SEA-KEEPING ANALYSIS OF AN OFFSHORE WIND FARM INSTALLATION VESSEL
DURING THE JACK-UP PROCESS

Philip H. Augener*
Research Assistant
Institute of Ship Design and Ship Safety
Hamburg University of Technology
Hamburg, Germany
Email: Philip.Augener@tuhh.de

Hannes Hatecke
Research Assistant
Institute of Ship Design and Ship Safety
Hamburg University of Technology
Hamburg, Germany
Email: hatecke@tuhh.de

ABSTRACT

Offshore wind farms are not planned in sheltered and shallow waters any longer. Especially in the North Sea there exist many approved offshore wind farm projects at water depth between 30 and 50 meters. In particular the installation process of these projects is strongly influenced by weather conditions and the sea-keeping capabilities of the installation vessels. For reliable planning of the entire project, not only the weather statistics, but also the vessel’s sea-keeping capabilities need to be known accurately. For this purpose different kinds of sea-keeping analyses can be conducted. In this paper a sea-keeping analysis is presented, where the focus is upon the jack-up process. For the numerical computation the sea-keeping code E4ROLLS is applied. The results of this sea-keeping analysis are operational limitations for the jack-up process, caused by two different criteria derived from jack-up classification requirements.

NOMENCLATURE

\( \theta \) Specified roll or pitch motion amplitude at the natural period
\( \dot{\theta} \) Maximum roll or pitch velocity
\( P_H \) Horizontal impact load
\( P_V \) Vertical impact load
\( k_H \) Overall lateral stiffness of the leg
\( k_V \) Overall axial stiffness of the leg
\( I_m \) Mass moment of inertia regarding to roll or pitch motion
\( d \) Eccentricity of the leg
\( h \) Water depth
\( E \) Young’s modulus
\( E_k \) Kinetic Energy
\( E_p \) Potential Energy
\( I_L \) Second moment of area of the leg
\( A_L \) Cross-sectional area of the leg
\( \Delta_y \) Horizontal lateral displacement of the lower end of the leg
\( \Delta_z \) Vertical lateral displacement of the lower end of the leg
\( T \) Natural period of roll or pitch motion
\( H_s \) Significant wave height
\( T_s \) Significant wave period

INTRODUCTION

The so called energy turnaround for sustainability, namely the changeover from power generation based on nuclear and fossil energy sources to renewable energies, is general will in German politics. One of the main pillars this change is supposed to be based upon, is the generation of electrical power with offshore wind farms. The installation areas of these wind farms are the exclusive economic zones of Germany in the North Sea as well as the Baltic Sea. For this reason the installation of thousand of wind turbine generators (WTG) is necessary within the next couple of years. In order to install the huge amount of WTGs and likewise for the maintenance of the WTGs, a fleet of specialized vessels is needed. These vessels have to withstand very harsh environmental conditions to minimize downtimes for the instal-

* Address all correspondence to this author.
loration of the wind farms in order to achieve the ambitious goals of the German politics. In the following years after the installation it is also important to have service vessels with large operational limits, in order to be able to maintain the WTGs even during bad weather and reduce their downtimes, and therefore the electrical power production, as well.

One very special feature of Offshore Wind Farm Installation Vessels is the ability to lift itself out of the water. The reason for this so called jack-up operation is the decoupling of the vessel from the seaway. Following from this the operational limit of the vessel where safe crane operations are possible is increased. Certainly these vessels have to be equipped with legs for the jack-up operations. The legs have to be designed to bear up possible impact loads from the sea bottom during the installation or retrieval conditions of the vessel, for which the designer of the vessel has to specify the limiting environmental conditions.

Jack-up operations are well known in the oil and gas industry, where they are used for the installation of specific kinds of platforms. The large difference between the requirements for jack-up operations in the oil and gas and the offshore wind industry is the amount of needed jack-up operations. While an oil platform normally is only installed once in its lifetime and this installation can be planned for a time of year, when good or moderate weather conditions can be expected, for the installation of offshore wind farms thousands of jack-up operations are required and in order to reduce the downtimes jack-up operations should be possible even in very harsh weather conditions. This is especially important because the economical margins in the offshore wind industry are smaller than in the oil and gas industry.

The focus of this paper is upon the operational limits caused by the maximum acceptable impact loads on the legs from the sea bottom during the installation or retrieval conditions of the jack-up vessel, due to the motions of the vessel caused by the seaway.

Problem Definition

Besides the limitations through the dynamic positioning capability of an Offshore Wind Farm Installation Vessel, there are also structural limits for the legs of the vessel. A leg may suffer impact forces from the sea bottom during the installation or retrieval position due to its motion in the seaway. The dynamic positioning capability as well as the magnitude of the impact load both depend on the environmental loads caused by wind, current and waves. The environmental loads a vessel has to withstand have to be agreed upon by the shipowner and the designer of the vessel. Under ideal conditions the legs should be designed for the same environmental loads as the dynamic positioning system of the vessel. According to the above said, the maximum tolerable impact forces on the legs are a limiting factor for the work capability of the vessel and it is very helpful for the crew to know the operational limits, not only due to the dynamic positioning system, but also due to the maximum tolerable impact loads.

The focus of this paper is a sea-keeping analysis to find the limiting seaway as a function of wave periods, significant wave heights and encounter angles, until which the Offshore Wind Farm Installation Vessel is not endangered to reach the maximum allowable design impact loads on one leg of the jacking system. The answer to this problem is a set of capability plots for different significant wave periods each showing the maximum allowable significant wave height until which the operation of the vessel can be considered as safe regarding the impact forces on the legs.

Theoretical Background

In this chapter the theoretical background of the performed sea-keeping analysis is described, which is based on the determination of the design impact loads for the legs of jack-up vessels according to [1].

The approach is based on the conservation of energy. As the worst case scenario the entirely kinetic energy of rotation from the ship’s motion in a seaway, namely here the roll and pitch motion, is supposed to be converted into potential energy in only one of the lowered legs by the impact onto the sea bottom. Additionally the sea bottom is assumed to be infinitely rigid. Furthermore it is assumed, that the lower end of the leg stops immediately, when it touches the bottom. Therefore the worst case scenario is described by the three following basic assumptions:

1. only one leg touches the bottom,
2. the lower end of the leg is stopped immediately when the leg touches the bottom,
3. the bottom is infinitely rigid.

The design loads following from these assumptions are the axial and radial impact forces acting on the bottom of one leg, while the impact itself results from the ship’s motion in a seaway. The equations needed in order to calculate these impact forces will be derived in the following and can also be found in the rules of Det Norske Veritas [1]. Figure 1 shows the definition of the impact loads, while Fig. 2 illustrates the analogous model of one leg.

As mentioned above the approach is based on the conservation of energy. For this reason the total rotational energy of the jack-up vessel must be absorbed by one leg which is shown in Eqn. (1):

\[ E_k, \text{before impact} = E_p, \text{after impact} \]  

By using the distribution of the bending moment \( M_p(z) \) and the normal force \( N(z) \) acting on the leg, this leads to Eqn. (2):
FIGURE 1. HORIZONTAL AND VERTICAL IMPACT LOADS ACCORDING TO [1].

FIGURE 2. ANALOGOUS MODEL OF ONE LEG.

\[ M_h(z) = P_H \cdot (z - h), \]  \hspace{1cm} (3)

\[ N(z) = P_V. \]  \hspace{1cm} (4)

If Eqn. (3) and Eqn. (4) are combined with Eqn. (2) this leads to Eqn. (5):

\[ I_m \dot{\theta}^2 = \frac{P_H^2 h^3}{3EI_L} + \frac{P_V^2 h}{EA_L}. \]  \hspace{1cm} (5)

Further transformation can be done by using the spring constant \( k_V \) for a tension rod, as defined in Eqn. (6), and \( k_H \) for an cantilever beam, which is defined in Eqn. (7):

\[ k_V = \frac{EA_L}{h}, \]  \hspace{1cm} (6)

\[ k_H = \frac{3EI_L}{h^3}. \]  \hspace{1cm} (7)

Equation (5) with Eqn. (6) and Eqn. (7) leads to Eqn. (8):

\[ I_m \dot{\theta}^2 = \frac{P_H^2 h^3}{k_H} + \frac{P_V^2 h}{k_V}. \]  \hspace{1cm} (8)

From Eqn. (8) it cannot be seen how the energy is divided into the lateral and the vertical impact force. Therefore kinematic relations are required that lead to a dependency between \( P_H \) and \( P_V \). In order to get this we use Eqn. (9) and Eqn. (10). It has to be mentioned, that these equations represent only the condition and system behaviour after the impact and thus can only be applied to the right hand side of Eqn. (8).

\[ P_H = k_H \Delta y_{\text{max}}, \]  \hspace{1cm} (9)

\[ P_V = k_V \Delta z_{\text{max}}. \]  \hspace{1cm} (10)

The maximum permissible horizontal and vertical lateral displacements of the lower end of the leg can be expressed with the kinematic relations in Eqn. (11) and Eqn. (12):

\[ \Delta y_{\text{max}} = h \cdot \theta_{\text{max}, \text{after impact}}, \]  \hspace{1cm} (11)

\[ \Delta z_{\text{max}} = d \cdot \theta_{\text{max}, \text{after impact}}. \]  \hspace{1cm} (12)
Now it is possible to describe the horizontal and the vertical impact forces in dependency on each other. By elimination of the unknown \( \theta_{\text{max}} \), after impact Eqs. (9) with Eqs. (10), Eqs. (11) and Eqs. (12) can also be written as Eqs. (13):

\[
P_H = \frac{h k_H}{d k_V} P_V. 
\]  

(13)

Equation (8) together with Eqn. (13) leads to Eqn. (14):

\[
I_m \ddot{\theta}^2 = \frac{P_H^2}{k_H} \left[ 1 + \left( \frac{d}{h} \right)^2 \frac{k_V}{k_H} \right]. 
\]  

(14)

The transformation of Eqn. (14) leads to Eqn. (15) and in the analog way Eqn. (16) can be derived:

\[
P_H = \dot{\theta} \cdot \frac{I_m k_H}{\sqrt{1 + \left( \frac{d}{h} \right)^2 \frac{k_V}{k_H}}} 
\]  

(15)

\[
P_V = \dot{\theta} \cdot \frac{I_m k_V}{\sqrt{1 + \left( \frac{d}{h} \right)^2 \frac{k_H}{k_V}}} 
\]  

(16)

Assuming harmonic motions in Eqn. (17):

\[
\dot{\theta} = \frac{2 \pi}{T} \cdot \theta 
\]  

(17)

the derived formulas for the horizontal and vertical impact loads in Eqn. (15) and Eqn. (16) are in accordance with the equations from [1] as shown in Eqn. (18) and Eqn. (19):

\[
P_H = \frac{2 \pi}{T} \cdot \dot{\theta} \cdot \frac{I_m k_H}{\sqrt{1 + \left( \frac{d}{h} \right)^2 \frac{k_V}{k_H}}} 
\]  

(18)

\[
P_V = \frac{2 \pi}{T} \cdot \dot{\theta} \cdot \frac{I_m k_V}{\sqrt{1 + \left( \frac{d}{h} \right)^2 \frac{k_H}{k_V}}} 
\]  

(19)

### Calculation Procedure

For this examination the sea-keeping code E4ROLLS is used, which is part of the ship design environment E4. E4ROLLS is based on ROLLS that was invented by Söding at the University of Hamburg for the analysis of the capsizing accident of the E.L.M.A TRES in 1987 [2]. Further development of this code is described in [3] and [4], while the most recent descriptions of the theory, on which ROLLS is based, can be found in [5] and [6]. E4ROLLS has been evaluated by extensive model tests, especially for ships with high B/T-Ratios as RoRo- and jack-up vessels.

The model of the vessel for E4ROLLS is based on the hull form and weight distribution, that are defined in E4 and are therefore available in the database. Additionally the required motion response amplitude operators (MRAOs) can be calculated based on the strip theory in E4 and are then available in the database as well. For the calculation of these transfer functions the real hull form of the vessel is considered. In E4ROLLS all six degrees of motion are considered, with special focus on the nonlinear treatment of the surge and roll motions. The other four degrees of freedom are accounted for by the MRAOS, which makes the code extremely fast and therefore applicable for extensive numerical sea-keeping investigations, without neglecting any relevant parameters.

For this sea-keeping investigation two new evaluation criteria have been implemented, which are namely the maximum roll angular velocity criterion and the maximum pitch angular velocity criterion.

For the generation of the natural seaway, which is required for this analysis, the JONSWAP spectrum with the peak enhancement factor of 3.3 in combination with a \( \cos^2 \)-angular distribution is used. For the calculation it is necessary to choose the significant wave period and the type of spectrum for a seaway and then the significant wave height is systematically increased, until one of the chosen limiting criteria is exceeded. This procedure is automatically repeated for the full range of selected encounter angles and ship’s velocities. For this examination it is only reasonable to evaluate both above mentioned maximum angular velocity criteria at the same time, which leads to the result, that always that criterion is the limiting one, which corresponds to the smaller legal significant wave height.

For this sea-keeping analysis the results of model roll decay tests are used in order to get the damping of the vessel with lowered legs right. These results are used to tune the damping coefficients needed for E4ROLLS. Afterwards numerical roll decay test are conducted with E4ROLLS for the validation of the damping.

### Results

As already mentioned above the legs of a jack-up vessel are designed to withstand a certain impact load based on the environmental conditions specified by the designer. Following from
As a matter of fact the geometrical and material specific parameters of the legs are set for an existing vessel and the maximum permissible impact loads are known from the procedure mentioned above. Following from this operational limits in terms of permitted combinations of significant wave heights and significant wave periods can be expressed in dependency on limiting roll and pitch angular velocities, which correspond to the limiting impact loads in combination with the existing geometrical and material specific parameters.

In order to find the operational limits of the vessel regarding the impact loads, numerous seaways are examined for the vessel in the relevant loading condition. In the following the results for six significant wave periods are presented. Two of the wave periods are the natural periods for the roll and the pitch motion of the vessel in the considered loading condition. Another two wave periods are chosen smaller, one in between and one larger than the natural periods.

The results of the sea-keeping analysis are shown in the following polar diagrams and afterwards in one capability plot. While the polar diagrams show results for different forward speeds of the vessel up to two knots the capability plot is only valid for zero forward speed of the vessel. The different forward velocities of the vessel are represented by the radial rings in the polar diagrams. Contrary to this the radial rings in the capability plot illustrate the significant wave height at which the limiting angular velocities are violated. In both types of diagrams head seas correspond to an encounter angle of $180^\circ$ and therefore following seas to an encounter angle of $0^\circ$. The encounter angle increases counterclockwise with an increment of $10^\circ$, while an encounter angle of $90^\circ$ means a main wave propagation direction from starboard side. An encounter angle of $270^\circ$ represents waves from port side respectively. In the polar diagrams the colors stand for the limiting significant wave height, at which the first of the two examined criteria, namely either the maximum permissible roll or the maximum permissible pitch velocity, is exceeded. In the capability plot this limiting significant wave height is indicated by the colored line.

For each of the nodes in the polar diagrams a number of five different discretizations of the seaway are used. Following from this five computations for every node are needed. With a simulation time of $20,000$ s each, this leads to $110$ days of simulated time for each polar diagram, when assuming symmetry of the polar diagram for encounter angles larger than $180^\circ$, which is legal for a loading condition without heel. This clearly indicates why this kind of sea-keeping analysis is only possible with a fast code like E4ROLLS. During the calculations the significant wave height is maximized in a way, that neither the maximum permissible value for the angular velocity for rolling nor the maximum permissible value for the angular velocity for pitching are exceeded at any combination of the considered speeds and encounter angles.

Figure 3 shows the results for a significant period of $T_s = 6.7$ s. The colors of this polar diagrams display, that the limiting angular velocities are not violated up to a significant wave height of $3.5$ m to $4.0$ m in head and following seas. In beam seas the limiting values are about $2.0$ m until $3.5$ m.

In Fig. 4 the results for a significant period of $T_s = 7.2$ s are shown. The limiting significant wave height in head as well as in following seas is about $2.5$ m until $3.5$ m, while the angular spreading for these values opens up with increasing speed. In beam seas at very little speed the limiting significant wave height is about $1.0$ m. This value rises with increasing speed up to about $1.5$ m and the angular spreading for these values open up with increasing speed as well.

Figure 5 shows the results for a significant period of $T_s = 9.1$ s, which is the natural period for the pitch motion of the vessel in the considered loading condition. In head and following seas the allowable significant wave height drops to values about $2.0$ m until $2.5$ m. In beam seas at low speeds the allowable wave height increases slightly compared to Fig. 4, while it stays almost unchanged for the higher speeds.

The results for the significant period of $T_s = 9.8$ s are presented in Fig. 6. This is the period chosen in between the natural periods of the roll and the pitch motions of the vessel in the examined loading condition. The permitted significant wave heights
drop further for head and beam seas compared to smaller periods presented above. The limiting value for head seas is about 1.5 m and for beam seas about 1.0 m. In following seas the wave height should not exceed 3.5 m to guarantee a safe jacking operation.

The natural period of the roll motion of the vessel in the considered loading condition is 12.3 s. The corresponding polar diagram calculated for a significant wave period of $T_s = 12.3$ s can be found in Fig. 7. This polar diagram shows, that the limiting values increase again in comparison to the last polar diagram. The limiting value for head seas is about 2.0 m. In beam seas the
limiting value stays low at about 1.0 m and in following seas the high limiting values of up to 3.5 m are still good.

The last polar diagram is calculated for rather long waves with a significant period of $T_s = 15.0$ s and it can be found in Fig. 8. The diagram clearly illustrates the increase of the limiting values for all encounter angles and velocities. In head and beam seas wave heights up to 3.5 m are allowed and in following seas wave heights as high as 4.5 m can be handled without a problem. But at this point it should be mentioned that for long waves the consideration of the impact loads caused by the heave motions of the vessel seems reasonable.

Figure 9 shows capability plots for the same significant wave periods as the polar diagrams displayed above, but only valid for one velocity of the vessel. All plots in Fig. 9 are valid for zero speed only. The colored lines in the impact force capability plot mark the maximum permissible wave heights in dependency of the encounter angle and the significant wave period, until which the chosen limiting criteria are not exceeded and the jack-up operation is safe regarding the compliance with the allowable impact forces on the legs. It can be clearly stated that the limiting significant wave heights for all wave periods in this analysis are higher in head and following seas than in beam seas. Furthermore the capability plots, as well as the polar diagrams, show higher limiting wave height for rather short and very long waves. The lowest limiting values are valid for the significant wave period selected in between the natural periods of the roll and the pitch motions of the vessel in the examined loading condition.

CONCLUSIONS

In this paper the importance of considering the maximum endurable impact loads on the legs of an Offshore Wind Farm Installation Vessel for the safe operation is pointed out. The results show that no general statement is possible and following from this individual sea-keeping calculations are required. The presentation of the results in capability plots is advantageous, because the crews of such vessels are familiar with this kind of diagrams from dynamic positioning capability plots. Additionally it can be said that for a holistic ship design the capability plots regarding dynamic positioning and impact loads should resemble each other in appearance, because in other respects either the dynamic positioning system or the legs are oversized, implied that the impact forces are the relevant loads for the dimensioning of the legs. Finally it has to be stated, that on the one hand the knowledge of the limitations caused by the impact loads is very helpful for the operator, but on the other hand it has to be emphasized that the operational limits of these vessels are not necessarily depending on the impact loads.
ACKNOWLEDGMENT

The work presented in this paper is supported by the Federal Ministry of Economics and Technology of Germany by funding the research project DYPOS. The authors are deeply grateful for this support.

REFERENCES


