CALCULATION OF THE DYNAMIC POSITIONING CAPABILITY OF AN OFFSHORE WIND FARM VESSEL DURING THE JACK-UP PROCESS IN THE EARLY DESIGN STAGE

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ABSTRACT

As a consequence of the planned exit from fossil-based energy in the European Union the exploitation of renewable energies has become a major aspect of the Offshore Industry. Especially the construction and operation of offshore wind energy turbines pose a challenge which is met by the use of jack-up vessels with extendible legs. In order to dimension the vessel’s manoeuvring devices in the early design stage and to ensure a safe jacking process for given environmental loads the dynamic positioning capability during the jacking including the influence of the legs has to be calculated. As part of the development of a holistic dynamic analysis this paper presents the implementation of the legs’ influence in an existing manoeuvring method. The manoeuvring method solves the equations of motion in three degrees of freedom (surge, sway, yaw). It is based on a force model which comprises various modular components. Therefore another component for the leg-forces is added. A Morison approach is chosen to calculate the hydrodynamic forces on the cylindrical legs. The legs’ hydrodynamic added masses are accounted for and added to the hull’s inertial terms. The benefit of the presented method is the possibility to calculate the dynamic positioning capability with extended legs without being dependent on the results of either time-consuming or non-specific model tests. Therefore the method represents a fast computing tool to design the vessel for the specific environmental conditions of the site of operation.

Keywords: Ship Design, Dynamic Positioning, Manoeuvring

NOMENCLATURE

\( A \) Sectional area
\( A_{6\times6} \) Hydrodynamic added inertia matrix
\( A_{3\times3} \) Added inertia matrix for manoeuvring
\( C_a \) Added mass coefficient
\( C_d \) Drag coefficient
\( C_d \) Damping coefficient
\( C_X \) Longitudinal force coefficient
\( C_Y \) Transversal force coefficient
\( C_K \) Heeling moment coefficient
\( C_N \) Yaw moment coefficient
\( C_{ij3\times3} \) Transformation matrix from j to i
\( D \) Diameter
\( f_{3\times1} \) Sectional normal force
\( F_{6\times1} \) Generalised external force
\( KG \) Vertical centre of gravity above the keel
\( LPP \) Length between perpendicularers
\( m_{3\times1} \) Moment due to sectional normal force
\( m_{3\times3} \) Sectional translational added mass matrix
\( M_{6\times6} \) Inertia matrix
\( O, O', O'' \) Frames of reference
\( \vec{r}_{3\times1} \) Body position
\( \vec{v}_{X3\times1} \) Normal part of the absolute body velocity
\( \vec{v}_{N3\times1} \) Normal part of the absolute body acceleration
\( s \) Cylinder axial parameter
\( \vec{u}_{3\times1} \) Fluid normal velocity
\( \vec{u}_{R3\times1} \) Relative normal velocity of body and fluid
INTRODUCTION

Jack-up vessels are used for the installation and maintenance of offshore wind turbines. These vessels are equipped with extendible legs which are used to jack-up the actual hull above the water surface. In this position the whole structure has to withstand a minimum of wave- and current-induced forces and also has a stable, gravity-based position for the execution of crane operations. For the design of such jack-up vessels this jacking process is a major design driver, therefore requiring fast computational tools for the early design stage. Especially the initial contact between the sea floor and the leg requires detailed dynamic analysis in order to avoid both horizontal and vertical motions. These define the contact forces, which shall be minimised to reduce structural loads onto the legs and the jacking mechanism. For ship-type structures various methods for the hydrodynamic analysis are implemented in the ship design environment E4, which, among others, is being developed by the Institute of Ship Design and Ship Safety. Generally these can be distinguished between manoeuvring and seakeeping applications according to Fig. 1. Figure 2 shows the model of the investigated ship with the ship-type structure highlighted by the dotted rectangle. This part of the jack-up vessel is already covered by the methods within in E4. Apart from the modified mass distribution, the extended legs will also have a hydrodynamic influence on the dynamic behaviour during the jacking process and therefore must be considered in all available methods in order to comprehensively calculate horizontal and vertical motions of the vessel. However the jack-up legs are commonly built of rather simple individual geometries and can be classified into typical offshore structures. The challenge is to merge the existing ship design methods with offshore elements on the limit of applicability of ship and offshore technology. In the following this paper presents the implementation of jack-up legs in the manoeuvring branch of the dynamic analysis methods as a major component in the development of a holistic analysis of the jacking process in the early design stage. A first requirement for the jacking operation is the ability of the vessel to withstand the static environmental conditions such as current or wind by using its propulsion and manoeuvring devices, thus ensure a sufficient dynamic positioning (DP) capability. As the static dynamic positioning is a special application of manoeuvring, a brief description of the fundamental manoeuvring model is shown in the following. Consequently an additional force component for the legs’ influence is described based on the Morison approach. Further the treatment of the hydrodynamic added masses is described for the application in the dynamic manoeuvring methods. A validation based on model tests for the current-induced forces is presented and finally the legs’ impact on the static DP capability is shown for an offshore wind farm vessel.

THE MANOEUVRING MODEL

The existing manoeuvring model uses a right-hand coordinate system as shown in Fig. 3. The origin $O$ of the ship-fixed coordinate system is located at $LPP/2$, centre line and $KG$. The manoeuvre simulation is carried out by solving the equations of motion in the three degrees of freedom surge, sway and yaw in time domain. Firstly these equations of motion are formulated according to Newton’s second law of motion in six degrees of freedom: 

$$ M \ddot{\mathbf{x}} = \sum \mathbf{F} $$

(1)
The normal forces on the jack-up legs which are commonly made of cylindrical structures. These are generally assumed to be hydrodynamically transparent, thus the flow is undisturbed by the presence of the legs and any diffraction or shielding effects are neglected. Furthermore the force component has to follow the requirement of computational efficiency. The normal forces on the legs’ circular sections $\mathbf{f}$ can then be calculated by using the Morison equation as shown in Eqn. (3), which individual terms are explained in the following. [3].

$$\mathbf{f} = \rho \left( A \cdot \mathbf{u} + C_A \cdot A \cdot \mathbf{u} - C_A \cdot A \cdot \mathbf{r}_N + \frac{D}{2} \cdot C_D \cdot |\mathbf{u}| |\mathbf{u}| \right)$$

The first term represents the Froude-Krylov force solely dependent on the fluid acceleration normal to the cylinder axis. The second and third term account for the hydrodynamic inertial forces dependent on the fluid acceleration and rigid body acceleration respectively. The last two terms are velocity-dependent drag and damping forces. Combining these latter terms by assuming identical drag and damping coefficients $C_D = C_D$ yields the relative velocity formulation for the hydrodynamic forces on a cylindrical section [4]. However the rigid body acceleration in the third term is the objective of the solution of the equations of motion according to the manoeuvring model. Therefore this term has to be considered on the left hand side of Eqn. (1). Furthermore the Morison equation only considers normal forces on the leg section itself but applying the force contribution of the section in the reference frame $O$ as shown in Fig. 3 will also result in a sectional moment $\mathbf{m}$. The final Morison force contributions in six degrees of freedom as used in the implemented force component in a time domain simulation are therefore:

$$\mathbf{f} = \rho ((1 + C_A) \mathbf{r} + A \mathbf{u} + \frac{D}{2} \cdot C_D \cdot |\mathbf{u}| |\mathbf{u}|)$$

$$\mathbf{m} = \mathbf{r} \times \mathbf{f}$$

The overall force contribution of each cylinder to Eqn. 1 for the corresponding time step is obtained by integrating the sectional force contributions along the cylinder’s axis. The fluid velocities $\mathbf{u}$ and accelerations $\mathbf{u}$ are assessed according to an arbitrary flow field model. In correspondence to the fundamental assumption of hydrodynamic transparancy the flow around the hull and its appendages is not affected by the presence of the legs so any interaction effects between hull, flow and legs are neglected. The coefficients $C_A$ and $C_D$ can either be chosen stationary according to experimental data [3] or calculated for each time step dependent on characteristic flow parameters such as roughness or fluid velocity [4]. The three dimensional influence of flow around the legs’ ends is accounted for by the modification of drag coefficients in the latter case. Unlike other external force-components such as mooring or wind forces the leg component

FIGURE 3. SHIP FIXED COORDINATE SYSTEM USED IN THE MANOEUVRING MODEL.
HYDRODYNAMIC ADDED INERTIA

The body-acceleration term of Eqn. (3) consists also of a constant factor $C_A \cdot A$. It represents the sectional translational hydrodynamic added mass of a circular cross section $\mu_{\theta \theta} = \mu_{\phi \phi}$ with respect to the section’s frame $O''$ as visualised in Fig. 4. Its origin is located in each section’s axis with its $z''$-axis pointing in the direction of the cylinder’s axis. Because of the circular cross section, the hydrodynamic added moment of inertia with respect to the cylinder axis $\Theta_{z''}$ is zero [4]. In order to solve Eqn. (1) for the body-acceleration vector and to consider the resulting sectional moments the 6x6 hydrodynamic added inertia matrix $\mathbf{A}$ has to be calculated and added to the body inertia matrix $\mathbf{M}$. The legs’ contribution to the latter is defined by their mass distribution and location in the ship’s frame of reference $O$. However the legs’ influence on the matrix $\mathbf{A}$ furthermore depends on the orientation of each sectional element. In the section’s frame the 3x3 translational added mass matrix $\mathbf{m}''$ consists of only two non-zero elements $\mu_{\varphi \varphi} = \mu_{\phi \phi}$ as the 2-dimensional solution for an infinitesimal section thickness $ds$ is applied. The matrix $\mathbf{m}''$ is then transformed by the transformation matrix $\mathbf{C}_{O''O}$ to an additional frame of reference $O''$ which is located in the origin of frame $O''$ but parallel to the ship’s frame $O$ as visualised in Fig. 5. A sectional element of the infinitesimal thickness $ds$ is shown with an inclination about the ship-fixed $y$-axis, which in this example corresponds to the axes $y'$ and $y''$. As the frames $O'$, which is also shown in Fig. 3, and $O''$ are parallel, for the sectional translational added mass matrices $\mathbf{m}' = \mathbf{m}$ holds. The contribution to the system can then be obtained by summing the integrations along each cylinder’s axis $s$ over its length:

$$A_{1-3,1-3} = \sum_{i=1}^{n} \int_{L_i} C^T_{O''O} \mathbf{m}''(s) C_{O''O} ds$$

The matrix’ residual elements are calculated similar to the rigid body’s inertia tensor but in this case the infinitesimal translational added masses $\mathbf{m}$ are dependent on their orientation with respect to the frame of reference $O$. The hydrodynamic added moments of inertia and products of inertia are calculated by the product of the perpendicular lever of the infinitesimal translational motion to the regarded coordinate axis and the perpendicular lever of the resulting translational force to the regarded coordinate axis. The levers are defined by the position of the circular section $\mathbf{r}$ as shown in Fig. 5. For instance the sectional hydrodynamic added product of inertia $\Theta_{z''}$ of a moment about the $y$-axis due to a rotational acceleration about the $z$-axis can be obtained with the translational forces and motions with levers as shown in Tab. 1. A positive moment about the $y$-axis is caused by a positive translational force in $x$ with a positive lever $z$. A corresponding positive rotation about $z$ is the result of a positive translational motion in $x$ with a negative lever $y$. Considering all couplings yields the sectional product of inertia and integrating over each cylinder’s length provides the contribution to the system’s added inertia matrix:

$$A_{5,6} = \sum_{i=1}^{n} \int_{L_i} \theta_{z''} ds = \sum_{i=1}^{n} \int_{L_i} xy \mu_{\phi \phi} - x^2 \mu_{\phi \theta} - yz \mu_{\phi x} ds$$
TABLE 1. FORCES AND MOTIONS WITH LEVERS FOR THE SECTIONAL PRODUCT OF INERTIA \( \theta_{yz} \)

<table>
<thead>
<tr>
<th>Force/Motion</th>
<th>Lever</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment about y</td>
<td>( z )</td>
</tr>
<tr>
<td>Rotation about z</td>
<td>( y )</td>
</tr>
</tbody>
</table>

The elements \( A_{1,6} \) can be calculated in the same way as shown in Eqn. (7). The force-rotation couplings \( A_{1-3,4-6} \) are calculated by the product of the translational force and the perpendicular lever of the infinitesimal translational motion to the corresponding axis which is caused by the rotational acceleration. The sectional hydrodynamic added force-rotation coupling \( \mu_{xy} \) of a force in \( x \) due to a rotational acceleration about the \( z \)-axis can be calculated with the rotational levers as shown in Tab. 1 and yields:

\[
A_{1,6} = \sum_{i=1}^{n} \int_{L_i} \mu_{xy} ds = \sum_{i=1}^{n} \int_{L_i} x\mu_{xy} - y\mu_{xz} ds \tag{8}
\]

The remaining force-rotation couplings are calculated likewise. As the hydrodynamic added inertia matrix is symmetrical only the top right hand side half of \( A \) has to be considered [5]. To use the resulting 6x6 hydrodynamic added inertia matrix for the manoeuvring application only the columns and rows must be considered which correspond to the three degrees of freedom. As the manoeuvring model neglects the coupling of longitudinal forces due to transversal and yawing acceleration these items are zero [2] and the added inertia matrix simplifies as follows:

\[
A^* = \begin{bmatrix}
A_{11} & 0 & 0 \\
0 & A_{22} & A_{26} \\
0 & A_{62} & A_{66}
\end{bmatrix} \tag{9}
\]

This added inertia matrix can then be used in the dynamic manoeuvring applications in shown in Fig. 1.

CURRENT FORCES

Model tests for an offshore wind farm vessel as shown in Fig. 6 have been conducted in a wind tunnel. The model below the design waterline is exposed to a stationary flow in the tunnel from encounter angles in steps of 10°. The resulting current forces and moments are measured and dimensionless coefficients \( C_i \) based on characteristic flow parameters are calculated. This procedure is conducted for the bare hull model and a setup with four extended legs with a circular cross section. Each leg consists of a main cylinder and a cylindrical spud can with a larger diameter. Both elements are connected by a conical joint as shown in Fig. 2. In order to examine the applicability of the Morison approach in the manoeuvring methods at the presented intermediate stage of development, this process is reproduced for the same ship within the ship design environment E4 by calculation of body-forces which are based on the manoeuvring model. The underlying ship model of these calculations is visualised in Fig. 2 for the condition with extended legs. Their force contribution is accounted for by the implemented Morison force component. As a steady, uniform flow is applied, only fluid velocity dependent forces occur. The relevant drag coefficient is set stationary to \( C_D = 1.05 \) for rough surfaces [4]. The hydrostatic floating condition is on even keel and in an upright position for both setups. It is not affected by the submersion of the legs as these are not part of the buoyancy body. Further, for an accurate representation of the model test conditions the floating position is not altered by the current forces in this investigation. In order to represent the hydrodynamic influence of the legs on the forces and moments, the differences \( \Delta C_i \) of the condition with extended legs and retracted legs are shown in Fig. 7-9 in dependency of the encounter angle. An angle of 0° corresponds to flow from ahead and 90° from starboard. The calculated graphs \( \Delta C_X, \Delta C_Y \) and \( \Delta C_K \) overestimate the forces and moments in their peaks compared to the model test data. This clearly shows shielding effects as the downstream legs are exposed to a smaller fluid velocity in the model test. This effect cannot be considered in the method as the Morison approach neglects diffraction according to the assumption of hydrodynamic transparency. This overestimation of the peak values however represents a conservative approach in the application of a manoeuvring simulation as the calculated external forces are larger and thus the DP capability is better than assessed. At lower coefficient values the measured graphs show larger differences.
in forces and moments than the calculated graphs. The forces’ quadratic dependency on the flow velocity as seen in Eqn. (3) does not correspond to the measured values at these encounter angles. As the graphs otherwise fit well, these deviations may be explained with interactions of the hull and legs which cannot be covered by the Morison approach due to the assumed hydrodynamic transparency. In contrast the differences in the yaw moment coefficients $\Delta C_N$ are shown in Fig. 9. Apart from symmetry to an encounter angle of 180° no distinct trend can be identified in the measured coefficients, for instance regarding the number of zeros. The values are also two magnitudes smaller than the force and heeling moment coefficients. Therefore this trend can be explained with the uncertainty in the differences of small values and the presence of the legs shows only a minor impact on the yaw moment of the vessel in the model test. Generally the calculated coefficients $\Delta C_N$ are of the same small magnitude as the measured coefficients and only in an interval of 50° - 90° the measured values are significantly higher. These differences occur especially at angles, which show one of the force coefficients close to zero. This may also be explained with shielding effects as this is the same interval of encounter angles in which $\Delta C_X$ shows rather large deviations while $\Delta C_Y$ is affected by shielding.
DYNAMIC POSITIONING

The dynamic positioning method provides the maximum permissible environmental forces the vessel can withstand without changing its position and heading. The static DP capability method therefore calculates an equilibrium of forces and moments under the influence of stationary environmental conditions [1]. The method is based on the manoeuvring model and takes all kind of force components into account as well as the interaction with the machinery. A current velocity can be applied and the DP capability is expressed in terms of a maximum permissible wind velocity $v_W$ from each encounter angle with the wind and current acting in the same direction. The wind forces are calculated depending on the lateral areas and wind coefficients for the forces and moments [7]. The current forces are calculated by the method presented. As this analysis is in stationary flow the hydrodynamic forces on the legs are only defined by the last term in Eqn. (3) and no acceleration-dependent effects occur. The drag coefficients are set to $C_D = 1.05$ as validated by the wind tunnel tests. In order to visualise the impact on the DP capability by the legs’ presence, the offshore wind farm vessel as shown in Fig. 2 is exposed to a current velocity of 2kn. To counteract the environmental forces the vessel is equipped with each two bow and stern thrusters, two controllable pitch propellers and two fully-balanced spade rudders in their slipstreams. The DP capability is calculated for a condition with retracted and fully extended legs as shown in Fig. 10. This latter situation can be understood as the critical moment just before the initial contact of legs and seabed which corresponds to maximum current loads during the jack-up process. The interaction effects of hull, current, tunnel thrusters and propellers [1] are not affected by the presence of the legs as these are assumed to be hydrodynamically transparent. The influence of the extended legs reduces the DP capability at all encounter angles due to the additional Morison force components. The decrease of permissible wind velocities is especially significant at transverse encounter angles.

CONCLUSION AND OUTLOOK

The Morison equation can be used to calculate the hydrodynamic forces and moments on cylindrical or conical elements such as legs of jack-up vessels. The obtained results for stationary flow show acceptable conformity to model tests for the application in the early design stage. The benefit of the method presented is the possibility to quickly calculate the static DP capability in current flow during the jack-up process, which is distinctly limited by the presence of the legs. The hydrodynamic added masses due to normal motion relative to the surrounding fluid can be used for the calculation of the hydrodynamic added inertia matrix in six degrees of freedom with respect to an arbitrary frame of reference including all couplings. This matrix can be used for instationary manoeuvring applications with simplifications due to the reduced degrees of freedom. Further research shall show the implementation of this added inertia in seakeeping applications. Additionally the damping and excitation influence of the legs shall be considered in the seakeeping methods to achieve the final objective of a holistic dynamic analysis of the jacking process. Calculations of the DP capability during the jack-up process including the additional influence of wave drift forces and the computation of contact forces in the non-linear time domain seakeeping method are further objectives.

ACKNOWLEDGMENT

The method presented has been developed as part of the research project MOPS, which aims at the development of new numerical methods for offshore and polar applications. Many thanks are due to the German Federal Ministry of Economic Affairs and Energy (BMWi) for funding this project. Further thanks are due to Prof. Krüger for his support and supervision.

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