EFFECTS OF MULTIDIRECTIONAL SEA STATES AND FLEXIBLE FOUNDATION ON DYNAMIC RESPONSE OF FLOATING OFFSHORE WIND TURBINE SYSTEM

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One reliable simulation tool was developed to be able to predict dynamic response of Floating Offshore Wind Turbines (FOWTs) to various sea states. To represent real environmental condition in field site, multidirectional wave simulation was carried out in this research to investigate effect of wave spreading on dynamic response of FOWT. On the other hand, effect of tower frequency change due to flexible foundation on fatigue load was studied. It was found that unidirectional assumption is conservative in terms of prediction of dynamic motion of platform and multidirectional sea state should be employed to reach cost-effect design. In addition, when wind turbine is supported by flexible foundation, the change of tower natural frequency will result in significant increase of fatigue load. Therefore, Effect of flexible foundation on tower frequency change needs to be taken into consideration in the design of platform and commercial wind turbine.

Keyword: Floating Offshore Wind Turbines, Simulation tool, Multidirectional sea state, Mooring system, Morison equation

1. INTRODUCTION

Development of floating offshore wind turbines is gaining increasing interest because huge wind potential energy is available offshore and less environmental impact is expected. In the design of floating foundation which supports commercial wind turbine, assessment of various load cases associating with sea state are required for safe concern. In IEC-61400-3[1)], unidirectional wave propagation is suggested if there is no measured directional information on targeted site. Basically, this unidirectional wave assumption will lead to conservative design since multidirectional wave spreading is expected to dissipate wave energy across wave direction and result in decreased motion of floating platform in dominant wave direction. From economic point of view, however, wave spreading is preferred to be taken into account for cost-effective design of floating platform.

Water tank experiment is thought to be one of popular and reliable ways to investigate performance of platform under hydrodynamic load or to validate developed simulation tool[2),3),4),5),6)]. Environmental condition in the water tank test, however, is only limited to simple cases, like wind only, wave only (regular or irregular wave), current only and combinations of those individually environmental conditions. Whereas, much more complex and more realistic environmental condition, such as multidirectional wave and misalignment between wind and wave, however, is difficult to carry out in most of water tanks. In real site, wave energy is actually not only function of wave frequency but also the function of angular wave direction. Figure 1 shows typical wave energy distribution at location 20Km offshore from Fukushima, Japan on 17,Sept,2015. One can easily notice that wave energy has a distribution across a specific wave frequency as well as wave direction. It is usually thorny to replicate this kind of complicated environmental sea states in water tank test, simulation tool with consideration of wave spreading function is one alternative way to study effect of multidirectional wave on dynamic response of FOWT. Description of spreading functions can be found in the research by Longuet-Higgins[7)], Mitsuyasu H[8)], T. Duarte et al.[9)] and Kohlmeier M[10)].

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Another important attention needed to be paid during design of floating platform is elastic impact on evaluation of natural frequency of wind turbine. Figure 2 exhibits variation of dynamic magnification factor versus tower natural frequency[11)]. It can be found that substantial dynamic magnification factor will be experienced and provoke significant fatigue loads in case of the situation that wind turbine natural frequency locates inside of upper and lower blade passing and rotational frequencies. Not like fixed foundation, floating foundation is flexible and will inevitably change the mode shape of wind turbine, which indicates commercial wind turbines might need to be made certain modification to employed in floating platform. Without any modifications, wind turbine which is supported by flexible foundation might encounter significant fatigue load and it might contribute to eventual damage within very short period.

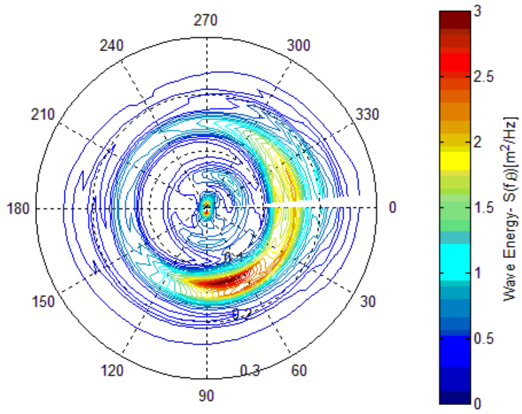


Figure 1: Typical wave energy distribution in Fukushima, Japan on 17,Sept,2015 22:50-23:10

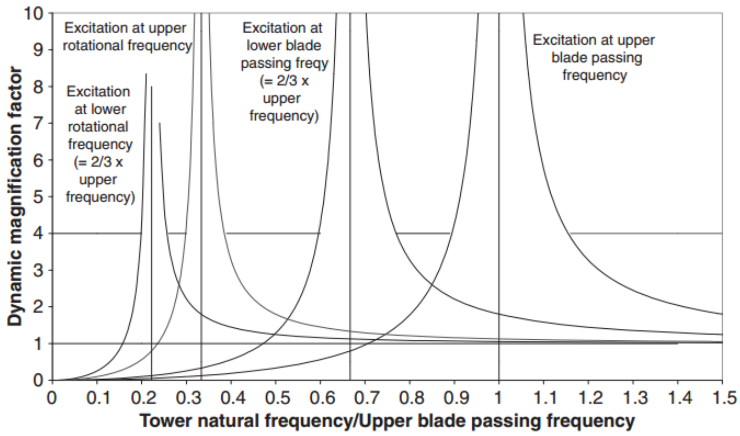


Figure 2: Variation of dynamic magnification factors with tower natural frequency for a two speed, three-bladed

The outline of this paper is as follows. Mathematical model is described in section 2, encompassing hydrodynamic model, wave model and spreading function employed in this research. Section 3 mainly address effect of multidirectional sea states on dynamic response of FOWT. Section 4 aims to discuss impact of change of tower frequency on evaluation of fatigue load. Section 5 gives future work and the paper is finalized with conclusions in Section 6.

2. MATHEMATICAL MODEL

A finite element scheme with beam, truss and spring type elements is developed to calculate dynamic response of full coupled wind turbine, support platform and mooring system. The time domain analysis enables the FEM to efficiently capture nonlinear characteristics of system in sea states. Morison equation is implemented to evaluate hydrodynamic load on platform. Nonlinear restoring load from mooring system of floating platform is estimated from either quasi-static model[12].

(1) Hydrodynamic model

Modified Morison equation is utilized to predict hydrodynamic loads on floating structures. Detailed discussion of improved Morison equation could be found in the research by Z. Shining. and T. Ishihara2[)]. Illustration of force acting on segment of slender cylinders and heave plate is shown in Figure 3.

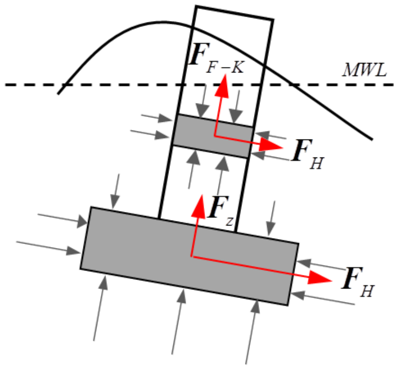


Figure 3: Illustration of hydrodynamic force acting on segment of cylinder and heave plate

a) Normal to axial of segment

The improved Morison equation used in this paper is expressed as following relative form:

$$\{\boldsymbol{F}_H\} = \underbrace{\rho_w \forall \dot{\boldsymbol{u}}}_{Froude-Krylov\ force} + \underbrace{\rho_w (C_M - 1)\forall \dot{\boldsymbol{u}}}_{Diffraction\ force} \underbrace{-\rho_w (C_M - 1)\forall \ddot{\boldsymbol{X}} - [C_{Rdtn}]\dot{\boldsymbol{X}}}_{Radiation\ force} + \underbrace{0.5\rho_w C_d A(\boldsymbol{u} - \dot{\boldsymbol{X}})\left|\boldsymbol{u} - \dot{\boldsymbol{X}}\right|}_{Viscous\ drag\ force} \tag{1}$$

Where, first term in right of Eq. (1) accounts for Froude-Krylov force due to undisturbed incident wave and second term represents diffraction force resulting from pressure effects due to presence of structure. The third terms indicates radiation force (hydrodynamic inertia force and radiation damping force) which is caused by motion of structural components in an ideal fluid. Fourth term gives viscous drag force due to the relative velocity between water particle and structural components. ρ_w is density of water; $\boldsymbol{u}$ and $\dot{\boldsymbol{u}}$ are vector of undisturbed fluid-particle velocity and acceleration respectively; $\{\boldsymbol{X}\}$, $\{\dot{\boldsymbol{X}}\}$ and $\{\ddot{\boldsymbol{X}}\}$ are vector of support platform displacement and their time derivatives; $[C_{Rdtn}]$ is linear radiation damping; $\forall$ is the displaced volume of fluid by each segment when the support platform is in its undisplaced position; A is cross-sectional area; C_M and C_d are inertia and drag coefficient respectively which depends on Keulegan-Carpenter number $K_C = u_{\max} T / D$, frequency parameter $\beta = D^2 / \nu T$ and surface roughness etc. $u_{\max}$ is the maximum water particle velocity, T is incident wave period, D is diameter of cylinder and ν is the kinematic viscosity of water.

b) Axial of segment

In order to effectively increase the hydrodynamic damping in heave direction and reduce heave response[13),14)], appendage such as a disk (heave plate) are usually added to the keel of a vertical cylinder such as the disk chosen in WindFloat and heave plate employed in Fukushima MIRAI15[)]. Ishihara et al.[15)] proposed Morison like equation to evaluate hydrodynamic force on heave plate in axial direction. Hydrodynamic force for a heave plate is formulated using modified Morison equation as given below

$$\{\boldsymbol{F}_z\} = \underbrace{0.25\pi D_h^2 p_b^{Hp} - 0.25\pi(D_h^2 - D_c^2) p_t^{Hp}}_{Froude-Krylov\ force} + \underbrace{\rho_w (C_{Mz} - 1)\forall_z \dot{\boldsymbol{w}}}_{Diffraction\ force} \tag{2}$$

$$\underbrace{-\rho_w (C_{Mz} - 1)\forall_z \ddot{\boldsymbol{X}}_3}_{Radiation\ force} + \underbrace{0.5\rho_w C_{dz} A_C (\boldsymbol{w} - \dot{\boldsymbol{X}}_3)\left|\boldsymbol{w} - \dot{\boldsymbol{X}}_3\right|}_{Viscous\ drag\ force}$$

Where, C_{Mz} is the added mass coefficient in the heave direction, $\forall_z$ is volume of heave plate, $\dot{w}$ is the vertical wave particle acceleration, $\ddot{X}_3$ is acceleration of the heave plate in heave direction, C_{dz} is the drag coefficient in the heave direction, A_C is the cross-sectional area of the heave plat, w is the vertical wave particle velocity, $\dot{X}_3$ is velocity of the heave plate in heave direction, D_h is the diameter of the heave plate, D_c is the diameter of the upper column (which is placed on top of the heave plate), and p_b^{Hp} and p_t^{Hp} are the dynamic pressure acting on the bottom and top faces of the heave plate. Dynamic pressure at position z in regular wave using Airy theory is expressed as follows

$$P = \frac{\rho g H}{2} \frac{\cosh k(z+d)}{\cosh kd} \cos(kx - \omega t) \tag{3}$$

Where, H is wave height (m), ω is wave frequency(rad/s), k is wave number, d is water depth, z is specified position.

To evaluate axial force on the other segments of elements (such as vertical columns, braces and pontoons), only Froude-Krylove force is taken into consideration by integrating dynamic pressure on member ends as follows,

$$\{\boldsymbol{F}_{F-K}\} = 0.25\pi D_c^2 (p_b - p_t) \tag{4}$$

Where, p_b and p_t are the dynamic pressure acting on the bottom and top faces of segment.

(2) Linear irregular wave theory

As for the dynamic response of FOWT to irregular wave in both unidirectional and multidirectional sea state, JONSWAP wave spectra was used in both simulation tool and water tank experiment. The spectrum is given as

$$S(f) = \alpha_* H_S^2 T_P^{-4} f^{-5} \exp\left\{-1.25(T_P f)^{-4}\right\} \gamma^{\exp\left\{-\frac{(T_P f - 1)^2}{2\sigma^2}\right\}} \tag{5}$$

$$\alpha_* = \frac{0.0624}{0.230 + 0.0336\gamma - 0.185/(1.9+\gamma)} \tag{6}$$

Where, f is wave frequency (Hz), H_S is significant wave height, T_P is peak wave period, γ is peak factor (γ =2 is used in this paper) and σ is shape factor ($\sigma = 0.07$ for $f \le (1/T_P)$ and $\sigma = 0.09$ for $f > (1/T_P)$).

(3) Spreading function

The spreading function used in this research is frequency independent cos-2s type implemented in WAFO[16]. Total wave spectrum can be defined as

$$S(\omega, \theta) = S(\omega) \cdot D(\theta) \tag{7}$$

Where, $S(\omega)$ is the frequency spectrum, independent of the direction of the waves, and $D(\theta)$ is the directional spectrum.

$$D(\theta) = \frac{\Gamma(s+1)}{2\sqrt{\pi}\Gamma(s+1/2)} \cos^{2s}\left(\frac{\theta - \theta_p}{2}\right) \tag{8}$$

Where, Γ is the gamma function. θ is the spreading angle, θ_p is the energy peak direction and s is the spreading parameter.

After spreading function $D(\theta)$ is determined, equal-energy method9[)] is used to discretize the wave direction. Then wave elevation can be written in following way

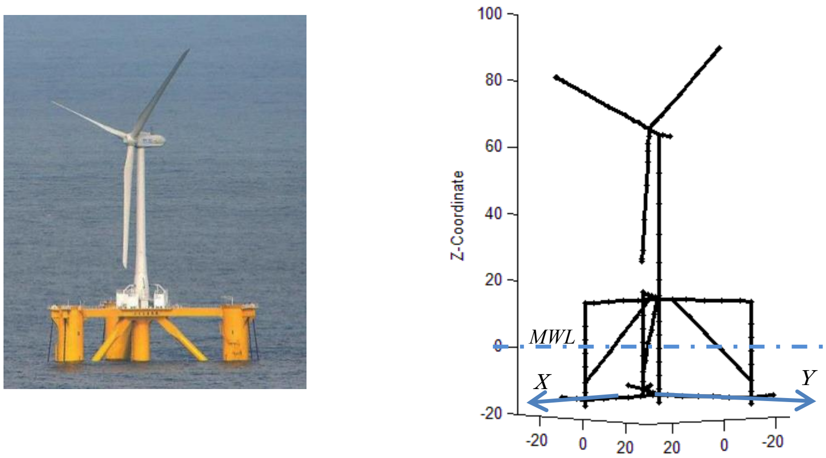
$$\eta = \sum_{n=1}^{N} A_n \cos\left(k_n \left(x\cos(\theta_k) + y\sin(\theta_k)\right) - \omega_n t + \varepsilon_n\right) \tag{9}$$

Where, A_n, k_n, ω_n, ε_n and θ_k are discretized wave height, wave number, wave frequency, random phase and wave direction.

Linear superposition can also be used to compose water particle velocity and acceleration required in Morison equation.

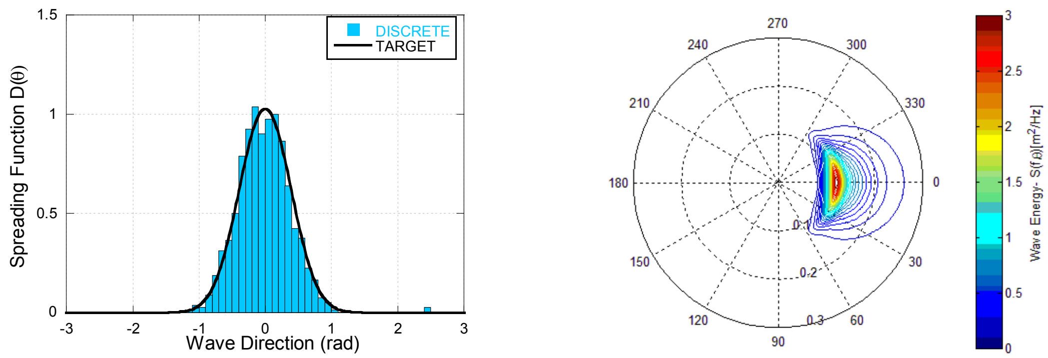
3. DYNAMIC RESPONSE OF FOWT IN MULTIDIRECTIONAL IRREGULAR SEA STATE

In this section, prototype of Fukushima MIRAI 2MW FOWT is established with FEM and dynamic response of floating system is investigated in terms of multidirectional wave spreading effect. Figure 4 shows image of prototype of Fukushima MIRAI and FEM model adoped in numerical simulation. It should be noted that aerodynamic load is excluded in the simulation to classify the solo wave spreading effect. To represent irregular wave, JONSWAP wave spectra with measured significant wave height 3.83m and peak period 8.3sec. is used in this research. Figure 5 illustrates wave spreading function and resulting wave energy distribution across wave frequency and wave direction. Spreading parameter s in Eq.(8) is 13 and dominant wave direction is 0 degree (Y-axis faces to north and wave propagates from west to east). In Figure 5(a), spreading function follows from Eq.(8), it can be concluded that discretized spreading wave direction could represent well for targeted spreading function.



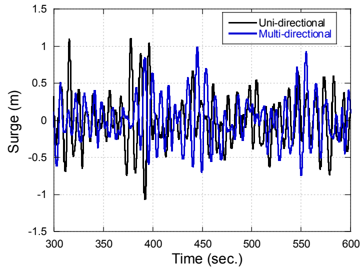
(a) Prototype of Fukushima MARIA (b) FEM model

Figure 4: Image of prototype of (a) Fukushima MARIA and (b)FEM model

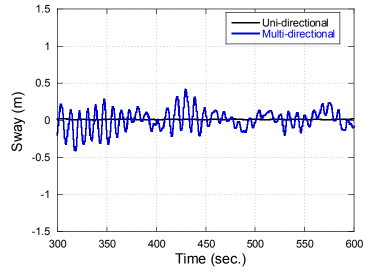


(a) Spreading function (b) Polar plot of wave energy distribution

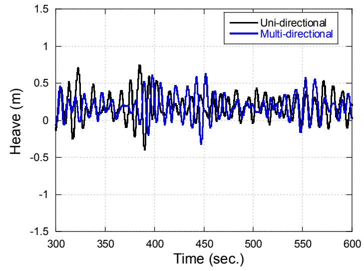
Figure 5: Wave spreading function and total wave energy distribution



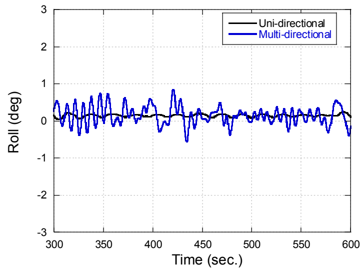
(a) surge motion



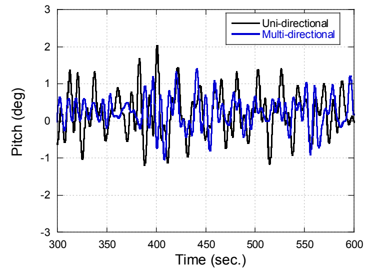
(b) sway motion



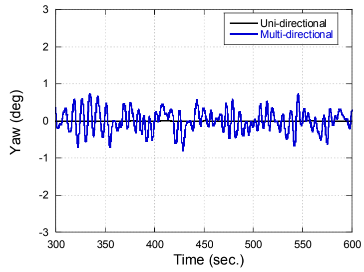
(c) heave motion



(d) roll motion

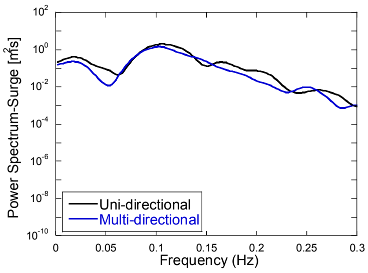


(e) pitch motion

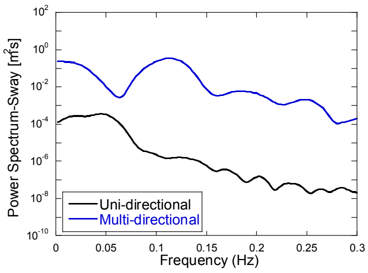


(f) yaw motion

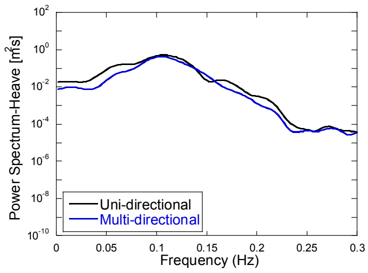
Figure 6: Dynamic motion of platform in unidirectional and multidirectional irregular wave



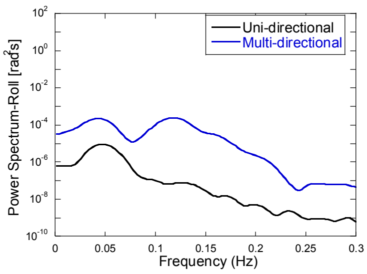
(a) PSD of surge motion



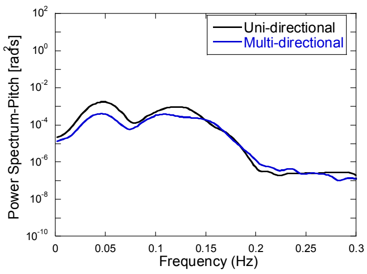
(b) PSD of sway motion



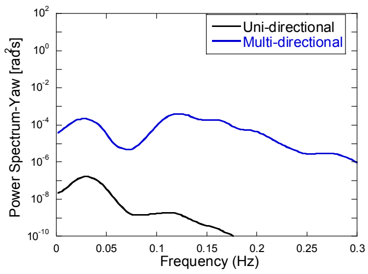
(c) PSD of heave motion



(d) PSD of roll motion



(e) PSD of pitch motion

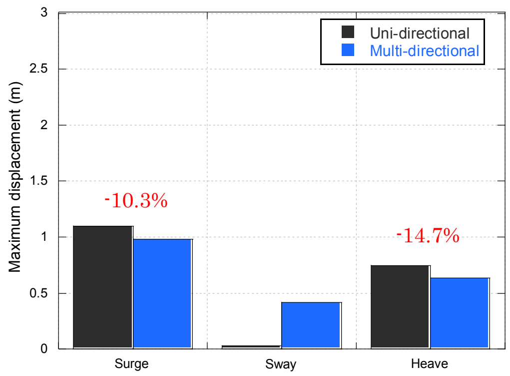


(f) PSD of yaw motion

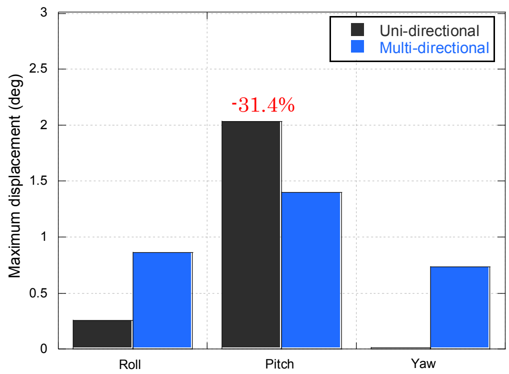
Figure 7: Power spectrum density of dynamic motion of platform in unidirectional and multidirectional irregular wave

Figure 6 provides time history of dynamic motion of platform under unidirectional and multidirectional wave condition within 5mins. It can be found that sway, roll and yaw motion in unidirectional wave condition are almost zero since platform geometry is symmetric about XZ-plane. Significant motion in these three modes, however, are excited in multidirectional sea state since wave is not propagate only in X-axis any more. Dissipation of wave energy over certain angular direction would amplify the motion in sway, roll and pitch direction. At the same time, this wave energy dissipation will decrease surge, heave and pitch motion as expected. Same conclusion can be derived from what shown in PSD of dynamic motion in Figure 7. Two peaks could be found in PSD of the motion, one is same in all modes which corresponds to wave peak period (0.12Hz) and the other one conforms with to natural period of floating system in each mode.

Figure 8 gives maximum of displacement in mentioned two sets of wave directional condition. Maximum surge, heave and pitch motion decrease by 10.3%, 14.7% and 31.4% respectively when wave spreading is taken into account. Considering the recommendation in IEC-61400-3 in terms of unidirectional wave assumption, appropriate evaluation and consideration of wave spreading will bring about cost-effective design.



(a) Max translational motion



(b) Max rotational motion

Figure 8: Maximum of (a) translational displacement and (b) rotational motion in unidirectional and multidirectional sea state

4. EFFECT OF FLEXIBLE FOUNDATION ON TOWER FATIGUE LOAD

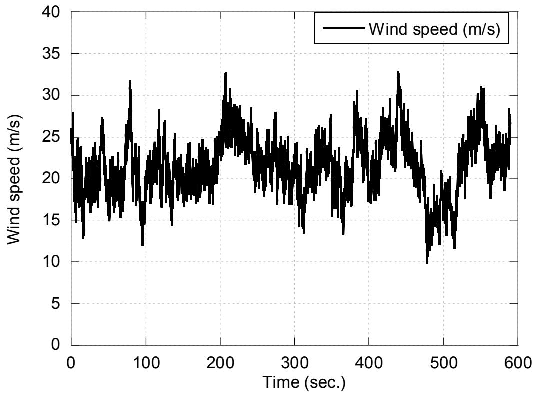
In this section, one 2MW offshore wind turbine will be used to clarify the effect of natural frequency of tower on fatigue load evaluation. One fixed foundation and flexible foundation will be investigated on resulting fatigue load. General characteristics of rotor and turbine are listed in Table 1. Rotor speed is 18rpm and 1P blade passing frequency is 0.3Hz. Information about time dependent wind field is summarized in Table 2. Six 10mins stochastic realizations are conducted to determine the equivalent fatigue load.

Table 1: General characteristics of rotor and turbine

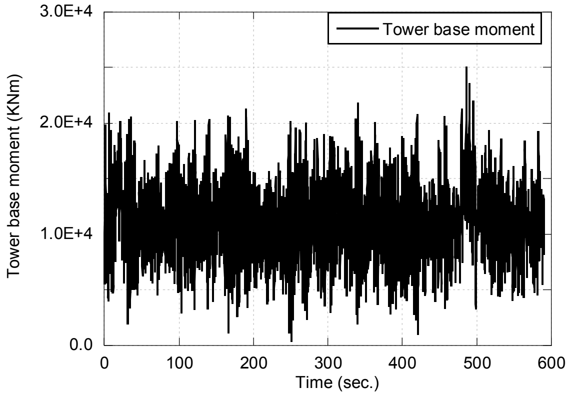
Rotor diameter	80	m
Number of blades	3	
Hub height	61.5	m
Tower height	60	m
Aerodynamic control surfaces	Pitch	
Fixed / Variable speed	Variable	
Cut in wind speed	4	m/s
Cut out wind speed	25	m/s
Rotor speed	18	rpm

Table 2: Time dependent wind field

Wind model type	Turbulent Wind	
Mean wind speed for simulation	21.5	m/s
Wind direction from North	0	deg
Longitudinal turbulence intensity	16.17	%
Lateral turbulence intensity	12.93	%
Vertical turbulence intensity	8.08	%

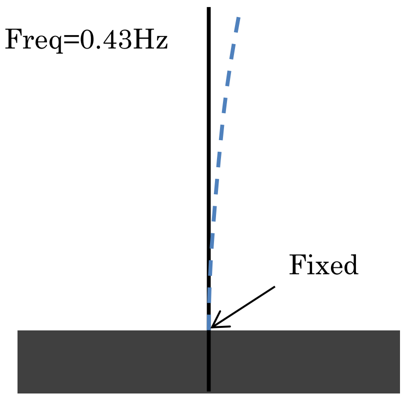


(a) time series of wind speed

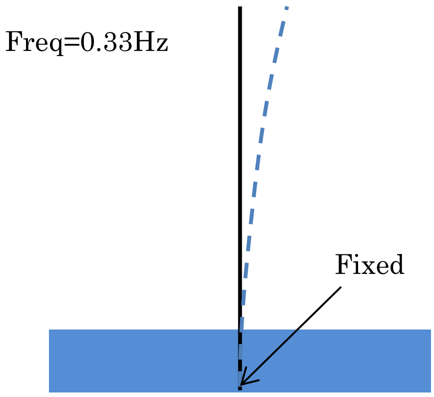


(b) time series of tower base moment

Figure 9: Time series of (a) wind speed and (b) resulting tower base moment in one wind seed



(a) Fixed foundation



(b) Flexible foundation

Figure 10: Mode shape of tower in fixed condition and flexible foundation

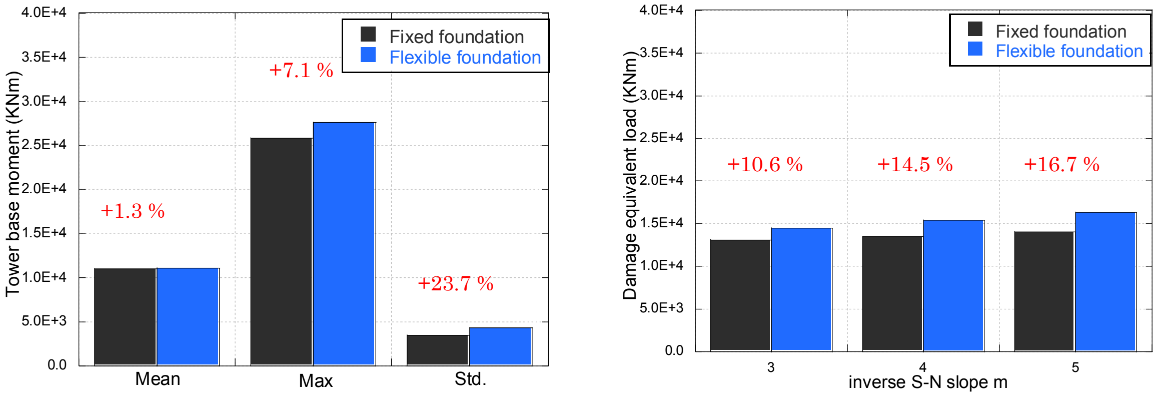
Figure 9 shows one of simulation results in term of turbulent wind and resulting tower base moment. Rainflow cycle counting is used to deal with time history of tower base moment to determine damage equivalent load which would produce the same fatigue damage as the original signal. The equivalent load M_{eq} is defined as follows,

$$M_{eq} = \left(\frac{\sum_i n_i S_i^m}{Tf} \right)^{\frac{1}{m}} \tag{10}$$

Where, n_i is the number of cycles in load range S_i ; T is the duration of the original time history (10mins); m is inverse S-N slopes and f is frequency of equivalent sinusoidal load.

Two types of foundation are shown in Figure 10. One assumes that wind turbine is supported on rigid foundation and natural frequency is 0.43Hz. The other one assumes foundation is flexible and natural frequency is 0.33Hz as a result. It is noteworthy that rotor speed is 18rpm and 1P blade passing frequency is 0.3Hz. Tower natural frequency under condition of flexible foundation is close to this rotational frequency. Consequently, larger dynamic magnification factor is expected when compared with the wind turbine with fixed foundation.

Figure 11 depicts statistics of tower base moment and evaluated damage equivalent load. In figure (a), one can find maximum and standard deviation of tower base moment increase by 7.1% and 23.7 respectively in case of flexible foundation. Damage equivalent load in fixed and flexible foundation with respect to various inverse S-N slope m is shown in Figure 11(b). One can conclude that equivalent load increase by at least 10.6% in case of flexible foundation with m=3.



(a) Tower base moment statistics (b) Damage equivalent load

Figure 11: Statistics of tower base moment and damage equivalent load in fixed and flexible foundation

5. FUTURE WORK

The results provided in this research are all based on simulation data. Accurate evaluation in effect of multidirectional sea state and flexible tower frequency will be further validated by field measurement.

6. CONCLUSIONS

Effects of multidirectional sea state on dynamic motion of platform and impact of flexible foundation on damage fatigue load are studied in this research. Main conclusions are as follows,

(1). Recommendation of unidirectional sea state assumption in IEC-61400-3 will lead to conservative design of platform. Multidirectional sea state employment can decrease the motion by 10.3%, 14.7% and 31.4% in surge, heave and pitch respectively which indicate cost-effective design could be reached when introducing reasonable wave spreading function.

(2). Flexible foundation would impact tower natural frequency and could increase damage equivalent load consequently. It means natural frequency of commercial wind turbine should be re-determined when it is supported on flexible platform and impact of flexible foundation on dynamic load on foundation needs to be investigated again. Otherwise, wind turbine will suffer significant fatigue load, which could shorten service time.

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