude criterion of 0.1 m for container placement and a surge velocity limit of 0.05 m/s

Figure 4: Container loading efficiency curves for a range of surge peak periods, for a surge amplitude criterion of 0.2 m for container placement and a surge velocity limit of 0.05 m/s
For example, according to Figure 5, for significant surge motions of up to the surge motion amplitude criterion of 0.3 m, the loading efficiency is 99% or better. For significant surge motions of two times the criterion (i.e. for a significant surge motion amplitude of 0.6 m) the loading efficiency will drop to between 85% and 93% and for a factor of three times the criterion (i.e. for a significant surge motion amplitude of 0.9 m) the efficiency will drop to between 72% and 85%, depending on the spectral shape and surge peak period.

4.5 Discussion

A direct simulation method of container loading efficiency has been presented and the model assumptions have been discussed. The model has been kept fairly simple to be able to do trend analyses and comparative studies. It should be realized that in practice other factors than those considered in the above approach also play a role, such as more stress and fatigue on the crane operator when the vessel would be moving past it allowable criterion. If surge motion would be combined with other ship motions, such as roll or yaw, the crane operator will have to make adjustments to the spreader orientation, which will take time. Therefore, the graphs as shown in Figures 3 to 5 should be considered as un-conservative. It would be
useful to check the above criteria and hypotheses with container terminal operators or even better, to perform a series of prototype measurements under extreme ship motion conditions.

The presented model is a first approach, where only surge motion is considered. However, the surge motions are accepted to be the most critical motions of the container vessel and thereby an important component of the loading efficiency. It would be fairly straightforward to extend the model to include other principal ship motions (e.g. sway). A further aspect of the present model is that it does not include the actual lowering time, but rather models the placement of the containers as instantaneous after the specified loading criteria are being met. Adjustments could be made to the model to incorporate the effect of a finite lowering time. This would have to be defined in conjunction with cell guide widths and surrounding container stacks to evaluate the possibility of lowering the container in place in time. The model would also benefit from calibration or comparison to other models or preferably prototype measurements.

5. Conclusions and Recommendations

From the numerical exercise that has been undertaken, it appears that the choice of the container or spreader placing criterion is quite important. It can indeed be argued with D’Hondt that this placing criterion should be of the order of 0.1 (for twist-lock pins) to 0.2 m (for spreader flaps). In such a case, Figures 3 and 4 would be applicable. From these figures it can be seen that for a loading efficiency of 95% or better, a significant surge motion amplitude of 0.2 m to 0.4 m would be accepted. For a lower acceptable efficiency, e.g. when large surge motions only occur occasionally, the ship motion criteria can be further relaxed.

Assuming a Rayleigh distribution for the surge motions and a surge peak period of 60 s for the vessel motions, the expected maximum motion over a period of 6 hours would be about 1.7 times the significant motion. In the above case with 95% efficiency, the acceptable maximum surge motion amplitude would then be 0.35 m to 0.7 m. These values are close to the 0.5 m surge criterion as specified by Smitz, Jensen et al and PIANC, which are the largest criteria shown in Table 1. This also illustrates that it is important to distinguish between a strict container or spreader placement criterion (D’Hondt) and the criterion for significant or maximum ship motion. The latter should be used by port or terminal design engineers.
For the design engineer, both the maximum allowable significant ship motions and the long-term allowable frequency of exceedance of these motions (or full (un)loading downtime) during the operation of the terminal need to be considered. Some container terminal owners or operators may stipulate a limit of 2% exceedance of the significant ship motions per year when an efficiency lower than 90% would be acceptable (Jensen et al., 1990), while others may require only one such exceedance per ten years. This would also depend on the intensity of use of the terminal.

For the design of a new or extended terminal, this may have consequences for the construction of breakwaters and layout of the basins. If the relationship between the wave climate outside the terminal and the resulting motions of moored ships at the terminal is known, the design engineer could undertake an optimization exercise between the cost of delays in container (un)loading and the cost of improved wave protection structures. A decision on the allowable frequency of exceedance of the moored ship motions can then be taken on the basis of the (present or future) minimum overall cost.

The various aspects related to moored container vessel motions and container (un)loading should be carefully evaluated. Detailed numerical and/or physical model studies and simulation exercises should be undertaken to investigate the overall consequences of accepting a specific criterion and acceptable efficiency. It should be realised that different ship sizes, different loading conditions and different mooring line material and mooring layout would result in different moored ship response to a specific wave climate at the quay.

Acknowledgements

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