Effect of climate change on dynamic behavior of monopile supported offshore wind turbine structure

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ABSTRACT

Dynamic behavior of monopile supported offshore wind turbine is challenging due to complex long term wind and wave loading. Design of offshore wind turbine (OWT) structure primarily requires estimation of the fundamental frequency which needs to be kept away from excitation frequencies of wind and wave loading to avoid dynamic amplification of response and early fatigue damage. Global warming changes the wind and wave pattern due to pressure changes over the earth. The effect of climate change is having significant effect on wind speed, significant wave height and wave period, which in turn changes the dynamic behavior of OWT system. Fluctuating wind speed and wave height due to the effect of climate change may result in increased response and early fatigue damage. This study focuses on dynamic behavior of the monopile supported offshore wind turbine structure due to the climate change variability corresponding to 50 years future wind speed values. Historic wind data is utilized to project the future wind speed. The system is modeled using a beam on nonlinear Winkler foundation model. Soil resistance is modeled using American Petroleum Institute based cyclic p-y and t-z curves. The dynamic response and change in fatigue life of OWT structure is examined due to the effect of climate change and design implications are also suggested.

Keywords: dynamics, climate change, monopile, offshore wind turbine

1 INTRODUCTION

Offshore wind energy is a viable alternative to extract power because it is cost-effective, sustainable and environmentally friendly (Mabel and Fernandez 2008, Monfared et al. 2009). Wind speed is the one of the major design parameters pertinent to the dynamic behavior of an offshore wind turbine structure. Therefore, design of the offshore wind turbine (OWT) structure considering extreme wind speed is essential for developing a sustainable structure (Deepthi and Deo, 2010). The OWT structure is to be designed to sustain up to 20 years (DNV-OS_J101 2010) which is the usual design service life. Offshore wind turbines are typically designed and operated under extreme wind speeds and significant wave corresponding to more than 50 years return periods (ABS 2010, API 2011). Global warming changes the wind and wave pattern due to pressure changes over the earth and result in rise in sea level and alters the intensity of extreme wind speed (Deepthi and Deo 2010). Therefore, it is necessary to examine how wind and wave parameters change, if climate change is taken into account and subsequently change in the design of an OWT structure. Statistical downscaling model is the widely accepted method to forecast the future wind speed values from the past wind speed data (Wilby et al. 2002, Fiseha et al. 2012). Climate projection in regional scale raw GCM data shows poor performance, hence a statistically downscaled GCM data are generally used for future climate prediction (Wilby and Wigley 2000).

Deepthi and Deo (2010) reported that the wind speed increases significantly when the global climate change effect is taken into consideration. Fiseha et al. (2012) defined that GCM model can play a vital role to simulate the large scale climatology to local scale climatology and showed an increasing trend in temperature and precipitation considering the effect of climate change. Kulkarni et al. (2014) depicted the increasing trend of long term wind speed of 60 years for the period of 1970 – 2030. In all these studies, impact of climate change on future wind speed and wave height were studied, however impact on design of OWT structure due to climate change is not addressed.

In this study, the impact of climate change on future wind speed is assessed at the location along the west coast of India where the latitude and longitude are 15.39°N; 73.76°E (Arabian Sea). The location is about 28 km away from the coast. The buoy data is collected from INCOIS server

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Statistical downscaling model is used to develop a relationship between large scale atmospheric variables and local surface variables. The observed wind speed data are compared with NCEP reanalysis downscaled data and GCM (http://www.ccva.ac.cn:81/Downscaling_Tools/SDSM-e.html) downscaled data in order to verify the model performance. The SRESA1B scenario is used for GCM predictors. Thereafter, GCM predictors are used over the period of 2001 – 2050 to forecast the future wind speed data for 50 years. The response of an OWT structure is assessed due to future wind speed data consider climate change. The wave height is considered to be constant for simplicity. The OWT structure is analyzed using beam on nonlinear Winkler foundation model. The soil resistance is modeled using cyclic p-y curves as suggested in API (2011). The monopile and tower responses, and fatigue life of the structure is examined due to impact of climate change. Finally design implications are suggested due future climate.

2 METHODOLOGY

2.1 Prediction of future wind speed

Statistical downscaling model is used in this study to correlate local scale climate variable and large scale climate variable (Wilby et al. 2002). The observed wind speed values were collected from INCOIS web server from the buoy installed at offshore location near to west coast of India (latitude: 15.39°N and longitude: 73.76°E). The observed data is used as predictor variable which is forecasted through the knowledge of the behavior of predictor variables (Wilby et al. 2002). In this study 26 predictor variables are used, a few of them are mean sea level pressure, surface zonal velocity, surface meridional velocity, 500 hPa geopotential height, surface wind direction, relative humidity and specific humidity etc. The wind speed data are collected at the selected region for the period of 1998 – 2001. NCEP and GCM predictors are considered to forecast the variation of wind speed due to climate change and subsequently the downscaled wind speed is used in order to validate with respect to the observed wind speed values. A stochastic weather generator and transfer function methods are used for statistical downscaling model (Wilby and Dawson, 2007) in order to predict the future wind speed for the year of 2001 – 2050 by considering the GCM predictors.

2.2 Modeling of OWT structure

In this study, the response of the offshore wind turbine structure is obtained using the beam on the nonlinear Winkler foundation model in which the monopile and tower are assumed to behave as an Euler-Bernoulli beam of flexural rigidity $E_p I_p$. The tower and monopile is discretized into beam elements. Each beam element of monopile is assumed to be attached to soil springs that generate the lateral resistance against pile movement within each element. A tapered cross-section for the tower is used and uniform cross-section for monopile is considered. The rotor blades, nacelle and hub are combined into a single mass placed at the top of the tower ($M_T$) with rotary inertia ($J_{RNA}$) (Figure 1). In this study, p-y curve for clay, recommended in API (2011) and DNV (2010), are adopted for analysis. The API (2011) recommended $t$-$z$ and $Q$-$z$ relationships for clay, are utilized for analysis. Soil is considered as homogeneous, isotropic and uniform soft clay deposit. An overall 12% damping of OWT structure is considered in this study.

![Fig. 1. A monopile supported OWT system in clay and p-y analysis.](image)

2.3 Estimation of wind and wave loads

The total wind load acting on the OWT structure is divided into two components, namely the load acting on the turbine blades and the load acting on the turbine tower. The load acting on the turbine blades ($F_b$) is estimated as (Jara 2006),

$$F_b = 0.5 \rho_s \pi R_T^2 V_{hub}^3 C_f (\lambda_s)$$

where $F_b$ is the wind load acting on the hub in N, $V_{hub}$ is the wind speed at the hub height in m/s, $R_T$ is the rotor radius in m, $\rho_s$ is the air density which equals to 1.23 km/m$^3$ at 15°C at 1 atm, $C_f(\lambda_s)$ is the thrust coefficient which is a function of the tip speed ratio ($\lambda_s = \frac{V_r}{R_T/N_{hub}}$, $V_r$ is the rotor speed in rad/s). The frequency of wind load is same as the rotor frequency ($f_r$) and it is applied as lateral point load at RNA, that is $F_b \sin(2\pi f_t t)$, where $t$ is the dynamic time. Wind load acting on the tower is calculated based on the velocity profile over the tower height as (DNV-RP-C205, 2010).
Wave force \( (F_{\text{wave}}) \) on the structure is estimated using Morison’s equation (DNV-OS-J101, 2010),

\[
F_{\text{wave}} = F_M + F_D = C_M \rho D^2 \int_{-z_c}^{0} \left( \bar{u} \right) dz + C_D \rho D |\bar{u}| \int_{-z_c}^{0} \left( \frac{dz}{dt} \right) dz.
\]

(2)

where \( F_M \) is the inertia force and \( F_D \) is the drag force, \( d_w \) is the water depth in m, \( C_M \) is the drag coefficient (0.7 for a smooth tubular section), \( C_D \) is the mass coefficient (2 for a smooth tubular section), \( \rho \) is the mass density of the sea water (1030 kg/m³ approximately), \( D \) is the diameter of the tower and monopile in m, \( \bar{u} \) and \( \bar{u} \) are the wave induced velocity and acceleration of water, respectively in the horizontal direction, and \( \eta(t) \) is the surface wave profile. Wave load is applied as lateral point load at mean sea level with the wave frequency \((\omega_n)\).

Table 1. Range of parameters for a 2 MW OWT.

<table>
<thead>
<tr>
<th>Property</th>
<th>Range of parameters</th>
<th>Selected values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor speed ((f_r))</td>
<td>0.17 - 0.4 Hz</td>
<td>0.17, 0.3 and 0.4 Hz</td>
</tr>
<tr>
<td>Rotor diameter ((D_r))</td>
<td>65 - 95 m</td>
<td>80 m</td>
</tr>
<tr>
<td>Rotor-Nacelle mass ((M_d))</td>
<td>80 - 140 ton</td>
<td>108.5 ton</td>
</tr>
<tr>
<td>Water depth ((d_w))</td>
<td>5 - 25 m</td>
<td>20 m</td>
</tr>
<tr>
<td>Tower height ((H_t))</td>
<td>60-100 m</td>
<td>80 m</td>
</tr>
<tr>
<td>Diameter of the tower and monopile</td>
<td>7850 kg/m³</td>
<td>7850 kg/m³</td>
</tr>
<tr>
<td>Thickness of the tower and monopile</td>
<td>4 - 6m</td>
<td>4 m</td>
</tr>
<tr>
<td>Embedded length of monopile ((L_e))</td>
<td>0.035 – 0.055 m</td>
<td>0.035 m</td>
</tr>
<tr>
<td>Young’s modulus of tower and monopile</td>
<td>15 - 33 m</td>
<td>25 m</td>
</tr>
<tr>
<td>Yield strength of steel ((Y_p))</td>
<td>2.1×10^5 MPa</td>
<td>2.1×10^5 MPa</td>
</tr>
<tr>
<td>Wave period ((T_w))</td>
<td>4 - 25 sec</td>
<td>10.5 sec</td>
</tr>
<tr>
<td>Wave height ((h_w))</td>
<td>1 – 10 m</td>
<td>1 m</td>
</tr>
<tr>
<td>RNA mass moment of inertia ((\text{J}_{RNA}))</td>
<td>1×10^7 kg – m²</td>
<td>1×10^7 kg – m²</td>
</tr>
</tbody>
</table>

3 PARAMETERS

A three bladed 2 MW OWT structure is considered for analysis. General ranges of the relevant parameters for a three bladed 2 MW OWT are collected from literature (Tempel & Molenaar 2002, Kapsali & Kaldellis 2012), which are summarized in Table 1. Present analysis considers API (2011) based cyclic p-y curves for \( s_u = 25 \) kPa. The p-y curves are generated based on three parameters: (i) undrained shear strength of soil \((s_u)\), (ii) strain corresponding to one-half the maximum stress on laboratory undrained compression tests of undisturbed soil \((s_c)\), and (iii) an empirical dimensionless constant \((J)\). The value of \( s_c \) is estimated for the given value of \( s_u \) from Ashour et al. (1998). A constant value of \( J = 0.5 \) is used for all cases. The t-z and Q-z curves are also estimated from the values of \( s_u \). The gap formation between soil and monopile is not incorporated due to simplicity.

![Fig. 2. Monthly maximum wind speed of observed data and downscaled data (NCEP - predictors) for the period of 1998 - 2001.](image2)

![Fig. 3. Monthly maximum wind speed of observed data and downscaled data (GCM - predictors) for the period of 1998 - 2001.](image3)

4 RESULTS AND DISCUSSION

Observed daily wind speed data for year period (1998 - 2001) are used to validate the performance of the statistical downscaled model. The wind speed data are downscaled using NCEP predictors and validated with the observed wind speed data for the period of 1998 – 2001 as shown in Fig. 2. The downscaled data are also driven using GCM predictors and compared with the observed data (i.e. buoy data) for the period of 1998 – 2001 (cf. Fig. 3). Monthly maximum wind speed values are compared by statistical performance assessment criteria. The results are in good agreement between observed wind speed and downscaled wind speed data as depicted in Fig. 2 - 3 with an exception of the downscaled maximum monthly wind speed for the month of June and July because of data sparseness. Hence, the models considering NCEP predictors and GCM predictors shows good performance to forecast the wind speed data.

In this study, future climate scenario is generated for
the maximum wind speed using GCM predictors for the period of 2001 – 2050. The maximum wind speed is increased up to 53% due to the effect of climate change mainly because of greenhouse gas emission.

Maximum rotation of monopile at sea bed level ($\theta_{\text{Pile, max}}$) and rotation at tower top ($\theta_{\text{Tower, max}}$) is estimated for the selected ranges of parameters using dynamic analysis in time domain using finite element (FE) approach. The impact of climate change is obtained using the maximum wind speed value predicted considering the future climate (i.e. for the year 2001 - 2050) and compared with the responses obtained based on present maximum wind speed (i.e. for the year 1998 - 2001).

Fig. 4 shows the $\theta_{\text{Tower, max}}$ and $\theta_{\text{Pile, max}}$ considering with and without climate change. In this study, 60 m tower height is considered for analysis. Embedded length of monopile is considered as 24 m. Thickness of the tower and monopile is considered as 35 mm. Three different rotor frequencies are considered for analysis (Table 1). A rotor frequency equal to fundamental frequency of the system is intentionally used in order to observe the behavior of the OWT at resonance condition for varying climate scenario. Fig. 4a-b shows that at resonance condition $\theta_{\text{Tower, max}}$ and $\theta_{\text{Pile, max}}$ are increased by about 20% and 30% respectively due to consideration of climate change than that of the values.
estimated without the effect of climate change. Whereas, $\theta_{\text{tower, max}}$ and $\theta_{\text{Pile, max}}$ are increased up to 50% when fundamental frequencies are away from rotor frequencies. It is observed that $\theta_{\text{tower, max}}$ is located below the allowable rotation of tower top (i.e. 5°) without the effect of climate change for the selected range of operating frequency of a 2MW OWT, as depicted in Fig. 4a. It is interesting to note, at resonance condition, the $\theta_{\text{tower, max}}$ increases and goes beyond the acceptable limit if climate change effect is accounted for analysis. Similar trend is also observed for $\theta_{\text{Pile, max}}$ (c.f. Fig. 4b). This is due to the fact that wind speed significantly increased (about 53%) at the selected offshore site due future climate change.

The fatigue life of an OWT is an important criterion for design. The impact of climate change on fatigue life is examined. The fatigue life of welded joints of OWT system is estimated based on DNV-OS-J101 (2010). The Von-Mises stress is generally estimated in order to estimate the fatigue life. Hence, amplification of Von Mises stress and fatigue life are investigated due to future climate scenario. Fig. 5a shows that Von Mises stresses increased by about 20% - 50% at or near the resonance. In general, design fatigue life of an OWT structure is considered as $10^7$ cycles in its design life (Pappusetty and Pando, 2014). Fig. 5b shows that fatigue life decreases significantly when climate change effect is accounted for analysis. It is interesting to note that at resonance condition, fatigue life decreases substantially for both the conditions due to amplification of the magnitude of stresses.

5 CONCLUSION

The impact of climate change on design of a 2 MW offshore wind turbine is examined. The future wind speed for the period of 2001 – 2050 are simulated considering statistical downscaling model at west coast of India. Future wind speed is significantly increased when climate change effect is taken into account, which affects the design criterion for an OWT structure. The maximum rotation at tower top and monopile head is increased significantly due to an increased wind speed within the design life of an OWT structure. Fatigue life of structure is also reduced drastically due to incorporation of the climate change.

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