STATIC AND DYNAMIC ANALYSIS OF JACKET SUBSTRUCTURE FOR OFFSHORE FIXED WIND TURBINES

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ABSTRACT

With the increase in demand of offshore wind energy, the need for offshore structures for supporting wind turbine is increasing. These structures can be floating and moored to the seabed or a fixed structure with its foundation on the seabed. In this paper, a jacket for supporting 5 MW NREL wind turbine is designed and analyzed for a site selected in the Indian sea near Rameshwaram, in Tamilnadu. The structure is designed based on the procedure followed in oil and gas industry which conforms to the API-RP2A WSD (2007). The structure includes the jacket, transition piece and the tower. The structure is modeled in SESAM Genie within which the static structural analysis is carried out. Dynamic analysis is carried out in USFOS for combination of wind and wave loadings. The preliminary analysis and design carried out meets the requirements specified in the codes API RP 2A and DNV-OS-J101.

Keywords: Offshore wind turbine, static, dynamic, aerodynamic loads, hydrodynamic loads

Introduction

The offshore wind energy is one of the most important renewable energy resources which can cover worldwide energy demands. The available land based wind energy is already been explored to its maximum potential in many regions and thus offshore wind gains importance. While the limited areas on land with high wind potential are identified and being utilized, the offshore sector is still to be developed, with the necessity to establish an availability chart for the offshore wind energy and the economics of harnessing such energy. Even though offshore wind energy has numerous bottlenecks in implementation the overall performance and efficiency of the new generation wind turbines producing power in MW could offset the disadvantages. A higher capital investment is required for offshore wind turbines because of the costs associated with marination of the turbine and the added complications of the foundation, support structure, installation, and decommissioning. The short construction period and low operation and maintenance cost make the wind energy more attractive. Many developed countries have achieved 20-30% dependency on renewable sources where as in India it is less than 12%. Centre for Wind Energy Technology (C-WET), Chennai, India is the primary nodal agency associated with wind energy. Preliminary studies and reports exists stating that there are many potential offshore wind sites in Indian waters and these areas till date remains untapped. India has a coastline of about 7,600 km and in order to harness the wind energy effectively, primarily the offshore wind potential should be estimated by installing offshore wind mast at potential sites.

The offshore wind turbines are installed far off the coast preferably and the water depths wherein these structures can be varying from shallow to deep. National Renewable Energy Laboratory (NREL), USA has classified 0-30 m as shallow water, 30-60 m as transitional waters and greater than 60 m as deepwater for installing offshore wind turbine.
However the concept of deepwater for offshore industries is greater than about 1000 m. In shallow water, the wind turbine is fixed on the substructures. Tripods, jackets, and truss-type towers, monopiles and gravity base serves as substructure. Most of the fixed wind turbines are applied for water depth 20-30m, and the support structure are typical monopiles and tripod structures. In order to extend the application of Offshore Fixed Wind Turbine (OFWT) in deep water where winds are stronger and steadier a stronger support structures like jacket and gravity base are proposed to withstand the met-ocean loads as well as dynamic loads from the wind turbine though this may prove to be expensive compared to floating structures. In deeper waters the wave and current loads will increase significantly and the jacket substructure which could provide adequate ultimate strength capacity becomes a good alternative. Many of the proposed concepts utilize designs borrowed from the oil and gas industry. The offshore wind energy can be viable only when the substructure cost is optimized, for which there is need to develop economical design and construction methods for installation of substructure for wind turbine. While the viability of each substructure varies from case to case, the optimal option shall be identified for each location. Fig. 1(a) shows a schematic diagram of a Jacket platform with a wind turbine and Fig. 1 (b) shows the complete substructure neglecting the wind turbine.

Chakrabarti (2005) discusses about the design of offshore jacket type structures. The guidelines considering the different loads for selecting the configuration of the jacket structure are discussed in the first part. Then the author talks about various design procedures for a fixed offshore platform (like API RP 2A WSD, API RP 2A LRFD etc.). The tubular joint design and strength check is stated next. The author also discusses about various met-ocean condition. Jurisic and Coric (2006) discusses about the strength of fixed offshore platform that is analyzed in order to determine its capability in withstanding the operating load with extreme environmental conditions. Critical conditions are taken into account, which include structure and equipment weight, operating load, wind load, hydrodynamic (wave & current) load using Morison equation. Stress analysis is performed by the finite element method. Hansen (2007) discussed about blade element momentum theory to calculate
In this paper, the static and dynamic analysis of a substructure jacket supporting an offshore wind turbine is presented. The analysis is carried out for a water depth of 50 m at an area near to Rameswaram in Tamil Nadu, India. The jacket structure including the tower was designed using SESAM Genie. Static analysis was carried out using SESAM Genie and dynamic analysis was done in USFOS.

**Jacket Substructure Design and Modelling**

The jacket supporting structure is designed for 100 year environmental condition with an average wind speed of 50 m/s, significant wave height of 2 m and spectral peak time period of 12 s. For a given environmental condition, the dimensions of the members of any offshore structure are obtained by iterative procedure. Size selection, static structural analysis and code checking and eigen value analysis are the different steps in design procedure. As a first step, reasonable dimensions of the members are obtained based on the wind and wave conditions and according to international offshore standards like API-RP2A-WSD (2006), DNV-OS-C101(2008) etc.

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Fig. 2 Main dimension of the jacket in meters
Fig. 2 shows the different dimension in meters. The total height of the structure is 139 m which includes the jacket height of 70 m, transition piece of 4 m and the tower height of 65 m. The total width of the structure at the top is 10 m and 27.5 m at the bottom in both the directions.

The structure was modeled in SESAM Genie for a water depth of 50 m (see Fig. 1 (b)). SESAM Genie is a software tool for analysis and design of offshore structures. A graphical user interface is used for modeling, analysis and processing of results. Hydrodynamic analysis as well as well as strength calculations can be done using this tool. For fixed platforms, the SESAM Genie software can perform static analysis and dynamic linear analysis under wave, wind and current loads considering non-linear pile/soil behavior. Code compliance of beams may be performed according to API/AISC, API/LRFD, Norsok/Eurocode or ISO (1992). The results are reported graphically or by using standard report layouts that can be customized.

The substructure jacket, see Fig. 1(b), is characterized by four legs which are stiffened by braces. The legs are fixed on the sea bed considering a hard soil stratum at the sea bed. The bracings used are X-bracings and are designed so that the angle between the leg and the brace exceeds 30 degrees in accordance to the NORSOK recommendations. Since the water depth is 50m at the site, four levels of X-braces are implemented in order to comply with the requirement of the minimum angle between chord and the brace. The transition piece is modeled using plates and shell elements. Stiffeners are introduced to have more strength for the piece. The tower is modeled as normal pipe element with a total height of 65 m from the transition piece. The modeled structure as FEM file was exported to USFOS using StruMan. The USFOS analysis module is a finite element program based on an updated Lagrangian formulation. Static collapse analysis, non-linear time series dynamic analysis as well as eigenvalue analysis of jackets, jackups, topsides and floaters can be carried out in Sesam Genie Usfos software tool. For the jacket substructure, the basic structural unit used in USFOS is the two-node beam. The beam elements are used to model the jacket structure and quad elements (four node linear elements) to model the transition piece. The model consists of a total of 1697 elements and 1474 nodes. The dynamic analysis, which includes free vibration analysis and forced vibration analysis are done in USFOS. Fig. 3 shows the meshed model of the jacket structure with the transition piece magnified. The turbine tower is connected to the transition piece by means rigid body elements which are small beam elements with high Young’s modulus and yield strength value which will not yield or deform in applied loads. Table 1 shows the different materials used for the structure.

<table>
<thead>
<tr>
<th>Structure Name</th>
<th>Material</th>
<th>E (N/m²)</th>
<th>Poisson’s ratio</th>
<th>σ_y (N/m²)</th>
<th>Density (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jacket</td>
<td>Steel</td>
<td>2.1×10¹¹</td>
<td>0.3</td>
<td>4.26×10⁸</td>
<td>12670</td>
</tr>
<tr>
<td>Transition Piece</td>
<td>Steel</td>
<td>2.1×10¹¹</td>
<td>0.3</td>
<td>4.26×10¹¹</td>
<td>7850</td>
</tr>
<tr>
<td>Rigid body elements</td>
<td>Steel</td>
<td>2.1×10¹⁵</td>
<td>0.3</td>
<td>4.26×10¹¹</td>
<td>7850</td>
</tr>
</tbody>
</table>

E- Young’s Modulus of Elasticity; σ_y -Yield strength
Static Analysis

The jacket supporting structure is designed for 100 year environmental condition with an average wind speed of 50 m/s, significant wave height, which is defined as the average of the highest one third waves, of 2 m and spectral time period of 12 s. Different load combinations for wave and wind as suggested by codes DNV-OS-J101(2011), IEC 61400-3(2009) are used for the static structural analysis of the offshore wind turbine jacket. For static analysis, the wind load was given as a static lateral load which was calculated using IEC code. The static analysis carried out using SESAM Genie yielded stresses and displacements which are within acceptable limits. In the deterministic analysis, the wave height of 4 m and a time period of 12 s are used. Current load of 1.5m/s was given at the water level along the direction of wave. A static lateral wind load of 1MN was given at the top of the tower. Due to these static loads, the maximum displacement found at the top of the tower was found to be 0.45 m which is within the safe limit. The displacement, in meters, of the structure after the static analysis in SESAM Genie (2012) for few cases are shown in Fig. 4.
Dynamic Analysis

The aerodynamic load calculation is done using an aerodynamic code called FAST provided by NREL for calculation of wind load on the turbine. It gives a time series of aerodynamic load which can be fed into the software USFOS (2012) for performing the dynamic analysis of the structure. The dynamic analysis of the jacket structure for offshore wind turbine is done in USFOS. The FEM model of the structure modeled in SESAM Genie is imported into USFOS using StruMan.

Free vibration analysis gives the natural periods and mode shapes of a structure. It is one of the most important factors to check before the dynamic analysis that the natural periods of the structure should be away from the periods of environmental excitation forces. If they are nearer resonance can occur, which results in the oscillation of the structure leading to the damage of members or to the entire structure, especially during long time operation. The periods of all possible excitation forces should be considered. We can alter the natural periods of the structure by changing the stiffness or mass of the entire structure so that the natural periods will be in the safe region. The equations of motion for a freely, undamping system can be written as:

$$\ddot{x} + Kx = 0$$  \hspace{1cm} (1)

where $[M]$ is the mass matrix, $[K]$ is the stiffness matrix.

Assume displacement vector as $x = A \sin \omega t$ and the equation of motion becomes:

$$(-\omega^2 [M] + [K])x = 0$$  \hspace{1cm} (2)

Here the eigen values would represent the natural frequency and eigen vector represent the mode shape corresponding to that frequency. The 1\textsuperscript{st} and 2\textsuperscript{nd} natural periods are 3.1124 s and 3.1117 s and other modal periods are less than 1 sec. After the free vibration analysis, it is found that the natural periods of the OFWT jacket are far away from the periods of external
excitation forces (wave and wind) which show that the structure will not resonate. The higher frequencies of the structures are also important in the context of interaction of frequencies of excitations.

Dynamic analysis of the offshore jacket structure needs to consider the environmental loads due to wind, waves and currents. For OFWT jackets, the effects of wind will be more unlike normal oil and gas jackets because the large blade dimensions. So both aerodynamic and hydrodynamic analysis should be done for the OFWT jackets. The dynamic analysis is done using the software USFOS. The response of the dynamic analysis is obtained as a function of time. The general equation of motion is given by:

\[ [M]\ddot{x} + [C]\dot{x} + [K]x = \{f(t)\} \]  

(3)

where \([C]\) is the damping matrix and \(\{f(t)\}\) is the external exciting forcing function.

The aerodynamic load calculation is done using an aerodynamic code called FAST provided by NREL for calculation of wind load on the turbine. It gives a time series of aerodynamic load which can be fed into the software USFOS for performing the dynamic analysis of the structure. This particular code makes use of blade momentum theory to calculate the aerodynamic load on the turbine. The basic assumptions in this theory are there is no aerodynamic interaction between the element, there is no radial flow, the forces on the blades are determined solely by the lift and drag characteristics of the airfoil shape of the blades, the blade is stiff and do not bend. Fig. 5 shows the time series of aerodynamic load obtained for 5MW NREL wind turbine.

For simulating a real sea scenario, random wave coupled with the aerodynamic load time series obtained from FAST, is used for the analysis of the OFWT jacket. The wave spectrum selected for the analysis is Pierson-Moskowitz. A significant wave height of 2 m and a time period of 10 s were used. The analysis was done for three different cases for proper understanding of the problem.

a) with wave only
b) with wind only
c) with wave and wind together

The responses of the structure for the dynamic analysis are shown in Fig. 6. From these results, we can find that the effect of waves on the displacement at the top of the
structure is very small compared to the effect of wind. The maximum displacement at the top of the turbine for the random wave is found to be $1.35 \times 10^{-3}$ m whereas the displacement at the top of the tower for wind alone was found to be 0.68 m maximum during the transient state and 0.5 m during the steady state. Also comparing the displacements for wind alone and wave and wind together, there is no much variation in the displacement at the top of the tower. It reflects that the effect of wave when the wind is acting on the structure is so insignificant.

**Conclusions**

A substructure jacket for an offshore wind turbine was analyzed using SESAM Genie and USFOS (2012). Static analysis was carried out using SESAM Genie and dynamic analysis was done in USFOS. Due to these static loads, the maximum displacement found at the top of the tower was found to be 0.45 m which is within the safe limit. In the dynamic analysis, the maximum displacement at the top of the tower with both wave and wind together was found to be 0.68 m during the transient state and 0.5 m during the steady state. The analysis carried out does not take into account of soil-structure interaction and complete analysis including the interaction effects of the soil has to be carried out.

![Displacement time graph for the dynamic analysis with random wave](image)

Fig. 6 Displacement time graph for the dynamic analysis with random wave


References


