Prediction of the Movement of Moored Vessels due to Exceeded Mooring Load Limits

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ABSTRACT

This paper presents the development and application of an in-house manoeuvring method for the movement prediction of moored vessels. The method is based on a force model with force components for environmental and body forces. The components cover forces due to wind, waves and current. For the purpose of mooring system analysis an additional force component for the mooring line loads is introduced by using load-deflection curves. The results show the vessels trajectory during a loss of station keeping capability as a consequence of exceeded permissible mooring loads. In the presented paper the method is used for the analysis of a marine casualty due to harsh weather conditions.

KEY WORDS: Station Keeping; Mooring; Anchor Dragging; Manoeuvring; Ship Design; Marine Casualty.

INTRODUCTION

Anchor dragging is a common problem in severe weather conditions. Recent examples are the heavy lift carrier Palmerton and the container ship MSC Vigo in January 2019 (Friedrich and Starke, 2019) as well as the bulk carrier Kuzma Minin in December 2018 (UK Government, 2018). The grounding of the bulk carrier Glory Amsterdam in October 2017 near the island Langeoog in the North Sea is also a well known example for the loss of station keeping capability in heavy weather (Kaspera, 2018).

In the following sections the manoeuvring method of the in-house ship design environment E4 is presented. The used force model is explained and the used force components are described. The routine for the calculation of mooring forces, which has been recently developed, is described in particular. Some exemplary results of the manoeuvring method are presented by means of the investigation of the Glory Amsterdam accident. All presented plots result from calculations carried out for Glory Amsterdam.

MANOEUVRING MODEL

The calculations of the investigation are carried out with the body force manoeuvring model that is implemented in the ship design system E4, which is developed by the Institute of Ship Design and Ship Safety, among others. The model was developed by Söding (1984) and continuously enhanced by Krüger et al. (1998) on the basis of full scale measurements of ships during sea trials and operation. The model is used in the initial design stage for the layout of propulsion and manoeuvring devices as well as in the ship’s delivery stage for the preparation of documents such as manoeuvring booklets.

Fig. 1 Ship-fixed coordinate system of the manoeuvring method.

The model uses a right-hand, ship-fixed coordinate system as presented in Fig. 1. The origin $O$ of the system is located at $L_{pp}/2$, on centre line and $KG$ above keel at the height of the centre of gravity. The method solves the equations of motion for three degrees of freedom: surge, sway and yaw. The following Eq. 1 is a generalized formulation of the equations of motion according to Newton’s second law of motion:

$$\sum \vec{F} = \vec{M} \ddot{\vec{r}}$$

(1)
These equations can be solved for each time step by calculating all external forces $F$ represented by the left-hand side of the equations and the inertia matrix $M$. The solution delivers the resulting accelerations of the rigid body $\ddot{\mathbf{r}}$, which can be used to calculate the velocities and position of the ship for every time step by the use of a forward Euler method. The sum of the external forces consists of multiple force components like body, propeller or steering forces. An additional component which takes into account the forces of a mooring system is developed for the presented investigation. The following Eq. 2 describes the simplified formulation of the equations of motion which are used in the manoeuvring model:

$$
\begin{bmatrix}
N_{\text{Env}} + N_{\text{Prop}} + N_{\text{Moore}} + \ldots \\
Y_{\text{Env}} + Y_{\text{Prop}} + Y_{\text{Moore}} + \ldots \\
N_{\text{Env}} + N_{\text{Prop}} + N_{\text{Moore}} + \ldots
\end{bmatrix} = 
\begin{bmatrix}
m & m & m \\
m & m & m \\
m & m & m
\end{bmatrix}
\begin{bmatrix}
\dot{u}_S - v_S \dot{\psi} - x_G \dot{\psi}^2 \\
\dot{v}_S + u_S \dot{\psi} + x_G \dot{\psi} \\
\dot{u}_S + u_S \dot{\psi}
\end{bmatrix}
$$

Hereby, $X$ is the longitudinal force, $Y$ the transverse force and $N$ the yawing moment. The ship’s mass is denoted by $m$ and the ship’s moment of inertia about the x-axis by $I_x$. The longitudinal and transverse speed of the ship are denoted by $u_S$ and $v_S$. $\dot{\psi}$ is the rotational speed about the $z$-axis and $x_G$ the centre of gravity in longitudinal direction.

The calculation of external forces due to environmental influences like wind, waves and current are described in detail in the following sections. Besides these environmental forces the model also takes into account forces which can be actively controlled during the manoeuvre e.g. propulsion forces. The corresponding variables like rotational speed and pitch of the propellers are checked by a control system and changed accordingly. A simplified diagram of the manoeuvring model layout is shown in Fig. 2. A detailed description of the propulsion system components can be found in (Haack, 2006).

**Environmental Loads**

The modelling of the environmental loads has a significant impact on the behaviour of the moored ship. The implemented calculation routines have been already extensively tested and validated. The following sections show a brief overview of the calculation procedures and give reference to publications with more detailed descriptions.

**Wind Forces**

The wind forces are calculated according to the concept of Blendedmann’s coefficients (Blendedmann, 2013). Figure 3 shows an exemplary plot of coefficients for the longitudinal force $C_X$ and cross force $C_Y$ as well as the yaw moment $C_N$. The resulting wind loads depend on the wind velocity $v_w$ and the windage areas $A_{\text{front}}$ and $A_{\text{side}}$ and can be calculated for all encounter angles $\alpha$ according to Eqs. 3-5.

$$
X_{\text{wind}}(\alpha) = \frac{1}{2} \rho_{\text{air}} \cdot C_X(\alpha) \cdot A_{\text{front}} \cdot v_w^2
$$

$$
Y_{\text{wind}}(\alpha) = \frac{1}{2} \rho_{\text{air}} \cdot C_Y(\alpha) \cdot A_{\text{side}} \cdot v_w^2
$$

$$
N_{\text{wind}}(\alpha) = \frac{1}{2} \rho_{\text{air}} \cdot C_N(\alpha) \cdot A_{\text{side}} \cdot v_w^2 \cdot L
$$

The implemented force components can be used with static wind loads as well as with fluctuating speed and encounter angle. The generation of such time series is described in (Lübcke, Augener and Falkenhorst, 2015).

**Wave Forces**

For the calculation of the wave forces an approach based on strip theory according to Augener (2016) is used. The method calculates second order wave forces which have a non-zero mean value. First order wave forces with a zero mean value are neglected. This simplification is considered acceptable under the assumption that the mooring system compensates for the harmonic motions caused by the first order wave forces. The results of the used method are validated and show good correlations to measurements. The used ship design environment also contains the panel method NEWDRIFT by Papanikolaou (Papanikolaou and Zaraphonitis, 2001) as an alternative to the strip method, which can...
be used for cases where the use of a strip method is doubtful. These frequency domain results are used for the determination of wave forces in time domain that are shown in Fig. 4 together with the resulting mean values.

Current Forces

The current forces are determined on the basis of a modified slender body method. The major part of the resulting hydrodynamic force is caused by the accelerated hydrodynamic masses. The calculated forces are corrected to consider three-dimensional effects of the flow around the ship. A detailed description of the method can be found in (Haack, 2006).

MOORING FORCES

The calculation of mooring forces is based on so called non-linear load-deflection curves that describe the horizontal tension in the mooring line depending on the distance between the fairlead and the anchor. In the case of single line moorings these curves can be calculated with analytical expressions well known from common catenaries. Depending on the geometry of the mooring line the used equation systems differ as a result of varying boundary conditions. Mooring systems containing line attachments like sinkers or buoys require more complex mathematical models. The description of the implemented calculation method can be found in (Eckmann, 2016). The method can be used for the design and analysis of different single-point and multi-point moorings.

Anchor Dragging

If the distance between fairlead and anchor becomes too large, the loads in the mooring line and the attached anchor can exceed the permissible values. Some possible consequences are breaking mooring chains or anchor dragging. Typically the needed line tension to drag the anchor is lower than the breaking load of the chain. The implemented mooring model includes a simplified method for anchor dragging consideration. When the horizontal load on the anchor exceeds a permissible limit, the anchor position is recalculated. An example of the movement of the anchor between two time steps is shown in Fig. 5. The displacements of the anchor (solid orange vectors) and of the fairlead (chain-dotted blue vectors) are scaled up by a factor of 200 for better recognisability. The anchors are represented as triangles which are connected with the fairleads which are represented as circles. The vectors of the anchor displacement are calculated as projection of the vector of the fairlead movement onto the vector between fairlead and anchor. Because only tensile forces can be transmitted by the mooring line, only dragging motions are considered. Once the permissible horizontal load on the anchor is exceeded, it is assumed that the remaining holding capacity equals the permissible horizontal load on the anchor. This assumption strongly depends on the used anchor and the seabed and needs to be further investigated.

Spread Moored Systems

In the case of spread moored systems with \( n \) mooring lines as shown in Fig. 6 the mooring line loads can be used to calculate ship-fixed forces.
Fig. 6 Geometry definition of a spread moored system (Eckmann, 2016).

as described in the following Eqs. 6-8 depending on the position of the fairlead \( x_i, y_i \) and the angle between the ship’s x-axis and the mooring line \( \beta_i \). The horizontal tension in the mooring line is denoted as \( T_{H_i} \):

\[
X_{\text{Moor}} = \sum_{i=1}^{n} T_{H_i} \cos(\beta_i)
\]

(6)

\[
Y_{\text{Moor}} = \sum_{i=1}^{n} T_{H_i} \sin(\beta_i)
\]

(7)

\[
N_{\text{Moor}} = \sum_{i=1}^{n} T_{H_i} \left[ x_i \sin(\beta_i) - y_i \cos(\beta_i) \right]
\]

(8)

STATION KEEPING INVESTIGATION

In the following sections the results of the described method are presented on the basis of the investigation of the grounding of the bulk carrier Glory Amsterdam.

Grounding of Glory Amsterdam

On 19 October 2017 the bulk carrier Glory Amsterdam was anchoring near the island of Langeoog in the North Sea. The approaching storm system Herwart caused severe weather conditions with wind speeds up to 74 kn and significant wave heights around 7 m. Although the vessel was using two anchors, the vessel started drifting towards the island Langeoog. The main dimensions of the vessel can be found in Table 1.

Table 1 Glory Amsterdam main dimensions.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length o.a.</td>
<td>225 m</td>
<td>Power</td>
<td>9326 kW</td>
</tr>
<tr>
<td>Breadth o.a.</td>
<td>32.26 m</td>
<td>Speed (max.)</td>
<td>15.4 kn</td>
</tr>
<tr>
<td>Draught</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scantling</td>
<td>12.20 m</td>
<td>Grounding</td>
<td>5.72 m</td>
</tr>
<tr>
<td>Displacement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scantling</td>
<td>87 729 t</td>
<td>Grounding</td>
<td>32 170 t</td>
</tr>
</tbody>
</table>

Calculation Model

The calculation is carried out with the ship design environment E4. The calculation model is shown in Fig. 10 and includes the following data:

- **Hydrostatics and Windage Areas** A typical hull of a bulk carrier has been transformed to the main dimensions and displacement of the Glory Amsterdam. The lines at bow and stern are faired to fit the shape of the real vessel. The windage areas are modelled according to the general arrangement plan (not shown in the figure).

- **Light Ship Weight and Loading Condition** Masses, centre of gravity and mass distribution are chosen in accordance with the conditions during the casualty.

- **Propulsion and Machinery** The propeller is modelled in line with the known dimensions and recreated on basis of the Wageningen B-Series with the known power demand and ship speed. The installed main engine is modelled in accordance with the project guide of the engine maker. It includes the load diagram, limits for overload and low load operation. The dynamic behaviour is taken into account with an empirical approach based on data provided by the engine maker.

- **Mooring** According to the logbook the vessel was using two anchors with 9 shackles of chain on portside and 4 shackles on starboard side. The starboard side anchor was deployed several hours after the portside anchor because the weather conditions were getting worse. This could be a possible reason for the asymmetrical mooring layout, because once the ship began to drift the mooring tensions were too big to deploy more anchor chain.

The weight of the anchors is approximately calculated to 10.5 t using the equipment number. The holding capacity of the anchors is estimated to 42 t according to Hancox (2004). The used chains are derived from the equipment number. The resulting load-deflection curves are shown in Figs. 7-8. The asymmetric mooring setup is depicted in Fig. 10.

Fig. 7 Load-Deflection curve of starboard side anchor.
Environmental Conditions

The presented calculation is carried out for one sequence of the drift. This allows to neglect the unknown profile of the seabed and the fluctuations of the environmental loads. For this exemplary case the environmental data is taken from the report of the German Meteorological Office. The wind speed is set to 74 kn. The wave forces are computed as short-crested irregular seaway with the JONSWAP spectrum with a significant wave height of 7 m and a significant period of 11 s. Wind and waves are coming from the same direction. Because only a single sequence is investigated, the initial encounter angle is set to head sea $\alpha = 0^\circ$. This assumption is valid because the aim of this investigation is the calculation of a stationary drift speed. No additional current speed is assigned in this case, although the manoeuvring model offers this option without any further development.

Results

The station keeping analysis is carried out for a duration of 2000 s. The calculation is started with a initial speed of -3 kn ($\approx$ -1.54 m/s). The trajectory of the vessel during this period is shown in Fig. 10. The black arrow represents the ship with the arrowhead at the bow. The anchors are represented as triangles. It can be clearly seen that both anchors are dragged due to exceeded load limits. This leads to a backward drift motion of the ship and a movement of the anchors towards the x-axis of the vessel. This effect obviously increases the longitudinal mooring forces on the vessel due to the trigonometric relation. The trajectory also shows the consequence of the asymmetric mooring setup which leads to a yawing motion of the ship.

The yawing motion is additionally illustrated as plot of the heading in Fig. 9. The ship’s heading is fluctuating in a range of $+2.5^\circ$ to $-2.5^\circ$. The same figure shows the plot of the longitudinal ship speed. The ship moves backward with the initial speed and decelerates to a nearly stationary speed of about -1.0 m/s after 1500 s. According to the logged speed of the Glory Amsterdam the ship was drifting at about -1.05 m/s, so the accordance of the calculated and logged values is sufficient.

During the nearly stationary motion of the ship, the sum of all longitudinal forces has to be zero. The forces are summarized in Table 2. The hull resistance has a low influence on the motion because of the low ship speed. The mooring loads of the portside mooring line are larger than on starbordside because of the longer chain.

Table 2 Mean longitudinal forces during the nearly stationary drift motion at $u_S = -1.0$ m/s.

<table>
<thead>
<tr>
<th>Environmental Forces</th>
<th>Waves</th>
<th>-647 kN</th>
<th>59%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>-447 kN</td>
<td>41%</td>
<td></td>
</tr>
<tr>
<td>Counteracting Forces</td>
<td>PS Mooring</td>
<td>460 kN</td>
<td>42%</td>
</tr>
<tr>
<td></td>
<td>SB Mooring</td>
<td>411 kN</td>
<td>38%</td>
</tr>
<tr>
<td></td>
<td>Thrust incl.  Deduction</td>
<td>209 kN</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td>Hull Resistance</td>
<td>14 kN</td>
<td>1%</td>
</tr>
</tbody>
</table>

CONCLUSIONS AND DISCUSSION

The paper presents the application of a manoeuvring method for the prediction of the track of a moored vessel due to anchor dragging. The theoretical background of the manoeuvring method is described. The used force model is introduced and exemplary force components are presented in detail. The routine for mooring force calculations, which has been recently developed, is described in particular. The results of the presented method are demonstrated by means of the investigation of the grounding of the bulk carrier Glory Amsterdam. The results show good conformity to measured values of the real casualty as shown in the results section.

ACKNOWLEDGMENT

The development of the presented method has been carried out within the research project MOPS, a project to develop new numerical methods for offshore and polar applications. Special thanks are given to the German Federal Ministry of Economic Affairs and Energy (BMWi) for funding and supporting this research project.
Fig. 10 Asymmetric mooring setup and sequence of the resulting motion of Glory Amsterdam plotted every 250s.

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