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Dynamic Analysis of Offshore Wind Turbine Supported by Jacket Substructure under Wind and Wave Loading

Seeram Madhuri [1], Sitesh Subhra Bera [2], [*], Brajkishor Prasad [3]

[1]Department of Civil Engineering, Assistant Professor, National Institute Technology, Jamshedpur, 831014, India
[2] Department of Civil Engineering, Post Graduate Student, National Institute of Technology, Jamshedpur, 831014, India
[3]Department of Civil Engineering, Associate Professor, National Institute Technology, Jamshedpur, 831014, India

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Abstract

Burning of fossil fuel for the production of energy causes severe global warming effects. Renewable energy sources like solar, wind and tidal etc. are the alternative renewable energy sources which contribute in the reduction of adverse global warming effects. Wind turbines are being used for extracting wind energy from several years. Wind blow is continuous with limited disturbance in the offshore region when compared with main land. Offshore wind energy extraction is in research stage at many locations and implemented in European countries. Prediction of response of wind turbine supporting systems is essential in the design to withstand the environmental loads such as wind, wave, current and seismic etc. In the present study, a horizontal axis offshore wind turbine (HAWT) supported on an offshore jacket structure is considered and the response studies are performed. The jacket is considered at a water depth of 51m, thus total height of the jacket is 61m with a free board of 10m. A wind turbine of 5MW capacity is considered to be on top of jacket structure. The height of the wind tower is assumed as 70m, and a transition structure of 4m height is positioned in between jacket and tower. A free vibration analysis is performed to estimate the natural frequencies and mode shapes of the jacket supported wind turbine. The modal analysis is carried out using ANSYS static structural module.
The response analysis under wind, wave, current and aerodynamic drag loads is performed using SACS 13.2 software. Wind force is estimated based on API 2005 provisions. The aerodynamic forces on the wind turbine blades are evaluated using Betz Theory. Wave loading is calculated using Morison equation and linear Airy's wave theory. A parametric study is carried out by varying wave period from 6s to 20s. As the structure is symmetric about longitudinal and lateral directions, a wave directional analysis is also carried by considering 0^{o} and 45^{o} wave directions. The structural responses are studied for the combined wind, wave and current loads. Cut-in, rated, cut-out and storm conditions are simulated by modelling wind and aerodynamic loads on the tower, wind interacting area of the jacket and blades. Wave period and direction are varied to simulate different wave conditions. It is observed that the structural response is increasing as the wind velocity is increasing and wave period is decreasing.

Keywords: Horizontal axis offshore wind turbine (HAWT), Wind load, Wave load, Betz Theory, Morison Equation, natural period

1. Introduction

Now global warming is becoming a serious problem of the world and to get rid out of this issue, mankind has to be more dependent on the renewable energy resources than non-renewable energy sources for power generation. This renewable energy is called as clean energy because it does not emit any harmful substances or pollutants during the process of power generation. Some of the examples of renewable energy sources are solar, wind, tidal, wave, hydro and biomass etc. Wind power is one of the promising sources of renewable energy. Generally wind mills are used to capture the wind energy and from that mechanical energy is converted into electrical energy. Thus, wind turbine produces electrical energy which is economical, clean and environment friendly. In the offshore region the wind blow is continuous and obstruction free. Offshore wind turbines may extract wind energy at large scale when compared to main land due to the above advantages. Mono-pile, jacket types of substructure is constructed to support the offshore wind turbine. For lower water depths, mono-pile may become suitable but for water depths up to 100m, jacket structure is suitable. In order to design these structures, the response under different operational conditions is required. Cut-in, rated, cut-out are the main wind operational conditions for an offshore wind turbine. In the present study, a jacket structure to withstand 5 MW wind turbine is taken into consideration. A dynamic analysis is performed to estimate the natural period of the structure. A parametric study is performed under regular waves of unit wave height and wave periods ranging from 6s to 20s with an increment of 2s. Wave directions of 0^{o} and 45^{o} are applied to study the effect of wave direction.

2. Literature Review

Many researchers have done researches on the dynamic analysis of offshore wind turbine by varying different

*Corresponding author. Tel: +918309942434; E-mail address: smadhuri.ce@nitjsr.ac.in

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parameters. Abhinav and Nilanjan [3] studied the dynamic response of offshore wind turbine by varying soil conditions from soft to stiff clay. Nianxin et al [5] studied the response of an offshore mono-pile numerically and experimentally under regular waves in operational conditions along with heave type wave converters in the offshore wind turbine. Kai et al [2] studied the response of jacket supported offshore wind turbine under wave load. For a jacket substructure of an offshore wind turbine Ashish and selvam [6] performed dynamic analysis and static analysis by using USFOS and SESAM Genie software respectively. Yao et al. (2014) modelled a 5 MW wind turbine tower in finite element model and studied its responses under fatigue and static loading. According to author, Weibull distribution was best fit to model both the maximum hourly and average wind speed. Pratik et al [4] performed a comparison study on the axial force, base shear and deflection for a 3-legged and 4-legged jacket substructure at a fixed water depth. Bhattacharya and Adhikari [15] estimated the natural frequencies of wind turbine supported by mono-pile structure. Cerasela [7] dynamically analysed a wind turbine tower considering rigid and elastic support in substructure method and finite element method. Author observed a higher frequency for the rigid base than soil structure interaction. Swagata and Sumanta [8] performed dynamic analysis of a mono-pile supported turbine tower considering soil-pile interaction by varying tower heights and wind velocities and was observed that structural response is slightly high for soil-pile interaction. Phani et al [10] studied the effect of surrounding soil properties and horizontal force on the mono-pile supported wind turbine. Steffen [11] and Yeter et al [9] discussed various numerical modelling methodologies like coupled springs, fixity length, uncoupled springs for simulating the soil-structure interaction. Wei shi et al [16] studied the marine growth effect on a wind turbine supported by jacket structure by varying densities, thickness and hydrodynamic coefficient values. Live [17] studied the variation of dynamic response of a jacket substructure due to the effect of additional non-structural mass and increased hydrodynamic load due to marine growth. From the critical literature study, it is observed that limited studies are performed under different operational wind velocities, wave periods and wave directions. The main objectives of the present study is to predict the response of jacket supported wind turbine under cut-in, rated and cut-out wind velocities and different wave periods. As the considered jacket is four legged symmetric structure, the effect of wave direction also studied.

3. Modelling of the Structure

Three bladed horizontal axis wind turbine is considered with fixed jacket foundation system. The configuration of the offshore wind turbine is based on the NREL offshore (Jonkman et al. 2009) 5MW baseline turbine. A horizontal axis upwind offshore turbine is considered in the present study. The length of each blade is taken as 61.5 m. Each blade consist seventeen cross sections along the length. LM Glass fibre of density 817.9 kg/m^3 and young modulus 139GPa is considered as the material for the blades. Steel material with density 7850 kg/m^3 is considered as the material for the jacket, tower and transition piece etc. The length of the tower is 70m. The tower is considered with tubular tapered members with decreasing diameter towards top. The diameter of tower at base is 5.6m and top is 4.0m with a thickness 2.65cm. The schematic diagram of the jacket is shown in Fig. 1.

The model is developed in ANSYS Design Modeller with dividing the structure in three main integral parts such as jacket, tower and blades. The tower is modelled using beam element, jacket is modelled using line element and blade is modelled using plate element. A dynamic analysis is performed in ANSYS. The developed model in ANSYS is shown in Fig. 2.

The model is also developed in SACS Offshore Structure with dividing the structure in two main integral parts such as jacket and tower. To simulate the effect of nacelle and blades, the mass of nacelle and blade are lumped at the top of the tower. A static analysis under environmental loads such as wind, current and wave loads is performed.

A 61m height of jacket with a water depth of 51m is modelled using ANSYS and SACS software's. The jacket consists of four legs with three levels of X braces and horizontal braces. The legs are modelled with 1.2m dia. X 50mm wall thick tubular members from mud-line to first horizontal bracing from the mud-line. The remaining lengths of the legs are modelled with tubular members of 1.142m dia. X 35mm wall thickness. Horizontal and vertical bracings are modelled with 0.8m dia. X 20mm wall thick tubular members. The four legs are oriented in plan to make a square section with edge length of 12m at the mud-line and 8m at the deck level. The bottom joints at the mud-line of the legs fixed in all translation and rotational degree of freedoms. A concrete deck with a mass of 666t and dimension of 4.0x 8.0x 8.0m is positioned on the top of the jacket and serves as a support platform for the tower of the turbine. The transition piece is modelled using plate elements which connect the bottom node of the tower to the top nodes of the jacket legs, and the mass of the transition piece is distributed uniformly. The jacket is modelled with a high strength structural steel with young modulus of 210GPa and density of 8500 kg/m^3. The jacket legs are assumed to be flooded. The developed model in SACS is shown in Fig. 3.

4. Estimation of Loads

Generally, offshore wind turbines consist of heavy structural components with larger heights. Due to larger height, besides of dead load, live load it faces high intensity of aerodynamic load and wind load. As it is constructed in the offshore region, wave and current loads also acts on the supporting jacket structure.

Dead load of the structure is considered as the total self-weight of the structural component. Live load of 10kN/m^2 is considered to account for installation and repair works. The mass properties of the wind turbine are given in Table 1.

The performance of wind turbine depends upon various conditions and one of these conditions is aerodynamics forces generated by wind. As per American Petroleum Institute [19] provisions wind load is estimated by considering different wind speeds for different conditions. The cut-in, rated, cut-out and storm wind velocities are taken as 3m/s, 11.4m/s, 25.72m/s and 50m/s respectively.

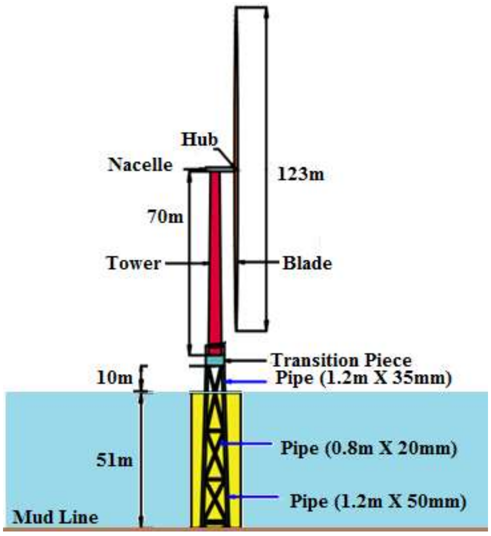

Fig. 1 Schematic diagram of jacket wind turbine

Fig. 2. Structure modelled in ANSYS

Table 1. Mass properties of jacket supported wind turbine

Description	Mass (kg)
Nacelle	240,000
Rotor (Hub and three blades)	110,000
Tower	217,016
Hub	56,780
Blade	17,740
Transition Piece	666000
Jacket	603240

The entire tower is divided into seven equal segments of length 10m and wind force is calculated. Design wind speed and wind force is estimated using equations 1, 2, 3 and 4. The distribution of wind speed and wind force along the height of the tower is shown in Figs. 4 and 5 respectively.

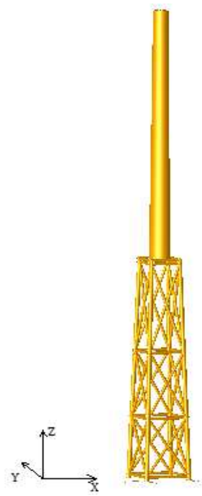

Fig. 3. Structure modelled in SACS

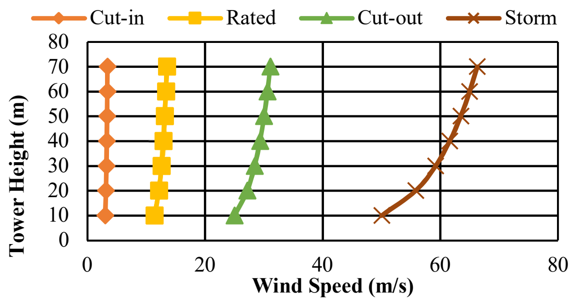

Fig. 4. Distribution of wind speed along tower height

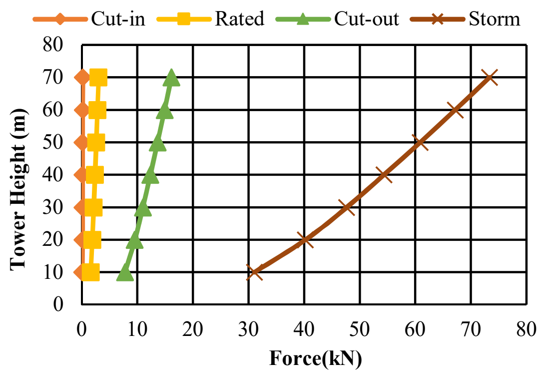

Fig. 5. Distribution of wind force along tower height

$$Uz = Uo \times [1 + C \times \ln \frac{z}{32.8}] \quad (1)$$

$$C = 5.73 \times 0.1 \times \sqrt{(1 + 0.0457 \times Uo)} \quad (2)$$

$$P = \frac{\rho}{2} \mu^2 \times Cs \quad (3)$$

$$F = \frac{\rho}{2} \mu^2 \times Cs \times A \quad (4)$$

The aerodynamic forces are generated by the wind due to the rotating of the blades. The aerodynamic loads are estimated using Betz theory, which gives the governing equations to calculate the aerodynamic forces acting on horizontal axis wind turbine rotor by considering the factors such as angle of attack, pitch angle and rotor speed with varying wind speeds such as cut-in, rated, cut-out. Each blade has seventeen cross sections with different specifications considered from NREL 5 MW baseline turbine [1].

The wind exposed cross-section area of the aerofoil section is calculated using Simpson's rule (Eq. 5). The lift (C_L) and drag force coefficients (C_D) are considered based on angle of attack (Jonkman et al [1]). Angle of attack (Eq. 8) is dependent on flow angle of the wind and pitch angle (Eq. 7) of the blade. Lift and drag coefficients for each aerofoil section is determined. Thus lift and drag force (Eq. 9 & 10) distribution along the turbine blade are estimated. The resultant drag force is applied as a point load on the top of the tower in the considered wind blow direction. The aerodynamic force distribution along blade length is shown in Fig. 6.

$$\int_a^b f(x)dx = ({}^{3h}/_8)\,[f(xo) + 3f(x1) + 3f(x2) + +f(xn)] \quad (5)$$

$$W = \sqrt{[(U^2) + (\Omega r)^2]} \quad (6)$$

$$\tan\theta = \frac{U}{r\Omega} \quad (7)$$

$$\alpha = \theta - \beta \quad (8)$$

$$L = \frac{1}{2} \times C_L \times \rho \times W^2 \times A \quad (9)$$

$$D = \frac{1}{2} \times C_D \times \rho \times W^2 \times A \quad (10)$$

Wave forces are estimated by using Morison equation (Eq. 11) along the jacket height from sea bed to mean sea level. Water particle velocity and acceleration are estimated according linear Airy's wave theory, (Eq. 12 and 13). A parametric study is performed by varying the wave period from 6s to 20s with an increment of 2s. Unit wave height of 1m is considered to simulate the small amplitude waves. The step size of each regular wave is taken as 20s thus total number of crest positions are 18 (360°/20°). The water particle velocity and accelerations are estimated at all the eighteen crest positions and wave force also determined. The phase angle at which maximum base shear occurred is considered as wave force for that particular wave. To account for current, a linearly varying current profile with velocity of 0.5m/s at sea bed and 1m/s at mean sea level is considered. The current velocity is added with water particle velocity (Eq. 11) to simulate the effect of current.

$$df = C_m \rho \frac{\pi}{4} D^2 \dot{u} + \frac{1}{2} C_d \rho D (u + u_c)|u + u_c| \quad (11)$$

$$u = \left(\frac{agk}{\sigma}\right)\left[\frac{\cos\ (d+z)}{\cos h\ kd)}\right] \cos(kx - \sigma t) \quad (12)$$

$$\mathring{u} = (agk)\left[\frac{\cos h(d+z)}{\cos\ \ kd)}\right] \sin(kx - \sigma t) \quad (13)$$

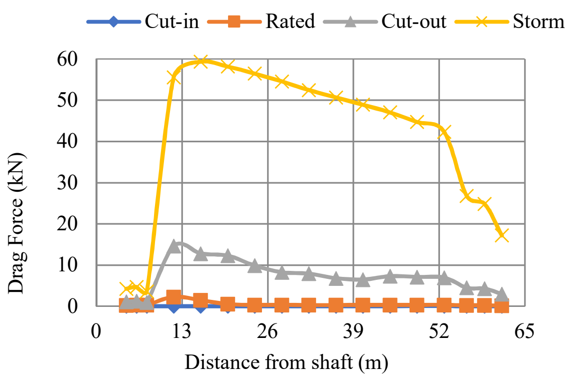

Fig. 6 Aerodynamic force distribution along the turbine blade

5. Analysis of Offshore Wind Turbine under environmental load

A static analysis is performed to study the response of the structure under dead, live, wind, wave and current loads. The structure is analyzed using SACS Offshore Structure software. The load combination is considered as per API, 2005 provisions by taking the combined effect of dead load, live load, wave load, wind load and current load. For a fixed water depth and wave height, wave period and wave angle are varied and structural response is observed. According to API RP 2A WSD [19], minimum eight wave directions are recommended for the wave direction study. As the present structure is symmetric in plan, hence 0° and 45° are considered as shown in Fig. 7.

A free vibration analysis is performed to study the dynamic characteristics of the structure. Free vibration analysis is performed using ANSYS. For the dynamic analysis, self-weight of the jacket, tower, transition piece and wind turbine are taken into consideration to simulate the mass of the structure.

6. Results and Discussions

A static analysis is performed under dead load, live load and major environmental loads. As the substructure jacket is fixed on the sea bed, the reaction force at the fixed end in X, Y and Z directions, and deflection of the jacket top and tower top in x direction are observed. The support reaction forces in X, Y and Z directions under cut-in, rated, cut-out, storm wind velocities and wave periods ranging from 6s to 20s are shown in Figs. 8, 9 and 11 respectively. Wave directions of 0° and 45° are also studied.

From the results it is observed that the support reaction in X direction is increasing as the wind velocity is increasing. The wave periods and direction are not much influencing the structural response. The reaction force in X direction under rated, cut-out and storm wind speeds is increased by 3%, 25% and 59% when compared with cut-in wind speed reaction in both the considered wave directions.

The reaction force in Y direction is increased as the wind velocity is increased. The reaction force in Y direction is increased by 0.22%, 1.21% and 4.65% respectively in rated, cut-out and storm wind speeds in both 0° and 45° wave directions when compared with reaction force in cut-in wind speed. The comparison of Y reaction under different wind speeds in 0° and 45° shows that the Y reaction is increased from 1.99% to 3.09%. in cut-in, cut-out and rated

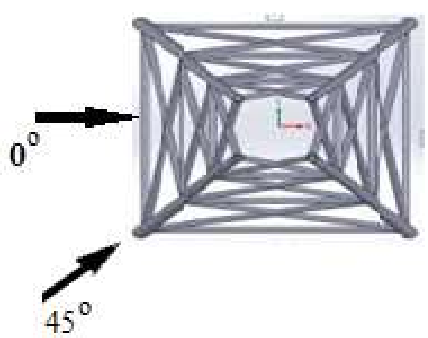

Fig. 7. Wave direction on the jacket (PLAN of Jacket at deck level)

wind speeds where as in storm condition the Y reaction is increased from 1.90% to 2.87%

The Y reaction force is decreased as the wave period is increased. The % decrease of Y reaction force with respect to Y reaction force under 6s wave period is shown in Fig. 10. The percentage variation is 0.38% to 1.183% in 0° wave direction and 0.58% to 2.237% under 45° wave direction when compared with Y reaction under wave period of 6s.

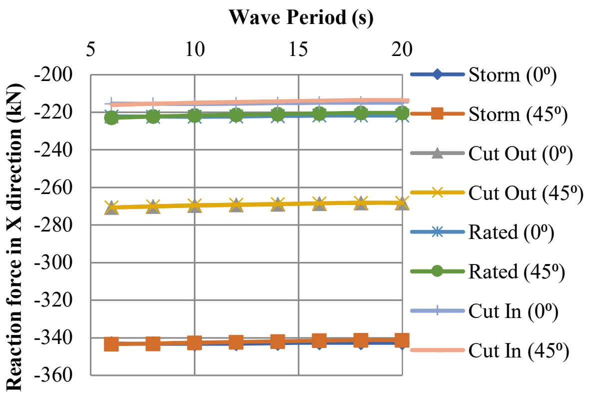

Fig. 8 Reaction force in X direction for different wave periods and directions

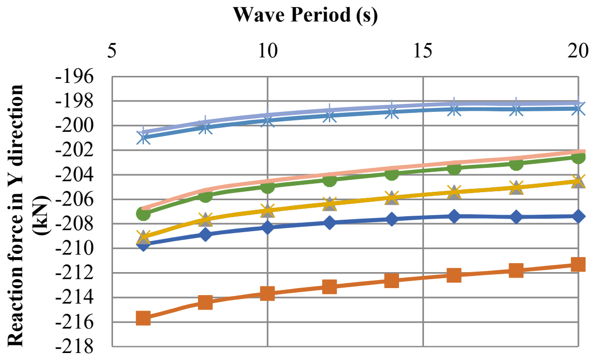

Fig. 9 Variation of reaction force in Y direction for different wave periods and directions

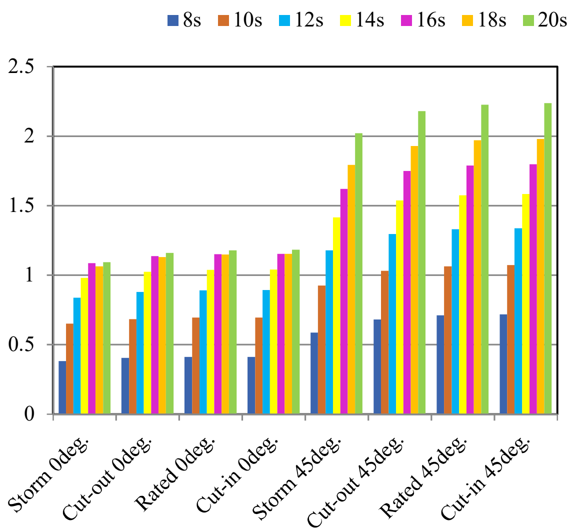

Fig. 10 Percentage decrease in Y reaction under different wave periods w.r.t. Y reaction under wave period of 6s

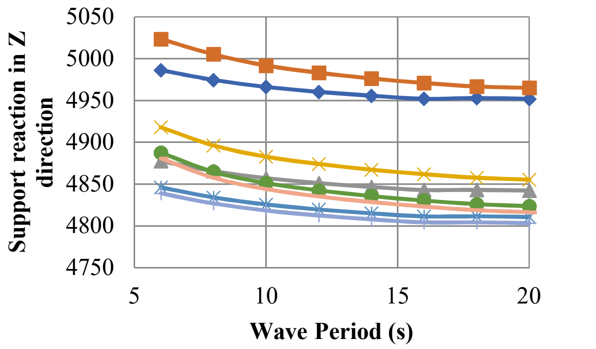

Fig. 11 Reaction force in Z direction for different wave periods and directions

The reaction force in Z direction is varied about 0.15% in rated wind speed, 0.80% in cut-out wind speed and to 3.09% in storm wind speed when compared with Z reaction in cut-in wind speed. The comparison of Z reaction in 0° and 45° wave direction shows that the Z reaction under wave direction of 45° is increased by maximum of 0.86% in cut-in, 0.74% in rated 0.83% in cut-out, 0.85% in rated and 0.75% in storm wind speeds.

The Z reaction is decreased from 0.38% to 0.72% (wave period is increased from 8s to 20s) when compared with Z reaction under 6s wave period.

The deflections in X direction at jacket top and tower top observed in the studied wind speeds and wave periods. The X deflection obtained at jacket top and tower top are shown in Figs. 12 and 13 respectively.

It is observed that the deflection is reducing with increase in wave period at jacket top under the considered wind speeds. The jacket top deflection has effect of 6.15% to 15.89% variation under 0° and 45° wave directions.

It is also indicating that the X deflection at tower top has no significant variation as the wave period is increasing. The direction of the wave also has no effect in the tower top deflection. Whereas the deflections increased as the wind speed increased. Cut-out and storm wind speeds are influencing the tower top deflection significantly. As the tower is not interacting with the waves, the tower top response is majorly due to wind speeds.

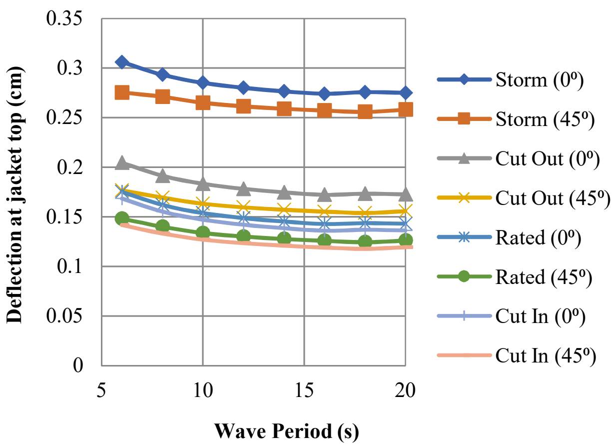

Fig. 12 Deflection in X direction at jacket top

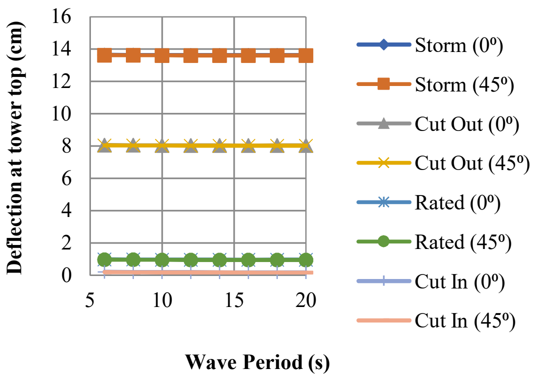

Fig. 13 Deflection in X direction at tower top

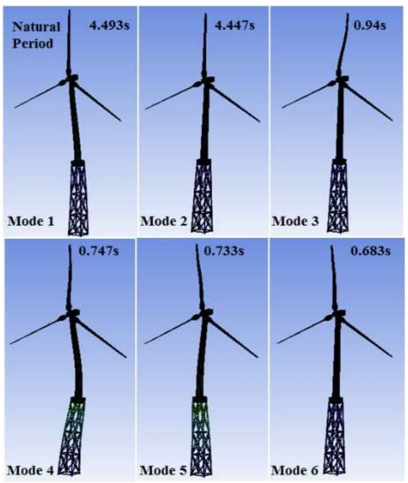

Fig. 14 Modes of vibration

Table 2. Natural modes and frequencies

Description	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Time Period (s)	4.493	4.447	0.940	0.747	0.733	0.683
Frequency (Hz)	0.223	0.225	1.063	1.337	1.363	1.463

A dynamic analysis is performed using ANSYS to study the dynamic characteristics of the system. The natural frequency and time period of the structure are estimated in the six modes of vibration. The mode shapes of first six modes of vibration are shown in Fig. 14 and the natural frequencies and time periods are listed in Table 2. It is observed that the natural period of the structure is ranging between 0.683s to 4.493s. As the wave period ranging from 6s to 20s, the structure may not experience resonance under wave loading.

7. Conclusions

From the static analysis it can be concluded that the support reaction forces in X direction is not significantly influencing under the studied wave periods. The combined effect of both wind and wave has significant effect in the Support reaction in X direction. The wave direction also has no significant effect. The reaction force in X direction under rated, cut-out and storm wind speeds is increased by 3%, 25% and 59% when compared with cut-in wind speed reaction in both the considered wave directions. This indicates that the structural response is predominantly influenced by the wind.

The reaction forces in Y and Z directions are also having significant effect under wind loading when compared with wave loading. The effect of wave direction is ranging from 0.26% to 3.091% in the considered wind speeds.

The jacket top deflections are influenced by wave period, wave direction and wind speeds where as tower top deflections are much influenced by wind speeds. As the tower is not interacting with wave the wave direction and wave period are insignificant. Both jacket and tower deflections are effected by wind speeds. Thus it can be concluded that wind speeds are predominant in the response of offshore jacket supported wind turbines.

The structural natural period in the first mode is observed about 4.493s. This indicates that the structure is highly stiff. Utmost care should be taken to design the offshore wind turbines to withstand the wind and wave loading.

8. Notations and Abbreviations

Uz	1 hour mean wind speed at level Z
Uo	1 hour mean wind speed at 32.8 ft
Z	height above sea level
P	wind pressure
ρ	mass density of air
μ	wind speed (ft/s)
C_s	shape coefficient
A	area of object
F	wind force
C_L	lift coefficient
C_D	drag coefficient
r	distance of aero-foil section from shaft
U	wind speed
Ω	turbine's rotation speed
W	magnitude of the relative wind speed
θ	flow angle
α	angle of attack
β	pitch angle
L	lift force
D	drag force
C_m	added mass coefficient
D	diameter of the transition member
u	water particle velocity
u_c	current velocity
a	wave amplitude
k	wave number
d	water depth
z	the depth of wave force estimation
σ	wave frequency
t	time step

Disclosures

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