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Hydrodynamic Analysis for a Jacket-Type Support Structure of the Offshore wind Turbine

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Abstract. In the present study, the hydrodynamic load due to extreme external condition, such as typhoon, on the offshore wind turbine (OWT) has been investigated by numerical simulations. The hydrodynamic loads including the sea current, regular and irregular wave on the structure are taken into account. The sea current is considered with the constant flow speed, whereas the wave is considered as regular and irregular based on the observed data at considered locations. Using Splash3D, a three-dimensional numerical model is developed for performing the force evaluation of the OWT. Multi-phase flow is evaluated by the volume of fraction (VOF) model, and the turbulent flow is described by the large-eddy-simulation (LES) model. It can be deduced that using the regular wave as the hydrodynamic load for the evaluation of the OWT system will vanish some instantaneous extreme wave. In the case of using the irregular wave, the instantaneous extreme wave is also taken into account. With such more practical hydrodynamic load, the average force for the case of irregular wave is 64% larger than that of the regular wave.

1 Introduction

Comparing to the onshore wind farm, the offshore wind farm has higher quality of wind power source, including higher average wind speed and lower turbulence. However, harsh environmental impacts, such as typhoon, wave, sea current, and earthquake, must be taken into the consideration for the development of a reliable offshore wind turbine (OWT) system. In order to provide safety and reliability for the construction of the OWT, site specific loads induced by the extreme wind, wave, current, and earthquake, should be employed to the analysis and the evaluation for the verification of the designed wind turbine and its support structure.

In the present study, a numerical model based on the reference 5MW OWT from the report of NREL is developed. The objective of this work primarily focuses on the evaluation of the hydrodynamic load. Specifically, the effects of the site-specific sea current and wave on the support structure of the OWT are investigated. By including the effect of the hydrodynamic loads on the support structure into the design procedure, the reliable and robust power production of the OWT system could be achieved.

The computational fluid dynamics (CFD) model is capable to predict the interaction between the wind turbine and hydrodynamic loads. The complicated effects of turbulence, wave, sea current, and structure should be considered comprehensively in the design analysis of the OWT. In recent studies, overly simplified assumptions were employed in the simulation of the ocean flow. For instance, it was commonly assumed that the flow is inviscid and irrotational to solve the potential equation. The semi-empirical Morison's formula was employed to describe the wave load. Those assumptions made the proposed model unable to evaluate the unsteady and highly turbulent flow [1]. Solving the Navier-Stokes equation with the method of fluid-structure interaction (FSI) is an effective way to evaluate the hydrodynamic load on the OWT. Another critical issue for the effective simulation is that the investigated environment is a multi-scale problem. The scale of the oceanic effect is usually measured by kilometer, while it is meter for the OWT. This scale difference makes the simulation more difficult. The method of the direct numerical simulation (DNS) results in the most correct solution. However, the flow field with large Reynolds number will slow down the calculation, making it an impractical option.

A reliable wave model should be able to predict the effect of the nonlinear and breaking wave to simulate the interaction among large waves, strong current, and structure. Wienke and Oumeraci [2] coupled the breaking wave theory and parameter model to evaluate the wave force of wind turbine due to the plunging and breaking waves. Yang and Shen solved the equations of the potential flow to calculate the behaviors of the wave [3]. Calderer et al. accounted for the effects of wave by the simplified linear theory [4]. Marino et al. [5], [6] coupled the aero-elastic model with non-linear wave theory to solve the dynamic force on the structure. It was found by the studies of Marino and Lugni [5]-[7] that the wave force and local pressure increase in a short period of time when wave breaking near the support structure of the wind turbine. Marino et al. [8] employed the nonlinear wave theory and statistical method to analyze the force on the wind turbine for a long time.

Since the traditional wave theories, whether linear or non-linear, are unable to appropriately describe the combined effects of typhoon induced wave and current, the study implements the internal wave maker module to produce the target wave. The behavior of the surface breaking wave is described by the volume of fluid (VOF) method. For the turbulent effect, the large-eddy simulation (LES) method is employed to describe its behaviors. By the LES model, the small scale turbulence, which is unable to be resolved by the computational grid, can be thus predicted with reasonable accuracy. The LES equation is solved by the projection method. The model of the wind turbine structure is developed by the partial-cell treatment.

2 Numerical model

Using Splash3D, a three-dimensional numerical model is developed for perfomring the force evaluation of the OWT. The LES model is incorporated into the simulation to describe the turbulent flow. The Slash3D model was modified from the Truchas developed by Los Alamos National Laboratory (LANL)[9, 10]. With the access of the source code, one can modify or add necessary functions. The developed model is capable to solve the three-dimensional, incompressible N-S equations, and track the position of the fluid surface by the VOF model. Parallel computation is available by using the Message Passing Interface with Chameleon portability system (MPICH) to increase the grid resolution and reduce the required computation time. The developed code is able to predict the breaking wave and the turbulence around the solid structure. Governing equations and important numerical models are described in the following sections.

2.1 VOF model

The VOF equation and its distribution during the calculation are discretized by the Finite Volume Method (FVM) as:

$$\frac{\partial f_m}{\partial t} + \nabla \cdot \left(f_m u \right) = 0 \tag{1}$$

$$f_m^{n+1} = f_m^n - \frac{1}{V_i} \sum_f \Delta t \left[A \cdot u^n \right]_f f_{m,f}^n \tag{2}$$

The free surface in each grid is re-built during the transient calculation to avoid the numerical diffusion at the interface. The Piecewise Linear Interface Calculation (PLIC) [11, 12] method is employed to calculate the position of the free surface in grids, and the interface between fluids are re-built accordingly. The PLIC method evaluates the fluid interface as a tiltable, horizontal surface. The normal vector of the free surface is calculated by the volume fraction of fluid in the cell.

2.2 LES model

For a simulation with the effect of breaking wave, a proper model to describe the turbulent flow should be considered. The LES method is capable to describe the turbulent flow [13]. Without evaluating the motion of all vortexes, the LES method employed the Spatial Filtered method to classify the physical properties into the grid-scale and the subgrid scale catalog. Effects of geometry and flow conditions on grid-scale properties are significant, while these are minor on the subgrid scale properties. Thus, vortexes of grid-scale are solved by the N-S equations, while those of subgrid scale are evaluated by the Turbulence Closure Model (TCM). If the size of a grid is smaller than that of the involved minimum vortex, results by the LES model would be consistent with that by the DNS method. If not (due to limited computational resources), vortexes with difference scale are described by different scheme. As a result, the trade-off is reached on the precision and practicality by the LES method. In this work, the LES method is employed to describe the complicated turbulent flow as the wave and current go through the support structure of the OWT.

The scale of the vortex is classified by the Spatial Filtered method. The physical property is filtered by the filter function as:

$$\bar{\phi}(x_i, t) = \frac{1}{V} \int_{C.V.} \phi(x_i, t) G(x_i) dV \tag{3}$$

The over-bar denotes that it is spatial filtered, and V is the volume of the computational cell. The filter function $G(x_i)$ is described as:

$$G(x_i) = \begin{cases} \frac{1}{V} & x \in V \\ 0 & otherwise \end{cases} \tag{4}$$

With the spatial filter, the momentum equation (N-S) can be re-written as:

$$\frac{\partial \overline{u_i}}{\partial \overline{x_i}} = 0 \tag{5}$$

$$\frac{\partial \rho \overline{u_i}}{\partial t} + \frac{\partial \rho \overline{u_i}\,\overline{u_j}}{\partial x_i} = -\frac{\partial \overline{P}}{\partial x_i} + \rho g + \frac{\partial}{\partial x_j}\left[\overline{\mu_{eff}} \left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right) \right] \tag{6}$$

where the subscripts i, j, and k represent the direction of x, y, and z. The effective viscosity is defined as:

$$\overline{\mu_{eff}} = \mu + \mu_{SGS} \tag{7}$$

The concept of the subgrid scale (SGS) is usually employed with the Smagorinsky model [14], and the viscosity of the SGS is described as:

$$\mu_{SGS} = \rho (C_s \Delta)^2 \sqrt{2\overline{S_{ij}}\,\overline{S_{ji}}} \qquad (8)$$

$$\overline{S_{ij}} = \left(\frac{\partial \overline{u_i}}{\partial \overline{u_j}} + \frac{\partial \overline{u_j}}{\partial \overline{u_i}} \right) \qquad (9)$$

where S_{ij} is the shear strain rate, C_s is the coefficient of SGS model. Depending on the considered environment, it ranges from 0.1 to 0.2. It is 0.15 for the present study. The term of Δ is the minimum resolvable scale of turbulence, and it depends on the grid size as:

$$\Delta = (\Delta x \Delta y \Delta z)^{1/3} \qquad (10)$$

where Δx, Δy, and Δz, are the length of grid on each direction, respectively.

2.3 Wave model and input data

In the present simulation, the considered wave is generated based on the observed data from the Central Weather Bureau of Taiwan during 2013 and 2014 at considered locations. Samples were taken every 10 minutes, and data were collected every hour. Measurement was made within 0.03 to 0.4 Hz with 41 frequencies and resolution of 0.01 Hz. In order to select the representative event, the case with relatively large significant wave height and single peak spectrum is preferred. Selecting the event with higher significant wave height is based on the engineering consideration. The single crest spectrum is preferred since there is only one crest for the employed Joint North Sea Wave Project (JONSWAP) spectrum. Furthermore, event with two or more crests spectrum is usually not representative and it is observed with special conditions. Based on the two selection criteria, the event observed on July 13 2013 is employed as the input data to generate the required wave for the simulation. After rearrangement and statistical methods, the wave parameters for the 3D simulation are obtained. For the observed data, the significant wave height is 5.78 m. The significant wave period is 9.8 seconds, and the peak wave period is 10.4493 seconds. The angular frequency of the transformed peak wave is 0.601301 rad/s. The average wave period is 7.5 seconds, and the corresponding probability density is about 7 m^2-s/rad.

Based on the dispersion relationship, the modified internal wave maker module is implemented to generate required wave as a site-specific load for the OWT. In addition to the generated wave, the effect of current is also considered as a coupled load. Numerical simulation is conducted with this coupled load for the analyzed referenced 5MW OWT.

3 Results and discussion

3.1 Force analysis for the jacket-type support structure under the regular wave with different flow direction

By the developed numerical model, the effect of the regular wave on the force of the structure is investigated with different flow directions. The investigated inflow direction includes the angle of 0° and 45° as illustrated in Fig. 1. Other parameters for the investigated case are listed in Table 1.

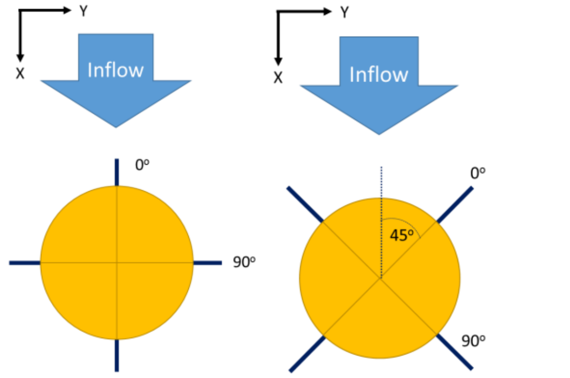

Figure 1. Schematic diagram for the flow direction.

Table 1. Parameters for the investigated case

Bottom Friction Effect	Not considered
Flow Velocity(m/s)	1.41
Finest Grid Resolution (m)	1.0
Residual of Convergence Condition	1.0e-6
Mean Water Depth (m)	25.0
Courant Number	0.85

The computational domain and layout is shown in Fig 2. The wave generating module is installed near the inlet region. Sponge zone is applied downstream to alleviate the numerical reflection from outlet. By a preliminary test without structure, the desired wave is obtained at the position of 350 m. Therefore, the structure is installed at the position of 350 m to investigate the wave-driven force as sown in Fig. 2.

For the computational cell, the grid refinement is applied near the region of the structure, while it is uniform grid for the region away from the structure. The ratio for the grid refinement in x-direction is 1.2, and it is 1.1876 in y-direction. In z-direction, the domain is divided with uniform grid size. The finest grid resolution is 1.0 m applied in the structure region.

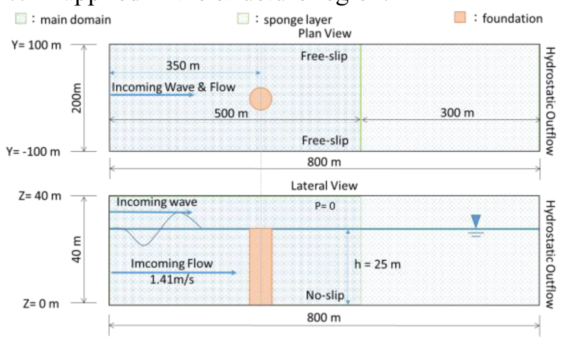

Figure 2. Geometry of the computational domain.

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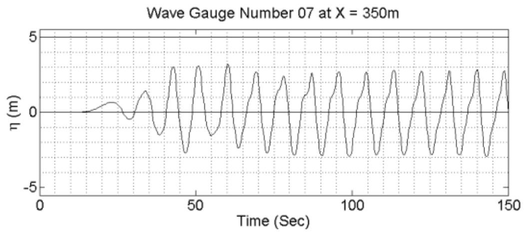
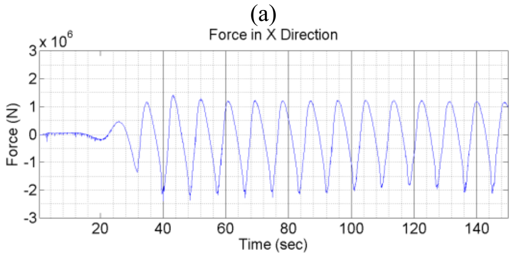
Results are taken at the position of the installed structure (x=350 m). The variation of the elevation and force on the structure for the case of regular wave and 0° flow direction is shown in Fig. 3. Force is positive if its direction is consistent with the coming flow, otherwise it is negative. Periodic variation of the elevation and force can be observed with the synchronized frequency. As the crest of the regular wave reaches the structure, the maximum force on the structure is up to +1.3 MN. Thereafter, the maximum force is -2.0 MN as the trough of the regular wave reaches the structure.



(a)



(b)

Figure 3. Variation of (a) elevation and (b) force on structure with time under regular wave and flow direction of 0°.

The variation of elevation and force on the structure for the case of regular wave and 45° flow direction is shown in Fig. 4. Periodic variations of the elevation and force are also observed with the synchronized frequency. As the crest of the regular wave reaches the structure, the maximum force on the structure is up to +1.9 MN. Thereafter, the maximum force is -1.7 MN as the trough of the regular wave reaches the structure.

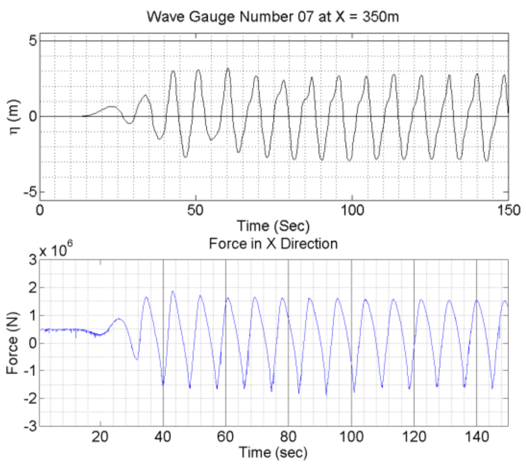


Figure 4. Variation of (a) elevation and (b) force on structure with time under regular wave and flow direction of 45°.

3.2 Force analysis for the jacket-type support structure under the irregular wave with different flow direction

In this section, the elevations of free surface and force on the structure due to the irregular wave and current are investigated. The inflow direction of 0° and 45° are implemented as well for the 5 MW OWT with jacket-type support structure. Similar trends on the variation of the elevation and force are observed for the case using the irregular wave as shown in Fig. 5 and Fig. 6.

In the case of 0° inflow direction, the maximum force is +4.5 MN as the crest of the irregular wave reaches the structure, and it is -1.5 MN at the moment of the trough reaching the structure. In the case of 45° flow direction, the maximum force is +3.3 MN as the crest of the irregular wave reaches the structure, and it is -2.0 MN at the moment of the trough reaching the structure.

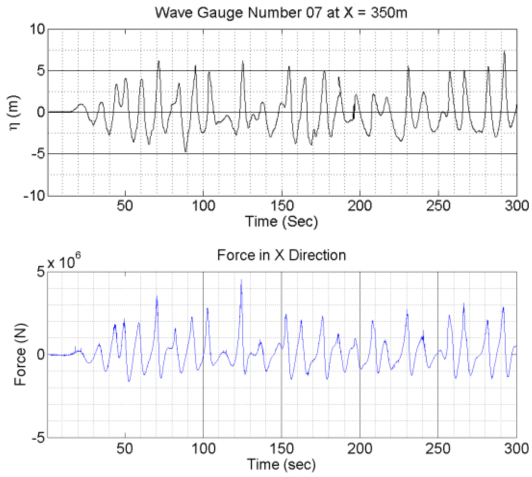


Figure 5. Variation of (a) elevation and (b) force on structure with time under irregular wave and flow direction of 0°.

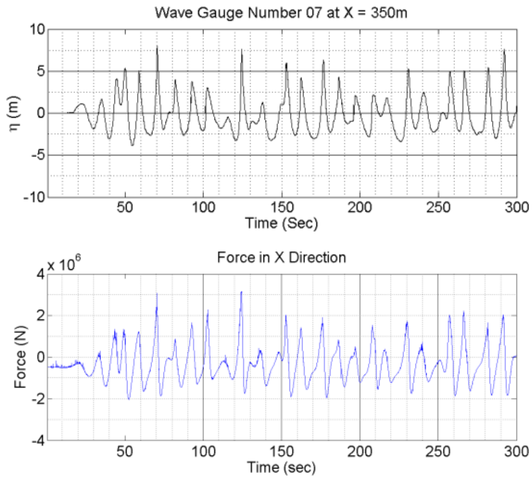


Figure 6. Variation of (a) elevation and (b) force on structure with time under irregular wave and flow direction of 45°.

A comprehensive comparison for the maximum force among the investigated cases is made in Fig. 7. In the case using the regular wave, the trough leads to the larger maximum force. The difference comparing to the crest is also larger (0.7 MN) at 0° of the inflow direction. In the case of 45° of the inflow direction, however, the larger maximum force is observed by the crest. The difference compared to the trough is also smaller (0.2 MN).

For the case of considering the irregular wave, the larger maximum forces are observed by crest for two considered inflow directions. The crest-generated force is significantly larger than the trough. Using the irregular wave also results in the much larger maximum force compared to the regular wave.

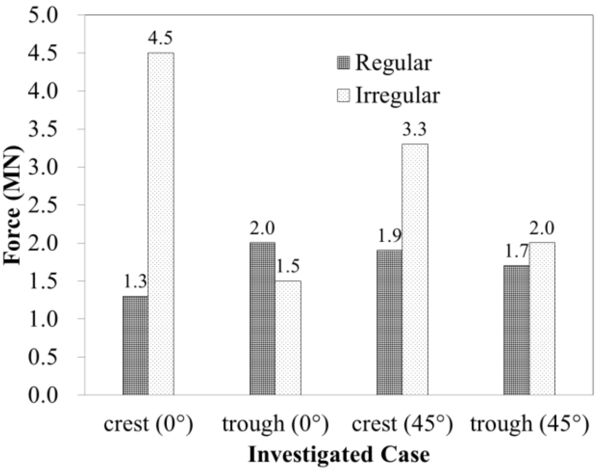


Figure 7. Comparison of the maximum force among investigated cases.

It can be deduced that using the regular wave as the hydrodynamic load for the evaluation of the OWT system will vanish some instantaneous extreme wave. The average force by the regular wave is about 1.7 MN.

In the case of using the irregular wave, the instantaneous extreme wave is also considered. With such more practical hydrodynamic load, the average force for the case of irregular wave is about 2.8 MN, and it is 64% larger than that of the regular wave.

4 Conclusion

In the present study, the hydrodynamic load due to extreme external condition, such as typhoon, on the OWT has been investigated by the numerical simulations. The hydrodynamic loads including the current, regular and irregular wave on the structure are taken into account. The sea current is considered with the constant flow speed, whereas the wave is considered as regular and irregular based on the observed data at considered locations. Using Splash3D, a three-dimensional numerical model is developed for performing the force evaluation of the OWT. Multi-phase flow is evaluated by the VOF model, and the turbulent flow is described by the LES model.

Besides the constant speed current, the regular and irregular waves are considered with different inflow directions (0 and 45 degree). For the computational cell, grid refinement is applied near the region of the structure, while it is uniform grid for the region away from the structure. The finest grid resolution is 1.0 m applied in the structure region.

Comprehensive comparison for the maximum force among the investigated cases is made. The trough leads to the larger maximum force in the case of using the regular wave. The difference comparing to the crest is also larger at 0° of the inflow direction. In the case of 45° of the inflow direction, the larger maximum force is observed by the crest. The difference comparing to the trough is also smaller. For the case considering the irregular wave, the larger maximum forces are observed by crest for two considered inflow directions. The crest-generated force is significantly larger than the trough. Using the irregular wave also results in the much larger maximum force comparing to the regular wave.

It can be deduced that using the regular wave as the hydrodynamic load for the evaluation of the OWT system will vanish some instantaneous extreme wave. In the case of using the irregular wave, the instantaneous extreme wave is also considered. With such more practical hydrodynamic load, the average force for the case using the irregular wave is 64% larger than that of the regular wave.

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