Coupled Dynamic Analysis of Offshore Wind Tower

[Anitha Joseph, Lalu Mangal, Jayasurya K. A]

Abstract—**An articulated type supporting structure for an offshore wind energy turbine, to suite Indian offshore conditions (east cost), is designed and analysed. Static as well as nonlinear coupled dynamic analysis is done to assess the performance of the proposed tower. The numerical investigation is carried out using an available finite element computer program specially suited for complaint offshore structures. A wave force model with diffraction-radiation loading on larger members and Morison loading on the slender members is adopted for computing the nonlinear dynamic response of the structure. The dynamic responses are presented in the form of Response Amplitude Operators. Fatigue analysis of the structure is carried out to estimate the fatigue life of the structure.**

Keywords— offshore wind tower, articulated tower, nonlinear dynamic analysis, finite element method

I. Introduction

Increasing energy demand and oil prices together with the threat of manmade global warming, commands the need and emergence of new energy solutions. Wind energy is a clean and inexpensive alternative to the nonrenewable energy resources. Offshore Wind Turbines (OWT) are being used in a number of countries to harness the energy of the moving air over the oceans and convert it to electricity [1], [2]. Offshore winds tend to flow at higher speeds than onshore winds, thus allowing turbines to produce more electricity. Structures in the marine environment are subjected to extreme wave action and violent storms that pose a major challenge for the stability as well as existence of these structures. Among the various options for use in such conditions, the articulated type is explored here. An articulated tower is a compliant structure, flexibly connected to the seabed through a cardon joint and held vertically by the buoyancy force acting on it. The part of the tower emerging from the water supports the super structure designed to suit the particular application. The concept has been applied to flarestacks, offloading terminals and deepwater mooring of vessels for floating production systems. As the connection to the seabed is through the articulation, the structure is free to oscillate in any direction and does not transfer any bending moment to the base. This helps in reducing the structural dimensions and consequently reduction in waveforce. In the case of multi leg articulated tower (which may have three or more columns connected by universal joints both to the deck and to the foundations), the use of universal joints ensures that the columns always remain parallel to one another and the deck remains in horizontal position.

OWT on floating support platforms are designed to be installed in a deep offshore environment several miles off the coast and in water depths greater than 60 m. The loads on these systems, are dominated by aerodynamic and hydrodynamic effects. The dynamic response of an articulated type supporting structure for OWT has been investigated using Finite Element (FE) method in the time domain with the objective of reproducing significant hull-leg coupling.

Sreekumar *et al.* [3] presented the coupled nonlinear dynamic analysis of the Seastar mini TLP in the time domain using finite element method with wave loading by the linear diffraction-radiation theory. Surge and heave response amplitude operators (RAOs) by Morison as well as potential theory models were quite close at all frequencies. Joseph *et al.* [4] reported the results of a detailed experimental and numerical investigation of the coupled dynamic behaviour of a mini TLP with special attention to hull-tether coupling. Nielson et al. [5] presented integrated dynamic analysis of floating OWT.

The present study deals with the numerical investigations for a suitable offshore wind turbine tower suiting the Indian offshore shallow water conditions. A fully coupled system can be modeled using finite element method. The coupled finite element analysis in the time domain yields the structural response simultaneously with platform response and can greatly improve the quality of fatigue life estimates.

2. Preliminary Design and Static Analysis

A wind turbine with a power rating of 5MW is chosen for the design of the floating structure. A hybrid design concept is considered which achieves static stability from buoyancy, by adding ballast and by providing articulated legs (Fig. 1).

Total water depth considered for the design purpose is 50m. Turbine tower was modeled with tapered steel tube section with diameter linearly varying from 3-6m which is above still water level. This tower is extended for a depth of 50m with a constant diameter of 6m, then supported on a frame structure which consists of three tubular legs of 25m each and truss members. The truss members are at 45° each. The three legs and the truss members are of tubular with 1.5m and 0.8m diameter. Horizontal members of the truss are 10m in length. Beam elements and plate elements are used to model

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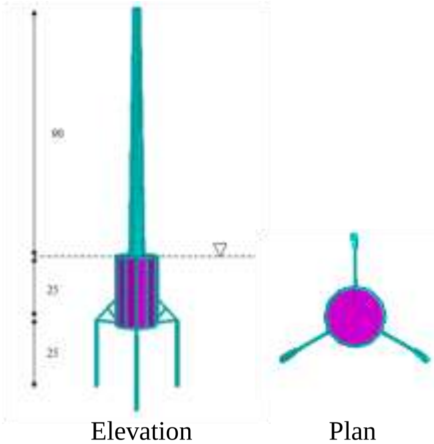

Figure 1. Offshore Wind Tower Model

the entire structure. Vertical tensioned leg is designed analogous to an articulated tower. One end is provided with a hinged support and the other end with a fixed support but moment released in x and y direction. For fixing the initial design of the structure, static analysis is done under the combination of self weight and wind load. Offshore basic wind speed taken is 44.85 m/s. Dynamic analysis is done in order to assess the performance of the structure and to choose an optimum design. The natural frequencies of the wind tower are found to lie far away from the wave frequency range. The maximum displacement of the structure due to wind and wave load is found to be within the safe limits.

3. Coupled Dynamic Analysis

The choice of appropriate wave model plays a major role in the accurate prediction of structure dynamics. For the entire range of practical wave frequencies, the underwater hull geometry of the articulated tower considered in this work falls both in Morison regime (for slender members, D/L_w <=0.2) as well as diffraction-radiation regime (for hydro-dynamically compact members, D/L_w >=0.2) for the purpose of wave force calculation. A wave force model with Morison equation for slender members of the hull and potential theory for large, compact volume hull components is considered for numerical analysis [6].

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A. Diffraction Radiation Analysis

In order to carry out linear diffraction-radiation analysis of the articulated tower for offshore wind turbine (OWT) (dimensions and axis system are shown Fig. 2), a cylindrical fluid domain of diameter approximately five times that of the large diameter (15m) pontoon is selected. The FE mesh is generated by the pre-processor utility of commercial FE software. Second order dampers have been used at the radiation boundary [7]. The body mass matrix and buoyancy

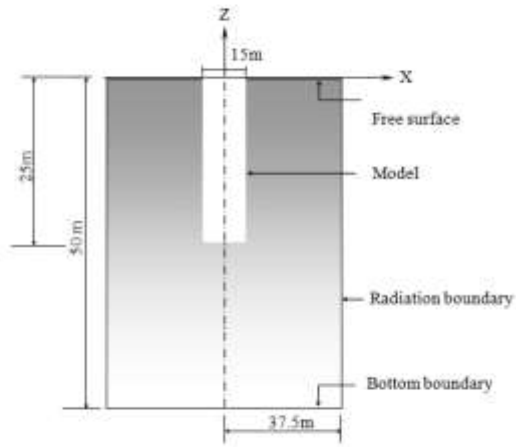

Figure 2. Geometrical details of Articulated Tower for OWT in fluid domain

restoring coefficient matrix are input to calculate the added mass and damping matrices and wave excitation force vector. The diffraction-radiation analysis is carried out for frequencies ranging from 0.05 Hz to 0.167 Hz. The analysis is done for two wave approach angles (θ = 0° and 30°). Due to symmetry, the surge and sway modes have identical hydrodynamic coefficients. The same is true for the roll and pitch modes. Both added mass and radiation damping coefficients are negligibly small in the yaw mode for both models. All the coupled mode coefficients are negligible except the surge pitch and sway roll modes. The diffraction force components as well as their phases for different sea states are shown in Fig. 3. The plots show that the phase angles in surge and pitch are independent of wave approach angle but their forces are dependent. For θ=30°, surge force and pitch moment reduces compared to when θ=0°. The heave force and phase are independent of wave approach angleθ. Sway force and roll moment vanish for θ=0°, as the structure is symmetric. Sway and roll phase is dependent of wave approach angleθ. The yaw moment is negligible for angle θ=30°. Surge force and pitch moment is greater compared to other force and moments.

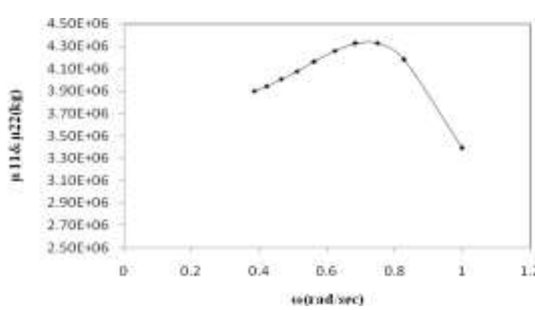

Figure 3. Surge and Sway added mass of Articulated Tower

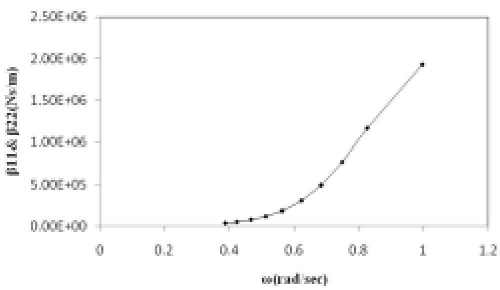

Figure 4. Surge and Sway damping coefficients

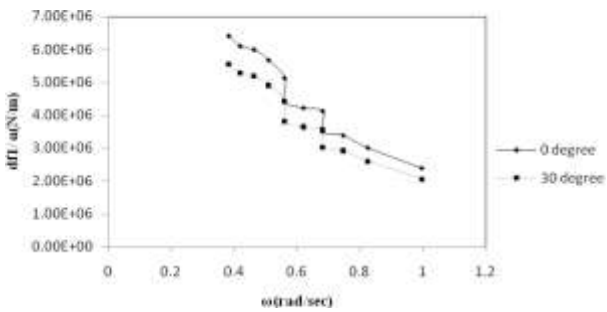

Figure 5. Surge force

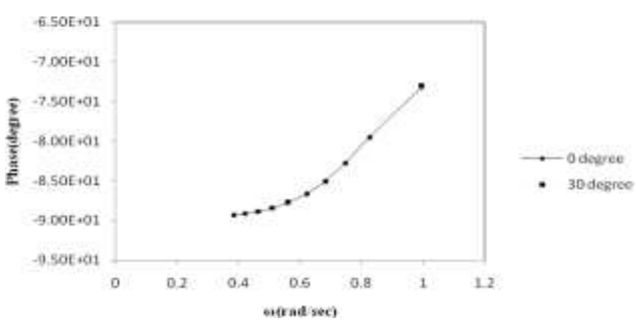

Figure 6. Surge phase

B. *FE Modeling and Analysis*

Elements used in structure modeling include beam element, 3D general spring element (uncoupled), 3D global spring element (coupled), 3D general damper element (uncoupled), 3D global damper element (coupled), 3D general mass element (uncoupled) and 3D global mass element (coupled). For the articulated tower model, the hydrostatic parameters used in numerical analysis are heave stiffness = 1767345.075 N/m, pitch stiffness = 24853289.49 Nm/rad and roll stiffness= 24853289.49 Nm/rad. The disk drag coefficient used for the flat bottom end of the cylinder was 0.85. The finite element model of the articulated tower for OWT is presented in Fig. 7.

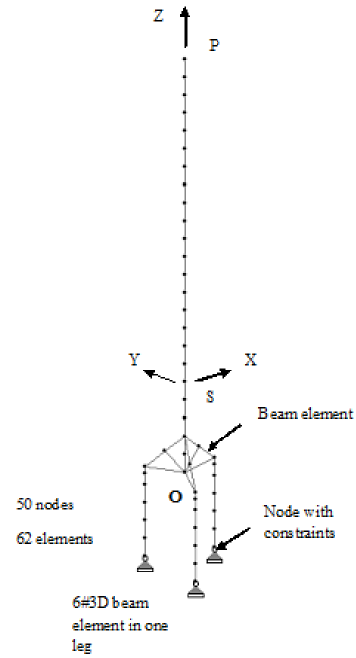

Figure 7. Finite Model of Articulated Tower

It comprises of 50 nodes, 62 beam elements, 1 spring element, 3 mass elements, 1 damper element and 300 equations. There are 6 beam elements per leg. The tower portion above and below SWL is divided into 18 and 6 respectively and two beam elements each per truss frame. A 3D coupled mass was used to model the nacelle and rotor mass. Six 3D coupled mass elements were used to model the ballast (lumped mass). The buoyancy effect of the structure is provided as pretension in the three legs. The geometry stiffness due to pretension in the legs has significant effect on the system dynamics. The pretension of the leg is input in to the finite element model as axial tension at both conditions. The whole structure was modeled using beam elements with their actual stiffness. To incorporate the double articulation effect, the leg nodes at the sea bed is given a hinge and a small beam element is provided at the top of the leg with very low moment of inertia to satisfy the hinge effect. Three 3D coupled mass elements (at the top and bottom nodes of the pontoon column elements) model the ballast (lumped mass) for varying the pretension values. Pretensions of 691×10^{7} N and two wave approach angles 0º and 30º are considered for parametric studies. The geometrical stiffness due to pretension in the tethers has significant effect on the system dynamics. The pretension of the articulated legs is input into the FE model as axial tension at both sides of each leg element.

The FE analysis resulted in the Response Amplitude Operators (RAO) of the six motions as well as Tension in the legs. Fig. 8 is a sample time series of surge. Fig. 9 and Fig. 10 show the RAOs of surge and leg tension.

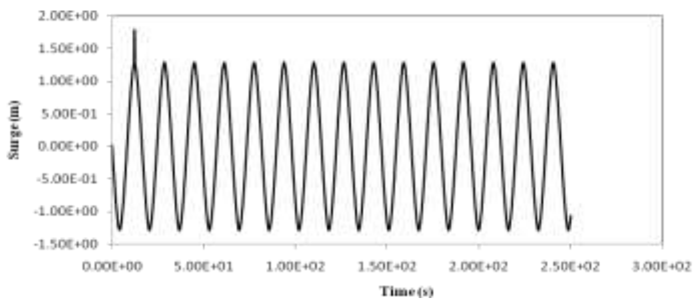

Figure 8. Computed Surge Time Series of Articulated Tower (H=9.2m, T=16.2s- 50 year return period value)

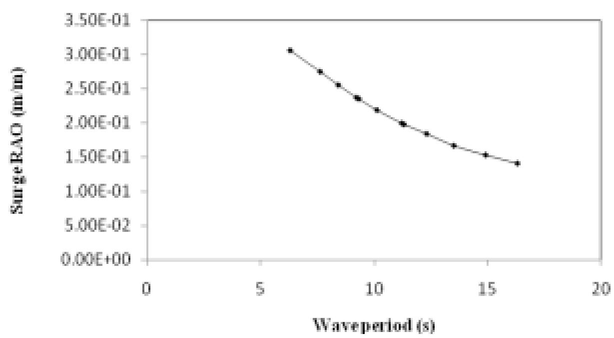

Figure 9. Surge RAO (H=9.2m, T=16.2s- 50 year return period value)

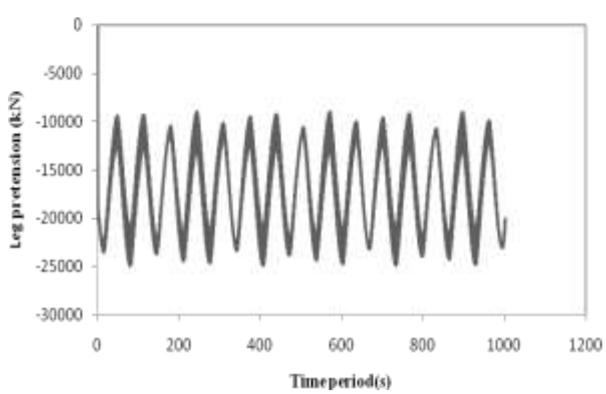

Figure 10. Leg Pretension (H=9.2m, T=16.2s- 50 year return period value)

4. Fatigue Analysis

To ensure that the structure will fulfill its intended function, a fatigue assessment is carried out for each individual member subjected to fatigue loading. The fatigue analysis is based on S-N data, determined by fatigue testing of the considered welded detail, and the linear damage hypothesis [8]. In the present study the maximum nominal stress range that can contribute to fatigue damage is obtained from the nonlinear time domain analysis of the structure. Nominal stress is simply the membrane stress that is used for plotting of the S-N data from the fatigue testing. In order to measure how close the number of cycles of a given stress range brings us to failure, a variable called fatigue damage was created.

$$\textit{Fatigue damage} = \frac{\textit{Number of stress cycles applied}}{\textit{Number of stress cycles resisted}}$$

In order to evaluate the fatigue damage caused by stress ranges of different amplitudes Miner Palmgren have introduced a rule, which says that the damage caused by individual stress cycles may be summed up linearly [9]. The fatigue life of the structure is taken as the inverse of the total damage of the structure. The fatigue life of the structure was calculated using a computer program written in C#. This program was used to calculate the maximum nominal stress in the members for two wave approach angles 0º and 30º for different sea states. The members providing the universal joint at the articulated legs were analyzed to obtain the maximum stress range, which was found maximum in the articulated legs. The maximum stress ranges were tested for Morison theory, Potential theory and a combination of the two theories. The maximum range was observed for the combination theory of Morison and Potential theories. One year base period was taken for the calculation of the number of cycles applied to the structure. Figure 11 shows the output for the computer program.

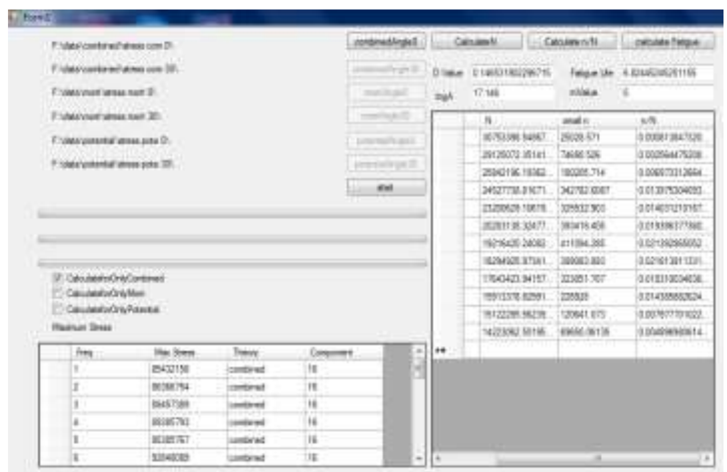

Figure 11. Fatigue Life calculation

The maximum nominal stress range was observed for 30º wave approach angle for the articulated leg members for the combined Morison and Potential theory. The total damage value was calculated as 0.1465. From this the fatigue life of the wind turbine tower was obtained as 6.824 years. Since the expected fatigue life of the structure was comparatively low, the estimated reliability of the structure will also be low. Even though the structure was feasible in the sea environment in question, the expected fatigue life of the structure was only 6.824 years. This shows the importance of a fatigue analysis of these types of structures. It is essential that the structural and geometric property of the OWT have to be increased (diameter & thickness) in order to attain longer fatigue life for the structure.

5. Discussion of Results

Figure 8 shows that surge attains steady state at about 50s. Therefore the simulation needs to be carried out at least for 500s. Except for surge, all the other responses are small. The surge displacement was obtained as around 2m for a 50 year return period wave parameter which was the same obtained from preliminary analysis.

Figure 9 shows the RAOs of the articulated structure. Although, the structure is excited by waves only in the surge mode, it displays motion in all the other modes. The structure's response in these modes indicates the effect of coupling mechanism. From the RAO graph, we can observe that only surge RAO is high compared to others and gives the highest peak value of 3 for a time period 0f 6.3 s (1^{st} mode natural period of the structure). All the other responses have RAO value less than 0.5. Figure 10 shows the leg tension combining both the static wind load and dynamic wave load. It is observed that there is no compression occurring in the legs hence buckling of the legs will not occur.

From the above it can be concluded that the proposed articulated structure is feasible. It is also evident that a coupled dynamic analysis is necessary since the uncoupled model gives high values for moments and shear.

6. Summary and Conclusion

In this design an articulated tower concept as supporting structure for the offshore wind turbine tower is proposed and investigated by numerical simulation using the finite element method for the Indian offshore conditions (east cost).For this a preliminary static analysis and design is done to fix the geometric configuration of the structure. The loads considered for the analysis were wind and wave load. Wave parameters for the analysis were taken for the study location from reliable source. To study the feasibility of the proposed structure, a nonlinear coupled dynamic analysis is done.

The principal conclusions of the present work are:

- A new 'Articulated Tower' concept is proposed for OWT for the Indian offshore conditions (east cost).
- Static, nonlinear dynamic and coupled nonlinear dynamic analyses are done to assess the performance of the proposed tower.
- Results show soft modes in surge and sway and stiff modes in other degrees of freedom.
- The peak response in surge and sway occurs away from the normal wave periods of the ocean waves.
- From the RAO plots it is also observed that the responses in pitch, roll, yaw and heave are very small.
- The time history plot of the forces in the articulated legs show that it only experiences tension and no compression; hence, buckling of the legs will not occur.
- Hence, from the above observations the articulated tower for OWT is found to be feasible.
- A coupled dynamic analysis is necessary since the uncoupled analysis gives high values for moments leading to uneconomical design.
- Fatigue life of the structure was analyzed which showed low fatigue life.

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