Analysis of Dynamic Response Characteristics for 5 MW Jacket-type Fixed Offshore Wind Turbine

Jaewook Kim1,2, Sanghwan Heo3 and WeonCheol Koo4

1Graduate Student, Department of Naval Architecture & Ocean Engineering, Inha University, Incheon, Korea
2Principal Engineer, Daewoo Shipbuilding & Marine Engineering Co. Ltd., Seoul, Korea
3Postdoctoral Researcher, Department of Naval Architecture & Ocean Engineering, Inha University, Incheon, Korea
4Professor, Department of Naval Architecture & Ocean Engineering, Inha University, Incheon, Korea

KEY WORDS: Offshore wind turbine, Jacket, Tower, Dynamic response, Combined wind and wave load, Fourier analysis, Turbulent wind

ABSTRACT: This study aims to evaluate the dynamic responses of the jacket-type offshore wind turbine using FAST software (Fatigue, Aerodynamics, Structures, and Turbulence). A systematic series of simulation cases of a 5 MW jacket-type offshore wind turbine, including wind-only, wave-only, wind & wave load cases are conducted. The dynamic responses of the wind turbine structure are obtained, including the structure displacement, rotor speed, thrust force, nacelle acceleration, bending moment at the tower bottom, and shear force on the jacket leg. The calculated time-domain results are transformed to frequency domain results using FFT and the environmental load with more impact on each dynamic response is identified. It is confirmed that the dynamic displacements of the wind turbine are dominant in the wave frequency under the incident wave alone condition, and the rotor thrust, nacelle acceleration, and bending moment at the bottom of the tower exhibit high responses in the natural frequency band of the wind turbine. In the wind only condition, all responses except the vertical displacement of the wind turbine are dominant at three times the rotor rotation frequency (considering the number of blades) generated by the wind. In a combined external force with wind and waves, it was observed that the horizontal displacement is dominant by the wind load. Additionally, the bending moment on the tower base is highly affected by the wind. The shear force of the jacket leg is basically influenced by the wave loads, but it can be affected by both the wind and wave loads especially under the turbulent wind and irregular wave conditions.

1. Introduction

Owing to the increasing global environmental regulations and energy crisis, wind energy is gaining global interest as eco-friendly alternative renewable energy that can be sustained. The wind power generation technology that converts fluid kinetic energy into electric energy has already been technologically verified, and large land-based wind turbines have been constructed worldwide since the 1980s (Jang and Sohn, 2011).

However, constructing large land-based wind turbines causes various issues such as spatial limitations, noise, radio interference, and visual discomfort. Moreover, high energy generation efficiency is difficult to obtain in land-based wind power generation owing to low wind speed and turbulence caused by interference from surrounding terrain features (Li et al., 2018). Offshore wind power generation results in high power generation efficiency because the offshore wind speed is, on average, at least 70% higher than that on land, and large wind turbines can be installed because wide installation spaces are available (Park et al., 2021).

Consequently, offshore wind turbines have recently been installed and operated in numerous regions, and many fixed type wind turbines have been installed in relatively shallow coastal areas. Particularly, in South Korea, the Jeju Tamla Offshore Wind Farm was constructed in 2017 and has ten 3 MW wind turbines in operation, and the Offshore Wind Farm in the Southwestern Coast of Yellow Sea was constructed in 2019 and has twenty 3 MW wind turbines in operation (Jeong et al., 2020; Oh et al., 2020).

As the demand for offshore wind turbines increases, studies on them have been actively conducted. Shi et al. (2011) carried out dynamic response analysis according to the shapes of the substructures of a 5 MW offshore wind turbine and reported that the load and dynamic response acting on a monopile-shaped substructure have larger values.
than those acting on tripod- and jacket-shaped substructures. Kim et al. (2015) carried out a design load analysis for a 5 MW offshore wind turbine system using various numerical analysis techniques and analyzed the qualitative results. Zwick and Musculus (2015) conducted a study for reducing errors from the input variables of numerical analysis and performing efficient simulations when turbulent winds and irregular waves act on a 5 MW jacket-type offshore wind turbine. Song and Yoo (2017) carried out dynamic response analysis according to the shapes (monopile, jacket, and dolphin) of substructures for a 2.5 MW offshore wind turbine and found that the wave load acting on the jacket-type substructure had the smallest value. Kim et al. (2019) examined a technique for predicting the wake of a wind turbine to remedy the weaknesses of the aerodynamic analysis model of the Fatigue, Aerodynamics, Structures and Turbulence (FAST) program (Jonkman, 2007) developed in the National Renewable Energy Laboratory (NREL) and conducted a study on the optimization of wind turbine arrangements. Tran et al. (2021) conducted a study on the bending performance of a substructure when sea winds, waves, and ocean currents act on a 3 MW jacket-type offshore wind turbine as environmental external forces.

Unlike a land-based wind turbine, a fixed wind turbine installed on the sea has motion responses of the structure by incident waves. Moreover, the motion responses of the wind turbine by combined environmental loads are fairly complex because the incident waves and wind speed act together. The effect of individual environmental loads (incident wave or wind speed) on the structure and motion response characteristics of the structure must be identified for the optimal design and stable operation of the offshore wind turbine. The authors of this paper, however, found only a few studies that analyzed the precise motion response characteristics of fixed wind turbines for individual environmental loads such as incident wave-only effects or wind speed-only effects and combined wave-wind effects.

In this study, therefore, the response characteristics of a 5 MW jacket-type fixed offshore wind turbine for environmental external forces acting on the wind turbine structure, namely, individual environmental loads such as the effects of regular waves and irregular waves (wave loads) or the effects of the presence of winds, wind speed changes, and turbulent winds (wind loads) were systematically analyzed and their features were identified. It is difficult to evaluate the dynamic responses accurately and objectively in strong wind and high wave conditions due to the mixed effects of the environmental loads; therefore, the wind speed, wave height, and wave period were set to small values to precisely analyze the response characteristics of the structure corresponding to each load based on the blade element momentum (BEM) theory. The FAST program of the NREL that is widely used in analysis studies on wind turbines and is expected to derive reliable results was used to obtain time-domain calculation results for each environmental load. These results were converted into frequency responses by fast Fourier transform (FFT) analysis to identify the responses of the structure for the individual environmental loads and analyze their characteristics. The goal of this study is to acquire the basic information required to design and operate a wind turbine by precisely identifying and analyzing the response characteristics of the structure according to the magnitude of each environmental load and whether the effect of the load is dominant.

### 2. Fixed Offshore Wind Turbine

#### 2.1 Fixed Substructure

The substructure of an offshore wind turbine can be either fixed or floating depending on its installation environment conditions. Floating offshore wind turbines are installed on the deep sea, whereas fixed offshore wind turbines are adopted as a more suitable form on shallow coasts. Conventionally, fixed substructures directly supported on the seabed largely fall into four categories monopile, tripod, jacket, and gravity-base (de Vries et al., 2011).

The jacket-type wind turbine substructure considered in this study is fixed on the seabed with piles after connecting thin braces to three or four cylindrical legs in a lattice structure. The load acting on the entire structure is axially distributed through structural members to stably withstand the relatively high vertical and lateral loads. Song and Yoo (2017) found that the jacket-type receives fewer wave loads than the monopile or dolphin types. Moreover, the jacket-type can be installed in relatively deep water up to a water depth of 50 m, whereas the monopile or improved tripod types can be installed only on shallow coasts.

#### 2.2 Load Analysis of Wind Turbine

Aerodynamic and hydrodynamic analysis according to each external force condition are required to conduct the load analysis for an offshore wind turbine. The force applied to the tower of the wind turbine is an aerodynamic external force created by wind. The BEM theory using the blade element momentum is applied to calculate the speed and load acting on the wind turbine rotors according to the wind speed, rotor rotation speed, and pitch angle (Agarwal and Manuel, 2008). The generalized dynamic wake (GDW) was developed for the aerodynamic analysis of high-speed blades such as helicopters (Peters et al., 1989; Suzuki, 2000; Kim et al., 2019). In this study, the results were derived by applying wind speeds below the rated speed to accurately identify the response characteristics of a wind turbine by the wind. Therefore, the BEM results were used for the aerodynamic analysis of slowly moving blades and were compared with the GDW results suitable for high-speed rotation to determine their difference.

The BEM theory, developed by Glaue in 1935, is based on normal flow, namely non-turbulent flow, and assumes that all annular shapes are independent (Fenu et al., 2020). The BEM theory finely divides a blade into element units and then calculates the lift ($dL$, N) and drag ($dD$, N) forces applied to the two-dimensional airfoil of each element to calculate the force and moment applied to the entire wind turbine using the sum of longitudinal forces (Faltinsen, 1993). The force acting on the blade can be obtained using the induced velocity vector...
of the cross-section of the blade in the momentum conservation equation based on the momentum and angle, and the torque and power applied to the rotor shaft based on the force acting on the blade (Snel, 2003). The relative velocity \( V_{rel} \) can be separated and expressed as follows.

\[
V_{rel} = V_y + \omega x
\]
\[
V_{rel} = V_z
\]

where \( x \) is the vertical direction with respect to the rotational axis of the rotor and \( z \) is the longitudinal direction of the blade. \( \omega \) represents the angular velocity of the rotor, and the angle of attack \( (\alpha) \) and inflow angle \( (\phi) \) on the airfoil plane in Fig. 1 can be expressed as in the following equations using the torsional angle \( (\theta) \) and pitch angle \( (\theta_p) \) (Burton et al., 2001).

\[
\alpha = \phi - (\theta + \theta_p)
\]
\[
\phi = \tan^{-1} \frac{V_{rel,x}}{V_{rel,y}}
\]

Finally, the thrust \( (dT, N) \) that is applied to the blade element and obtained by numerical calculation can be expressed as in Eq. (5), and the torque \( (dQ, N \cdot m) \) can be expressed as in Eq. (6) based on the horizontal force \((dH, N)\), where \( \rho \) is the air density \((kg/m^3)\), \( V_{ref} \) is the wind speed \((m/s)\), \( B \) is the number of blades, \( r \) is the distance \((m)\) from the hub to the blade sector, \( c \) is the chord length, and the lift coefficient \( c_l \) and drag coefficient \( c_d \) are dimensionless coefficients of the airfoil associated with the Reynolds number (Lanzafame and Messina, 2007).

\[
dT = \frac{1}{2} \rho V_{ref}^2 c_l(c_s \cos \phi + c_p \sin \phi) dx
\]
\[
dQ = rdH = \frac{1}{2} \rho V_{ref}^2 c_d \sin \phi - c_p \cos \phi) cr dr
\]

An external force that is hydrodynamically created has a horizontal incident wave force applied to the vertical substructure of the offshore wind turbine; this force consists of the inertial force by the acceleration of wave particles, the drag force by boundary conditions, and the frictional force. Morison’s equation as in Eq. (7) was used to numerically calculate the wave loads applied to slender bodies with smaller structure diameters than the wavelength, namely, structures whose diffraction parameter is smaller than 0.2 (Morison et al., 1950; Wei et al., 2014).

\[
F = F_d + F_i = \frac{1}{2} \rho C_d A u^2 + \rho C_m \frac{dH}{dt}
\]

where \( C_d \) is the drag coefficient and \( C_m \) is the inertial coefficient. The load of a fixed structure created by accelerating the fluid particles is expressed as an inertial force as in Eq. (8).

\[
dF_i = \rho C_m \frac{\pi D^2}{4} \frac{du}{dt}
\]

The wave load by Morison’s equation that considers the wave elevation \( \eta \) and water depth \( d \) can be obtained using the water particle velocity \( u \) as in Eq. (9) below.

\[
F = \int_{-d}^{\eta} \rho C_m \frac{\pi D^2}{4} \frac{du}{dt} dz + \int_{-d}^{\eta} \rho C_d \frac{\pi D^2}{4} dz
\]

3. Calculation Results and Analysis

3.1 Numerical Analysis

FAST v.8.16.00a-bjj, an open-source code program, was used in our numerical analysis. A 5 MW offshore wind turbine was modeled by referring to the NREL reference model. The jacket OC4 (offshore code comparison collaboration continuation) project structure, one of the fixed models that can meet the characteristic and environmental conditions of the seas around Korea, was applied to the substructure. The system components of the FAST program are illustrated in Fig. 2.

Six module programs were used for the fixed wind turbine simulation analysis, and AeroDyn was used for the wind load...
calculation. The analysis code, AeroDyn, calculates the aerodynamic loads of the tower and blades, considering a wind speed and wind direction inputted via InflowWind in a BEM-based wind force analysis mode (Jonkman et al., 2015). The two-dimensional force and moment of each node were calculated as distributed loads per unit length, and the sum of these loads was used to calculate the three-dimensional aerodynamic load of the horizontal axis applied to the entire tower in the time domain. The unit wind speed acting on the blades or tower nodes is determined as in Eq. (10) below (Moriarty and Hansen, 2005; IEC, 2019).

\[
V(z) = V_{hub} \left( \frac{z}{z_{hub}} \right)^{\alpha}
\]

(10)

where \( V(z) \) is the wind speed at a point where the vertical displacement from the mean water level is \( z \). \( V_{hub} \) represents the wind speed at the hub height \( z_{hub} \). The hub height of the NREL 5 MW wind turbine used as a calculation model in this paper is 90 m. \( \alpha \) represents the wind shear index indicating an abrupt change in the wind speed or direction. The international standard for designing fixed wind turbines recommends that an \( \alpha \) value of 0.14 be used (IEC, 2019), but this value is set to 0 in this study to linearly increase the wind speed from the water surface.

The hydrodynamic load applied to the substructure (jacket) of the wind turbine is calculated using HydroDyn, an independent analysis module for calculating hydrodynamic loads based on the maritime information of an inputted region such as the wave height, wave period, and waveform (regular wave or irregular wave) (Jonkman et al., 2014). The calculation for wave motion was done in the area between the still water level and flat seabed, whereas the dynamic load analysis for each substructure node within the corresponding area was carried out in the time domain. The governing equation of motion used for the analysis is given as Eq. (11) below. \( M \) and \( K \) are global matrices consisting of the element unit mass matrix and stiffness matrix of the substructure, respectively. \( U \) represents the displacement and \( F \) is the external force (Damiani et al., 2015).

\[
[M](\ddot{U}) + [C](\dot{U}) + [K]U = F
\]

(11)

The three-direction displacement (x-axis direction displacement, x-z-direction rotational displacement, and z-direction vertical displacement) of the fixed wind turbine was designated as the main motion response for analyzing the calculation results because this motion response is most affected by winds and waves entering in the x-direction. It is also important to examine the rotor rotation speed and

| Property                  | Specification                  |
|--------------------------|--------------------------------|
| Rated power              | 5 MW                           |
| Rotor orientation, Configuration | Upwind, 3 Blades, 61.5 m length |
| Rotor, Hub diameter      | 126 m, 3 m                     |
| Hub height               | 90 m                           |
| Cut-in Vin, Rated, Cut-out Vout wind speed | 3 m/s, 11.4 m/s, 25 m/s |
| Cut-in, Rated rotor speed | 6.9 rpm, 12.1 rpm              |
| Drivetrain concept       | Geared                         |
| Gearbox ratio            | 97.1                           |
| Overhang, Shaft tilt, Precone | 5 m, 5°, 2.5°      |
| Rotor mass               | 110,000 kg                     |
| Nacelle mass             | 240,000 kg                     |
| Tower mass               | 347,460 kg                     |
| Tower base diameter      | 6 m                            |
| Tower top diameter       | 3.87 m                         |
| CM location              | -0.2 m, 0.0 m, 64.0 m          |
| Control system           | Variable-speed & Collective pitch |
thrust determined according to the effect of the wind and the nacelle acceleration directly connected to the actual power generation efficiency of the wind turbine. Another important result to be analyzed in this study is the bending moment of the base connection of the tower created by fore-aft shearing loads, the largest force acting on the turbine. Lastly, the effects of the wind and wave forces were compared by checking the shear force in the x-direction to identify changes in the force applied to the jacket. Specific information on the model used in this study is described through Table 1 and Figs. 3-4.

Fig. 5 shows the results of comparing the rotor power and thrust according to the wind speeds by various analysis methods. The FAST analysis results of Kim et al. (2015) were compared to verify the FAST calculation results of the fixed 5 MW offshore wind turbine mentioned above. The calculation results overall matched the previous results. The BEM results of the same analysis program (FAST) are very close, and the GDW results suitable for high-speed rotation as in a helicopter are fairly close except for the wind speed of 11 m/s. The CFD results deviate from the rest owing to computational differences caused by the absence of information on some input values and model configuration differences caused by the different analysis programs.

The analysis model is for 5 MW turbines, hence, the rotor power rapidly increases up to 11 m/s and tends to converge to 5 MW after that. It can be inferred that the model has the highest efficiency at the
wind speed of 11 m/s because the thrust is the largest at the corresponding wind speed. The application of GDW analysis is recognized as a general method for reducing errors to carry out numerical analysis that considers the abnormal characteristics of wind because such characteristics are severe in extreme design wind speed conditions; however, the wind speed, wave height, and wave period were set to low values to precisely analyze the response characteristics of the tower according to the input values based on the BEM theory because the effects of environmental factors are mixed in such analysis under strong wind and high and rough wave conditions, which makes it difficult to objectively conduct accurate response analysis.

3.2 Design Load Case
Various design load cases (DLCs) were selected as in Table 2 and the analysis was carried out to identify the response characteristics according to the wind speed and wave state of the 5 MW fixed jacket-type offshore wind turbine. DLCs 1-5 were examined to check the natural response characteristics of the fixed wind turbine, and DLCs 6-9 were selected and examined to identify the effects in the load conditions where waves and winds are combined.

To analyze the cases, constant speeds ($V_{\text{Steady}}$) were inputted for steady winds, and the results calculated by turbulent wind simulations with designated speeds ($V_{\text{Turbulence}}$) were used as input values for the turbulent winds. The wind speeds were set based on the point of the hub height of 90 m. In the windless scenario (DLC 1), the wind turbine was in a parked condition and the analysis was carried out in the state where the rotors were fixed. The fixed wave height and wave period values were inputted for regular incident waves, and the significant wave height $H_s$ and peak period $T_p$ were designated by applying the JONSWAP spectrum for irregular incident waves.

In DLCs 1-5, to check the natural response characteristics, regular waves or steady winds were applied to carry out numerical analysis on single loads for 1,000 s, and the time series results were used for the last 100 s, considering the transient effect. In DLCs 6-9 in which combined loads, irregular waves, and turbulent winds are applied, the numerical analysis was carried out for one hour (3,600 s) to derive more precise interrelations and reliable results; FFT analysis was carried based on the results of the last 300 s, and the time step of each case was set to 0.01 s. There was little difference in the results although the FFT analysis interval was extended to a maximum of 1 h. The graphs of the results of the cases were generated and comparative analysis was carried out by extracting the time series results of the latter half to remove the transient interval, minimize convergence value variability, and increase the legibility of the time series and frequency data trend.

3.3 Analysis of Calculation Results

3.3.1 Wave Only Case
The incident wave with a six-second period (0.17 Hz) was substituted in a windless state to identify the response characteristics of the wind turbine structure for the incident wave. In Fig. 6, the response frequencies of the horizontal displacement, vertical displacement, $x$-$z$-direction rotational displacement, and jacket shear force of the structure match the wave frequency of 0.17 Hz, and the thrust, nacelle acceleration, and bending moment have the same frequency response as the wave frequency in the windless state. There is also a response at 0.32 Hz, which represents the natural frequency of the analysis model as reported by Jonkman et al. (2009). Therefore, the tower of the wind turbine has a considerable response in the natural frequency band even in the windless state simply by the effect of the incident wave.

Fig. 7 compares the changes in the bending moment of the base connection of the tower according to different incident wave conditions (DLCs 1-3) to examine the response changes of the wind turbine structure according to the incident wave height and wave period changes. The response frequency point changes to 0.17 Hz and 0.13 Hz (1/7.5 s) with wave periods of 6 and 7.5 s, respectively. Fig. 7 (right) also shows that the bending moment response of the tower base is rapidly amplified as a result of setting the incident wave period to 3 s (near the natural frequency of the model) to accurately analyze the response of the bending moment because the response of the bending moment was considerable even in the band of the natural frequency (0.32 Hz) as mentioned above in connection with Fig. 6. Although the wave height increased from 2 m to 4 m, a large response was absent, but a large impact was created when the incident wave period matched

| Case | Description | Waves | Wind | Turbine condition |
|------|-------------|-------|------|-------------------|
| 1    | Regular wave | Reg., $H = 2.0$ m, $T = 6.0$ s | - | Parked |
| 2    | Regular wave | Reg., $H = 2.0$ m, $T = 3.0$ s | - | Parked |
| 3    | Regular wave | Reg., $H = 4.0$ m, $T = 7.5$ s | - | Parked |
| 4    | Steady wind | - | Steady, $V_{\text{Steady}} = 6.0$ m/s | Operating |
| 5    | Steady wind | - | Steady, $V_{\text{Steady}} = 12.0$ m/s | Operating |
| 6    | Operational | Reg., $H = 2.0$ m, $T = 6.0$ s | Steady, $V_{\text{Steady}} = 6.0$ m/s | Operating |
| 7    | Operational | Reg., $H = 2.0$ m, $T = 6.0$ s | Turb., $V_{\text{Turbulence}} = 6.0$ m/s | Operating |
| 8    | Operational | Irreg., $H_s = 2.0$ m, $T_p = 6.0$ s | Steady, $V_{\text{Steady}} = 6.0$ m/s | Operating |
| 9    | Operational | Irreg., $H_s = 2.0$ m, $T_p = 6.0$ s | Turb., $V_{\text{Turbulence}} = 6.0$ m/s | Operating |
the natural frequency band of the structure.

3.3.2 Wind Only Case

The wind speed (6 m/s) below the rated speed was substituted to identify the response characteristics of the 5 MW jacket-type wind turbine structure by the wind while the structure was not affected by the wave (Fig. 8). All responses of the tower and jacket were maximum at 0.39 Hz (rpm = 7.88/60 s × 3 blades) corresponding to a frequency increase by the number of blades caused by the rotation of each blade at the rotor rotation speed (7.88 rpm) output by the wind speed (6 m/s). Therefore, the response of the wind turbine structure by the wind is closely related to the rotor rotation. The vertical displacement of the structure is quite small and converges to 0 even in the time series results; thus, it can be inferred that the vertical displacement caused by the wind is absent in the fixed wind turbine structure.

The results of DLCs 4 and 5 are compared in Fig. 9 to identify changes in the response characteristics of the structure caused by wind speed changes. The rotating speed of the rotor is derived by the steady wind in the absence of incident waves, which causes a response at the frequency increased by the number of blades. The maximum response of the thrust occurs at the frequency of 0.39 Hz resulting from
multiplying the rotor rotation speed (7.88 rpm) by the number (3) of blades with the wind speed of 6 m/s and frequency of 0.61 Hz (rpm = 12.1/60 s × 3 blades) resulting from multiplying 12.1 rpm by the number (3) of blades with the wind speed of 12 m/s. Similar to the thrust, the shear force applied to the jacket is also significantly affected by the wind. Additionally, as the wind speed increases two folds from 6 m/s to 12 m/s, the thrust and shear force increase approximately three folds. The wind speed of 12 m/s also caused a weak response at the natural frequency (0.32 Hz) of the wind turbine structure (green circle). This means that the response of the structure also occurs in the natural frequency band from the increasing force acting on the structure as the wind speed increases.

### 3.3.3 Response to Combined Wind and Wave Case

In the previous section, the effect of the incident wave on the response of the fixed jacket-type wind turbine structure and the effect on the wind were identified. Based on this finding, the response characteristics of the structure are to be evaluated in an environmental load where the incident wave and wind are mixed. First, the steady wind speed ($V_{\text{steady}}$) and turbulent wind speed ($V_{\text{Turbulence}}$) of 6 m/s were

**Fig. 8** Response to DLC #4, steady wind only (No wave, $V_{\text{steady}} = 6$ m/s)

**Fig. 9** Comparison of rotor thrust and shear force on jacket for DLC #4 & #5, steady wind only cases
substituted in the regular wave condition \((H = 2 \text{ m}, T = 6 \text{ s})\) in Fig. 10 to compare the response changes in the difference between the steady wind and turbulent wind in the regular incident wave condition (DLCs 6 and 7). The turbulent wind spectrum is dominant at a low frequency in comparison to the incident wave frequency, and the frequency change from a Fourier analysis is 0 because a constant-speed wind was inputted for the steady wind.

The shear force applied to the jacket was predominantly affected by the incident wave in a condition where the same regular wave entered (period: 6 s, frequency: 0.17 Hz), and the effect of the turbulent wind was approximately 8% in comparison to the maximum response at the corresponding point in the low-frequency interval (green circle). A small response of approximately 13% was also derived at the frequency of 0.39 Hz \((\text{rpm} = 7.8/60 \text{ s} \times 3 \text{ blades})\) by the rotor rotation speed (7.8 rpm) and the number of blades at a wind speed of 6 m/s. This is because the same frequency as the rotor blade rotation frequency verified in the previous results, is included in the frequencies of the turbulent wind. However, the bending moment in the tower base has a small response of approximately 14% at the incident wave frequency of 0.17 Hz in comparison to its maximum frequency response. However, it has a maximum frequency response at the frequency of 0.39 Hz by the low-frequency interval affected by the turbulent wind and rotor rotation. Therefore, the bending moment in the tower base has a considerable response in the frequency (0.39 Hz) band by the low-frequency interval of the turbulent wind, the natural frequency (0.32 Hz) of the structure, and the rotor rotation.

Fig. 11 compares the response characteristics of the bending moment and shear force when the steady wind (6 m/s) and turbulent wind are applied in a condition where the same irregular wave enters (DLCs 8 and 9). The shear force has a high response at a low frequency of the turbulent wind spectrum, the peak frequency of the irregular wave, and the frequency of 0.39 Hz by the rotor rotation speed; it has its maximum response at the peak frequency region (0.1–0.2 Hz) of the irregular wave regardless of the form of wind. As verified by the regular wave condition in Fig. 10, the shear force of the jacket is predominantly affected by the incident wave. However, because the significant wave height (average of top 1/3 wave heights) is applied to the irregular wave, a wide response spectrum results in approximately 0.17 Hz and the maximum response is reduced to approximately 1/4 in comparison to the regular wave, to be similar to the response by the turbulent wind. Similar to Fig. 10, the bending moment response of the tower base is slightly affected by the incident wave and is
Fig. 11 Comparison of shear force on jacket and tower bending moment for DLC #8 & #9, irregular wave with different wind types.

Fig. 12 Response to DLC #9, combined wind and wave condition ($H_s = 2.0$ m, $T_p = 6.0$ s, $V_{turbulence} = 6$ m/s).
predominantly affected by the wind, judging from the maximum response in the low-frequency region of the turbulent wind spectrum and the frequency region of the rotor rotation speed.

In Fig. 12, the overall response characteristics of the structure for the irregular incident wave were identified in the turbulent wind speed \((V_{\text{Turbulence}} = 6 \text{ m/s})\) condition. All the responses of the analysis model are affected by the low-frequency turbulent wind speed. The vertical displacement is relatively less affected because the wind turbine is a fixed structure. The shear force of the jacket and vertical displacement have their maximum responses at the incident wave peak frequency (period of 6 s, 0.17 Hz), which means that they are significantly affected by the incident wave. However, the horizontal displacement and \(x-z\)-direction rotational displacement of the structure have their maximum responses near 0.4 Hz outside the low-frequency region, which indicates that they are predominantly affected at a frequency of 0.39 Hz (rpm = 7.8/60 s × 3 blades) resulting from multiplying the rotor rotation speed frequency by the number of blades at the inputted wind speed \((V_{\text{Turbulence}})\) of 6 m/s. The shear force also has a large value at the same frequency.

The rotor rotation speed and thrust have dominant responses in the same low-frequency region by the application of the turbulent wind spectrum. Particularly, the rotor rotation speed is expressed with a spectrum of a very slow long waveform by the turbulent wind speed \((V_{\text{Turbulence}})\) of 6 m/s. The nacelle acceleration has its maximum response at 0.39 Hz resulting from multiplying the rotor rotation speed of 7.8 rpm by the number of the blades. The bending moment of the tower has a large response at the frequency (0.39 Hz) by the rotor rotation and low-frequency region of the turbulent wind spectrum and shows a trend similar to the \(x-z\)-direction rotational displacement response, which shows a correlation between the bending moment and rotational displacement.

Therefore, all the responses of the jacket-type wind turbine are affected by the low frequency of the turbulent wind spectrum. Particularly, the horizontal displacement, rotational displacement, nacelle acceleration, and bending moment are significantly affected at the frequency (0.39 Hz) by the rotor rotation from the wind. The effect of the incident wave frequency is dominant in the vertical displacement of the structure. The shear force of the jacket is predominantly affected in all the frequency regions above.

### 4. Conclusions

In this study, the dynamic response characteristics corresponding to each environmental external force of a 5 MW fixed jacket-type offshore wind turbine model were analyzed. The characteristics of the frequency responses were compared by analyzing the FFTs of the time series results calculated using the FAST program. The motion responses of the analysis model were analyzed by applying single environmental conditions such as an incident wave-only condition and a wind-only condition to identify the characteristics of the motion responses of the analysis model. The external force that predominantly affects the combined load was identified.

1. In the incident wave-only condition, the motion response and load response of the wind turbine structure were dominant at the wave frequency; the rotor thrust, nacelle acceleration, and bending moment of the tower base had high responses in the natural frequency band of the structure.

2. In the wind-only condition, all the responses except for the vertical displacement of the structure were dominant at the frequency resulting from multiplying the rotor rotation frequency caused by the wind and number of blades.

3. In a combined external force where the wind and wave are simultaneously applied, the vertical displacement of the structure was mainly affected by the incident wave; the shear force applied to the jacket was affected by both the wind and incident wave; the bending moment in the tower base was predominantly affected by the wind.

The response analysis results of the fixed offshore wind turbine according to the wind and wave that were obtained in this study are expected to help in deriving more suitable models for installation in sea areas and developing improved designs by response performance comparison with different types of fixed or floating substructures in the future. It is difficult to state that the FAST program used in this study always derives accurate analysis results. However, it is currently widely used in areas related to wind turbine analysis, is open source code, and is useful in identifying the overall trend of the motion response of a structure.

### Funding

This study was supported by grants of the Korean-English Offshore Plant Global Expert Training Project of the Ministry of Trade, Industry and Energy and the Korea Institute for Advancement of Technology and Technology Study Abroad of Daewoo Shipbuilding Engineering Co., Ltd. This study was also supported by a grant of the Basic Research Project in Science and Engineering Areas of the National Research Foundation of Korea (NRF-2018R1D1A1B07040677).

### References

Agarwal, P., & Manuel, L. (2008). Extreme Loads for an Offshore Wind Turbine Using Statistical Extrapolation from Limited Field Data. Wind Energy, 11(6), 673–684. https://doi.org/10.1002/we.301

Burton, T., Sharpe, D., Jenkins, N., & Bossanyi, E. (2001). Wind Energy Handbook. New York: Wiley.

Damiani, R., Jonkman, J., & Hayman, G. (2015). SubDyn User's Guide and Theory Manual (Technica Report NREL/TP-5000-63062). USA: National Renewable Energy Laboratory. https://doi.org/10.2172/1225918

de Vries, W., Vermula, N.K., Passon, P., Fischer, T., Kaufer, D., Matha,
D., & Vorpalh, F. (2011). Final Report WP4.2: Support Structure Concepts for Deep Water. (UpWind_WP4_D4.2.8).

Faltinsen, O. (1993). Sea Loads on Slips and Offshore Structures. USA: Cambridge University Press.

Fenu, B., Attanasio, V., Casalone, P., Novo, R., Cervelli, G., Bonfanti, M., & Mattiazzo, G. (2020). Analysis of a Gyroscopic-Stabilized Floating Offshore Hybrid Wind-Wave Platform. Journal of Marine Science and Engineering, 8(6), 439. https://doi.org/10.3390/jmse8060439

International Electrotechnical Commission (IEC). (2019). Wind Energy Generation Systems – Part 3-1: Design Requirements for Fixed Offshore Wind Turbines (IEC 61400-3-1). IEC.

Jang, J.S., & Sohn, J.H. (2011). Analysis of Dynamic Behavior of Floating Offshore Wind Turbine System. Transactions of the Korean Society of Mechanical Engineers A, 35(1), 77-83. https://doi.org/10.3795/KSMA-A.2011.35.1.077

Jeong, S.M., Oh, U.G., Lee, Y.C., Lim, J.T., Lee, K.B., & Choi, J.S. (2020). A Study on the Evaluation of the Economics and Environmental Contribution to the Jeju Power System from Tamla Offshore Wind Farm. The Transactions of The Korean Institute of Electrical Engineers, 69(7), 955-963. https://doi.org/10.5370/KIEE.2020.69.7.955

Jonkman, J.M. (2007). Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine (Technicla Report NREL/TP-500-41598). USA: National Renewable Energy Laboratory.

Jonkman, J.M., & Buhl, Jr., M.L. (2005). FAST User’s Guide (Technical Report, NREL/EL-500-38230). USA: National Renewable Energy Laboratory.

Jonkman, J.M., Butterfield, S., Musial, W., & Scott, G. (2009). Definition of a 5-MW Reference Wind Turbine for Offshore System Development (NREL/TP-500-38060). USA: National Renewable Energy Laboratory.

Jonkman, J.M., Hayman, G.J., Jonkman, B.J., Damiani, R.R., & Murray, R.E. (2015). AeroDyn v15 User’s Guide and Theory Manual. USA: National Renewable Energy Laboratory.

Jonkman, J.M., Robertson, A., & Hayman, G.J. (2014). HydroDyn User’s Guide and Theory Manual. USA: National Renewable Energy Laboratory.

Kim, H.K., Han, W.S., & Lee, S.G. (2019). Wind Farm Layout Optimization Considering Dynamic Characteristic of Floating Wind Turbine. New & Renewable Energy, 15(3), 1-10. https://doi.org/10.7849/knrenee.2019.9.15.3.001

Kim, K.H., Kim, D.H., Kwak, Y.S., & Kim, S.H. (2015). Design Load Case Analysis and Comparison for a 5MW Offshore Wind Turbine Using FAST, GH Bladed and CFD Method. The KSFM Journal of Fluid Machinery, 18(2), 14-21. https://doi.org/10.5293/kfma.2015.18.2.014

Lanzaflame, R., & Messina, M. (2007). Fluid Dynamics Wind Turbine Design: Critical Analysis, Optimization and Application of BEM Theory. Renewable Energy, 32(14), 2291-2305. https://doi.org/10.1016/j.renene.2006.12.010

Li, L., Gao, Y., Hu, Z., Yuan, Z., Day, S., & Li, H. (2018). Model Test Research of a Semisubmersible Floating Wind Turbine with and Improved Deficient Thrust Force Correlation Approach. Renewable Energy, 119, 95-105. https://doi.org/10.1016/j.renene.2017.12.019

Moriarty, P.J., & Hansen, A.C. (2005). AeroDyn Theory Manual (NREL/TP-500-36881). USA: National Renewable Energy Laboratory. https://doi.org/10.2172/15014831

Morison, J., Johnson, J., & Schaaf, S. (1950). The Force Exerted by Surface Waves on Piles. Journal of Petroleum Technology, 2, 149-154. https://doi.org/10.2118/950149-G

Oh, H.T., Yeo, M.Y., Jung, H.E., & Shim, J.M. (2020). Status and Improvement of Environmental Impacts Assessment on the Marine Endangered Species Around the Coastal Area of Offshore Wind Energy – Case Study of the Marine Mammals and Sea Birds. Journal of fisheries and Marine Sciences Education, 32(6), 1428-1444. https://doi.org/10.13000/JFMSE.2020.12.32.6.1428

Peters, D.A., Boyd, D.D., & He, C.J. (1989). Finite-State Induced-Flow Model for Rotors in Hover and Forward Flight. Journal of the American Helicopter Society, 34(4), 5-17. https://doi.org/10.4491/KSEE.2021.43.3.196

Popko, W., Vorpalh, F., Zuga, A., Kohlmeier, M., Jonkman, J., Robertson, A., ... & von Waaden, H. (2012). Offshore Code Comparison Collaboration Continuation (OC4), Phase I-Results of Coupled Simulations of an Offshore Wind Turbine with Jacket Support Structure. In The Twenty-second International Offshore and Polar Engineering Conference, Rhodes, Greece, ISOPE-I-12-117.

Shi, W., Park, H.C., Chung, C.W., & Kim, Y.C. (2011). Comparison of Dynamic Response of Monopile, Tripod and Jacket Foundation System for a 5-MW Wind Turbine. In The Twenty-first International Offshore and Polar Engineering Conference, Maui, Hawaii, USA, ISOPE-I-11-266.

Snel, H. (2003). Review of Aerodynamics for Wind Turbines. Wind Energy, 6(3), 203-211. https://doi.org/10.1002/we.97

Song, C.Y., & Yoo, J. (2017). Dynamic Response Analyses of Fixed Type Substructures for 2.5 MW Class Offshore Wind Turbine. Journal of Advanced Research in Ocean Engineering, 3(1), 15-24. https://doi.org/10.5574/JAROE.2017.3.1.015

Suzuki, A. (2000). Application of Dynamic Inflow Theory to Wind Turbine Rotors (Ph. D. thesis). University of Utah.

Tran, T.T., Kang, S., Lee, J.H., & Lee, D. (2021). Directional Bending Performance of 4-Leg Jacket Substructure Supporting a 3MW Offshore Wind Turbine. Energies, 14(9), 2725. https://doi.org/10.1016/j.renene.2006.12.010
Wei, K., Sanjay, R.A., & Myers, A.T. (2014). Incremental Wind-Wave Analysis of the Structural Capacity of Offshore Wind Turbine Support Structures under Extreme Loading. Engineering Structures, 79, 58-69. https://doi.org/10.1016/j.engstruct.2014.08.010

Zwick, D., & Muskulus, M. (2015). The Simulation Error Caused by Input Loading Variability in Offshore Wind Turbine Structural Analysis. Wind Energy, 18(8), 1421-1432. https://doi.org/10.1002/we.1767

**Author ORCIDs**

| Author name       | ORCID            |
|-------------------|-----------------|
| Kim, Jaewook      | 0000-0002-7652-7314 |
| Heo, Sanghwan     | 0000-0003-0033-5022   |
| Koo, WeonCheol    | 0000-0002-4384-0996   |