The platform pitching motion of floating offshore wind turbine: A preliminary unsteady aerodynamic analysis

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Dynamic mesh  
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Direct local relative velocity approach  
Blade-tip vortices  
Blade–wake interaction

A B S T R A C T

The flow-field around the rotor blades of an FOWT may be significantly influenced by the six rigid-body motions of the floating platform via the blade–wake interaction. Therefore, the accurate prediction of unsteadiness of aerodynamic load which is calculated by many conventional numerical approaches is still questionable for an FOWT. In this study, the periodic pitching motion of the rotating turbine blades due to the floating platform motion is considered to investigate the effects of vortex–wake–blade interaction for the aerodynamic performance of an FOWT. The unsteady computational fluid dynamics (CFD) simulations based on the dynamic mesh technique were applied for analyzing the pitching motion of wind turbine due to the platform motion. The in-house unsteady blade element momentum code using the direct local relative velocity approach was also applied to simulate the unsteady aerodynamic performance. The equivalent average velocity approach which simplifies the relative velocity contribution due to the platform motion was proposed and incorporated to the in-house code. It is shown that the unsteady aerodynamic loads of the floating offshore wind turbine become sensitively changed due to the variation of frequency and amplitude of the platform motion. Additionally, there are strong flow interaction phenomena between the rotating blades with oscillating motions and generated blade-tip vortices.

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1. Introduction

Various Multi-MW turbine systems have been installed in the offshore area since the year 2000 (EWEA, 2013a, 2013b). Until the end of June 2013, total amount installed offshore wind turbine (OWT) rose up to 1939 units, with a combined capacity of 6040 MW fully grid connected in European waters in 58 wind farms across 10 countries (EWEA, 2013a, 2013b). The reason may be explained that a wind speed is typically stronger and much more sustained in the offshore area since the year 2000 (EWEA, 2013a, 2013b). The reason may be explained that a wind speed is typically stronger and much more sustained in the offshore area since the year 2000 (EWEA, 2013a, 2013b). If above issues can be effectively solved, the FOWT farms are expected to generate a large amount of clean energy with a competitive price compared to other energy resources. Thus, the FOWT still has many challenges to design, manufacture, install, control, and maintain (Butterfield et al., 2005). It has been attracted by many researchers, engineers as well as the universities, institutes, and governments.

Physically, the flow-field around a rotating wind turbine blade is inherently complex because of the existence of wind shear, turbulence, gust, and yaw motion of the nacelle. For a floating offshore, horizontal axis wind turbine (HAWT), flow characteristics become more complex than those of a fixed offshore wind turbine. Because of the motion of floating platform, which includes three translational components (heave in the vertical, sway in the lateral, and surge in the axial) and three rotational components (yaw about the vertical axis, pitch about the lateral, and roll about the axial) motion as shown in Fig. 1, the additional effect of the wind contribution which is basically transmitted to the rotor due to the platform motion needs to be considered. In those motions, platform pitch and yaw degrees of freedoms significantly lead to the unsteady aerodynamic effects on the rotating blades combining the effect of wind shear, gradient across the rotor disk, dynamic stall, rotor blade–wake interaction, and skewed flow, etc. (Sebastian and Lackner, 2012a, 2012b, 2012c;
As an example, a typical floating offshore HAWT (Fig. 2 (Sebastian and Lackner, 2012c), from left to right) shows a flow-field around a rotor blade during the pitching motion of the spar-buoy FOWT type. As the rotor blade begins to pitch back, it interacts with its own wake which leads to the development of turbulence region. In Fig. 2, the toroidal recirculations can be seen and this transitional aerodynamic phenomenon is called the vortex ring state, or settling with power (Peters and Chen, 1982). The pitching motion intermediately causes a transient flow condition which is one of potential operating and simulating problems for a floating wind turbine. Particularly, it is believed that pitching and yawing motions lead to large variation of the aerodynamic performance of a floating offshore HAWT system because of the above issues (Sebastian and Lackner, 2012a, 2012b, 2012c).

One of the common challenges to all support structure designs is the ability to predict the dynamic load responses of the coupled wind turbine and platform system which usually combines stochastic wave and wind loading. Because of the load prediction challenges for design requirements, various experiments with floating sub-structures have been performed. At present, several experimental floating substructures of floating offshore horizontal axis wind turbine seem to be in test phases: Statoil Hywind (Spar), SWAY (Spar), Blue H (TLP), Gusto Trifloater (Semisubmersible) and Poseidon (Semisubmersible) in Europe, Fukushima (Semisubmersible), Kabe-shima Island (Spar) and WindLens Floater (Semisubmersible) in Japan and DeepCwind (Semisubmersible) and Principle Power WindFloat (Semisubmersible) floating turbine in the US (EWEA, 2013a, 2013b; Main(e) International Consulting LLC Report, 2013). However, to effectively design an FOWT system, the designer, researcher, and engineer need to produce an analysis tool that is able to accurately predict loads and resulting dynamic responses of the coupled wind turbine and platform system caused by combined stochastic wave and wind loading. The fully coupled aero–hydro– servo–elastic dynamic approaches (Jonkman and Buhl, 2007a, 2007b; Jonkman, 2009a, 2009b; Shim and Kim, 2008; Roddier et al., 2010; Cermelli et al., 2009; Marshall et al., 2009; Crozier, 2011; Cordle, 2010; Bossanyi, 2003), or a simplified aero–hydro-dynamic method (Karimirad and Moan, 2012) have been considered to calculate the dynamic responses of a floating offshore wind turbine. FAST code (Jonkman and Buhl, 2007a, 2007b; Jonkman, 2009a, 2009b) for the aeroelastic analysis of a horizontal axis wind turbine (HAWT) has been developed by NREL’s National Wind Technology Center (NWTC). Now, it is extended with a HydroDyn model to have additional capability of the fully coupled time-domain aero–hydro– servo–elastic simulations considering floating platform motions. FAST has been coupled with several sub-modules in order to model FOWT such as Charm3D (Shim and Kim, 2008), TimeFloat (Roddier et al., 2010; Cermelli et al., 2009), ADAM (Marshall et al., 2009), etc. Additionally, the other time-domain programs for the modeling and simulation of an offshore structure have been developed such as SIMO, HAWC2, 3Dfloat, DeepC, Bladed, etc. (Crozier, 2011; Cordle, 2010; Bossanyi, 2003). However, almost all design codes currently capable of performing integrated modeling of floating wind turbines are based on the commonly-used sufficient aerodynamic analysis method, blade element momentum (BEM) theory to calculate aerodynamic forces on the wind turbine rotor. The conventional blade element moment (BEM) method is applied based on empirical
models and with correction factors (Glauert, 1983; Hansen, 2000; Hansel et al., 2006; Moriarty and Hansen, 2005) (e.g., tip and hub loss model, Glauert correction, skewed wake correction, etc.) instead of using their original theoretical assumptions. As Matha et al. (2011) mentioned, the large low-frequency platform motions experienced by floating offshore wind turbines result in flow conditions which are considerably more complex than those experienced by conventional onshore or fixed-bottom offshore wind turbines. In particular, there are different interactions between the turbine rotor and its wake, with the rotor in some cases traversing back over its own wake. This phenomenon can also be illustrated in Fig. 2 (Sebastian and Lacker, 2012c). The transitions between windmill and propeller states, where the rotor interacts with its own wake cannot be accurately modeled using traditional BEM theory with common corrections (Sebastian and Lacker, 2012c). They also indicated that reduced frequency is a product of the non-dimensionalized Navier–Stokes equations and is a dimensionless metric often used to characterize the degree unsteadiness of an aerodynamic. They indicated that the BEM method is still lacking and is questionable in its prediction of the aerodynamic loads of FOWT. Therefore, modeling tools and numerical codes that simulate whole structure behavior should be developed and validated to allow for an improved design (EWEA, 2013a, 2013b). In particular, the effective analysis tool for the aerodynamic simulation of FOWT is still a challenging work (Matha et al., 2011; Cordle, 2010).

The major objective of the present work is to show the case dependent differences of aerodynamic prediction for an FOWT model among the traditional blade element momentum, general dynamic wake, and advanced computational fluid dynamics approaches. In this study, Phase IV of the IEA Annex XXIII Offshore Code Comparison Collaboration (OC3) (Jonkman, 2009b) which considered the spar-buoy concept, was chosen to conduct the calculation of unsteady aerodynamic loads due to the platform motion. The computational fluid dynamics (CFD) analysis of a three-dimensional unsteady flow of 5-MW FOWT considering the effects of the pitching degree-of-freedom (DOF) motion of the support platform has been performed. Using the computational fluid dynamic approach, the Reynolds–averaged Navier–Stokes equations with the shear-stress transport (SST) $k$–$\omega$ turbulence model were applied. It has the strong potential to simulate full physical flow behaviors of a complex flowfield around a wind turbine blade (Sarun, 2006). The dynamic meshing algorithm was used to model the rotating blades where its computational domain is moving with respect to time because of the motion of the blade surface boundaries. The in-house Matlab code of the unsteady blade element momentum (UBEM) with the direct local relative velocity method (DLRM) has been also performed and this approach was previously verified for the NREL 5-MW baseline wind turbine model (Tran et al., 2013). Additionally, we recently proposed an equivalent averaged velocity method (EqAM) that simplifies the handling of local relative velocity on a rotating blade due to the platform motion. Using EqAM, both in-house UBEM and modified FAST–AeroDyn codes were applied to make comparison for the predicted aerodynamic power and thrust by different numerical tools. Unsteady aerodynamic loads acting on the rotating blades can be altered due to its pitching motion on the platform. The predicted aerodynamic power and thrust obtained by CFD, UBEM and modified FAST’s AeroDyn showed overall good agreement in case of small pitching motion amplitude such as 1–2°. It is however importantly found that there are differences among predicted results for increased amplitude pitching motions such as 4°. The instantaneous blade-tip vortices behind the wind turbine blades during the pitching motion have been successfully captured and visualized using an advanced unsteady CFD method. The effect of different position of the pitching axis (center of mass) has been also investigated depending on the different rotating platform types such as spar-buoy and barge types.

2. Numerical methodology

2.1. Equivalent average method for platform pitching motion using unsteady blade element momentum method (UBEM)

In the present study, unsteady blade element momentum (UBEM) code was originally developed based on the theory introduced by Hansen (2000). This aerodynamic model is a very efficient and applicable approach for the design and performance prediction of a wind turbine blade. Fig. 3 shows the computational process for the present UBEM approach. Herein, the current UBEM adopted the 3-D correction method (Snel et al., 1994) which allows much more accurate prediction of the aerodynamic force for a wind turbine blade regarding the lift coefficient correction considering the blade rotation, aspect ratio, and stall phenomenon. The local speed ratio dependency derived on the basis of centrifugal pumping model which usually appears during the operation of a wind (Lindenburg, 2004) is taken into account for the current code. The Prandtl’s tip loss factor and Glauert correction which is an empirical relationship between the thrust coefficient $C_T$ and the axial induction factor $\alpha$ have been also applied in the current UBEM code. To take into account the time delay for the equilibrium aerodynamic load, a dynamic inflow phenomenon which has an influence on the fluctuation in the motion of a wind turbine blade must be included. One of the engineering models, proposed by Oye (1994) is a filter for the induced velocities consisting of two first order differential equations. The wind shear, yaw/tilt misalignment and tower passage are included in the current work.

As we mentioned above, the aerodynamic unsteadiness of an offshore floating wind turbine is due to the additional DOFs...
associated with the platform motions: surge, sway, heave, roll, pitch and yaw. These platform DOFs result in the effective velocity contribution with respect to a turbine blade. Particularly, the effective velocity contribution greatly influences on the loads of wind turbine blade when the platform has a high frequency motion such as 0.1–0.5 Hz due to ocean wave (Forristall, 1981; Vandemark et al., 2005) and long arm distance for the platform pitching motion. The additional local velocity contribution due to the 6-DOFs platform motion can be given as

$$\mathbf{V}_{l, \text{platform}} = \left( U_{\text{surge}} + R_{CG} \phi_{\text{pitch}} \cos \phi_{\text{pitch}} - R_H \phi_{\text{yaw}} \cos \phi_{\text{yaw}} \right) \hat{\mathbf{x}}$$

$$+ \left( U_{\text{sway}} + R_{CG} \phi_{\text{yaw}} \sin \phi_{\text{yaw}} - R_H \phi_{\text{roll}} \cos \phi_{\text{roll}} \right) \hat{\mathbf{y}}$$

$$+ \left( U_{\text{heave}} + R_{CG} \phi_{\text{roll}} \sin \phi_{\text{roll}} - R_H \phi_{\text{pitch}} \sin \phi_{\text{pitch}} \right) \hat{\mathbf{z}}$$

where $R_{CG}$ and $R_H$ represent the distance from the rotation center of a platform (the center gravity of full FOWT system) to the local blade radius position, and local rotor radius, respectively.

It should be noted here that the magnitude of additional velocity contribution is different along each blade span direction under the platform rotation motions. For the platform translation motions, the additional velocity is uniformly distributed on each wind turbine blade. As shown in Fig. 4, the additional local velocities are varied from the blade root to the blade tip (i.e., blade number 1) due to the platform pitching motion. In this study, the local velocity contribution on each blade position due to the platform motion was directly calculated. Thus, this can be called as the direct local relative velocity method (DLRM) in the present study. Moreover, we proposed an equivalent averaged velocity method (EqAM) for the unsteady aerodynamic analysis of an FOWT due to the platform pitching motion. This method assumes that a non-uniform distributed velocity on each blade can be considered as a uniform type as shown in Fig. 4. The distributed local velocity on each blade due to the platform pitching motion can be given as

$$V_{l, \text{pitch}_b, 1} = \left( H + \frac{R}{2} \cos \omega \right) \phi_{\text{pitch}} V_{l, \text{pitch}_b, 2}$$

$$= \left( H + \frac{R}{2} \cos \left( \omega + \frac{2 \pi}{3} \right) \right) \phi_{\text{pitch}} V_{l, \text{pitch}_b, 3}$$

$$= \left( H + \frac{R}{2} \cos \left( \omega + \frac{4 \pi}{3} \right) \right) \phi_{\text{pitch}}$$

where $R$, $H$, and $\phi$ represent the radius of a rotor blade, the distance from the rotation center of a platform to the rotor center, and the azimuth angle of a rotor blade as shown in Fig. 4, respectively.

The averaged uniform distributed velocity of three blades due to the platform pitching motion can be considered as the additional velocity contribution at the hub position. This assumption, in fact, conserves a mass flow cross over a plane rotation. Herein, the EqAM introduced is used for a further comparison of the predicted unsteady aerodynamic of a floating offshore wind turbine subject to the platform pitching motion. This approach can be considered for all platform motion modes, except for the platform yaw motion. It can be used to effectively estimate aerodynamic loads based on almost design load cases (DLCs) which usually is referred to several international design standards such as IEC 61400-1, GL Guideline, or DNV.

In this study, both uniform and non-uniform distributed velocities on each blade were considered to make comparison. The additional velocity contribution due to the platform motion will be added to the relative velocity including freestream velocity component, $V_0$, velocity due to rotation blade, $\omega \mathbf{v}_r$, and induced velocity, $W$. Additionally, skewed inflow angle due to rotational motions will be taken into account in the present study.

### 2.2. Computational fluid dynamic model

Computational fluid dynamic is being increasingly used to highlight complex flow physics of wind turbines. In the current study, we applied the Reynolds-averaged Navier–Stokes (RANS) equations with the shear-stress transport (SST) $k$–$\omega$ turbulence model (Sarun, 2006; Menter, 1994) to provide closure for the Reynolds stress term and multiple reference frames (MRF) to simulate the complex flow.
around a huge rotating rotor blade. It should be noted that the MRF approach does not account for the relative motion of a moving zone with respect to the adjacent zones; the mesh remains fixed for the computation. The first-order implicit time scheme that is unconditionally stable with respect to the time step size was chosen for segregated, unsteady, 3D solver. Pressure-implicit with splitting of operators (PISO) based on a higher degree of approximation between the iterative corrections for the pressure and velocity was chosen. This algorithm also significantly reduces convergence difficulties associated with highly distorted skewed cells. The second-order upwind spatial discretization was applied for the momentum, turbulent kinetic energy, turbulent dissipation rate, and energy; the SIMPLE algorithm was used to iterate the pressure field. Using this algorithm, it is not necessary to fully resolve the pressure–velocity coupling in each consecutive step.

Furthermore, the dynamic mesh algorithm was applied to model turbine movement due to the platform motion. When the motion of the moving body is large, poor quality cells, based on volume or skewness criteria, are agglomerated and locally remeshed when it is necessary. On the other hand, when the motion of the body is small, a localized smoothing method can be much more effectively used and in this case grid nodes are moved to improve cell quality, but the connectivity remained unchanged. A so-called spring smoothing method is employed to determine the new locations of deformed grid points. In this method, the cell edges are modeled as a set of interconnected springs between nodes (Pirzadeh, 1999; Blom, 2000).

In order to conduct accurate and robust unsteady aerodynamic analysis of the rotating blades due to the platform motions of the FOWT, it is significant that the coordinate of blade hub center and the direction of the blade rotating axis must be instantaneously recalculated with respect to time. Fig. 5 shows the flowchart for the unsteady CFD simulation in the present analysis. As mentioned above, the remeshing and deforming grid method was applied in the current computational procedure. In order to do the unsteady aerodynamic analysis of an FOWT, user defined functions (UDFs) incorporated to the commercial FLUENT software were originally created and used. The primary purpose of UDFs is to exactly obtain the rotation center and rotation axis of a rotor blade. Moreover, these UDFs will directly generate output data for aerodynamic loads of an FOWT for each time step.

2.3. Calculation procedure for rotor center and rotor axis

The rotating center of the pitching motion was located at the mass center of the full FOWT model. Its location and orientation of the floating structure system automatically update at every time step such that

\[
x_{c,g}^{n+1} = x_{c,g}^n + v_{c,g} \Delta t
\]

where \(x_{c,g}^n\) and \(v_{c,g}\) are the position and orientation of the center of a full FOWT system, \(v_{c,g}\) and \(\Omega_{c,g}\) are the linear and angular velocities of the center of the full FOWT system.

The orientation of a full FOWT system can be determined using a standard 1–2–3 Euler angle rotation that we rotated first about the x-axis, then the y-axis and finally the z-axis. Such a sequence of rotation can be represented as the transformation matrix as follows:

\[
\begin{pmatrix}
\cos{\phi} & \sin{\phi} & 0 \\
-\sin{\phi} & \cos{\phi} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

with the shorthand notation \(\Phi = \cos{\xi}\) and \(\Sigma = \sin{\xi}\) have been used.

In order to identify the rotating center of wind turbine blades due to the FOWT platform motions, its position vectors on the rotating domain need to be updated based on the platform rotations with the instantaneous angular velocity vector \(\Omega_{r,g}\). For a finite rotation angle of the floating platform \(\Delta \theta = \Omega_{r,g} \Delta t\) as shown in Fig. 6, the instantaneous hub position of a vector \(\vec{x}_r\) due to only the platform rotations at each time step with respect to \(\vec{x}_{c,g}\) can be expressed by the following equation:

\[
\vec{x}_{r}^{n+1} = \vec{x}_{r}^{n} + \Delta \vec{x}
\]

where

\[
\Delta \vec{x} = \left[ \vec{x}_{c}^{n} - \vec{x}_{c,g} \right] \left[ \sin{\Delta \theta} \hat{e}_h + (\cos{\Delta \theta} - 1) \hat{k} \right]
\]
The unit vectors $\hat{e}_\theta$ and $\hat{e}_r$ are defined as

$$\hat{e}_\theta = \frac{\hat{\Omega}_g \times \hat{x}}{|\hat{\Omega}_g \times \hat{x}|}, \quad \hat{e}_r = \frac{\hat{\Omega}_g \times \hat{r}}{|\hat{\Omega}_g \times \hat{r}|}$$

(6)

In case of an FOWT, it does not only rotate about the center of gravity but also translates with $\vec{v}_g$; the position vector at time $m+1$ on a wind turbine blade can be expressed as

$$\vec{x}_{hub}^{m+1} = \vec{x}_{cg}^{m} + v_g \Delta t + \vec{x}_r^{m+1}$$

(7)

Applying the concept of Euler angle and updated position vector of a wind turbine blade under the floating motion of an FOWT system, the rotating center of the wind turbine blade was calculated as well as the force component vectors on a blade coordinate system. Additionally, the standard 1–2–3 Euler angle can be applied to find desired vector on a wind turbine rotor experiencing the 6-DOFs motion of a full FOWT system.

### 3. Numerical simulation

#### 3.1. Specification of the NREL 5-MW baseline wind turbine and supporting platform

The NREL 5-MW reference wind turbine (Jonkman et al., 2009; Bazilevs et al., 2011) model that is designed by the Energy Research Center of the Netherlands (ECN) 6 MW offshore wind turbine (Lindenburg, 2002; Kooijman et al., 2003; Lindenburg et al., 2001) is a representative utility-scale wind turbine suitable for a floating offshore wind turbine. It is a conventional three-bladed upwind turbine. Major properties of the NREL 5-MW baseline wind turbine and its rotor blade are given in Table 1.

The variety of anchors, moorings, floater geometry and ballast options that are available made numerous floating platform concepts for a floating offshore wind turbine. Idealized designs, i.e. the barge, spar buoy and the TLP illustrated in Fig. 7 (Jonkman, 2009a) which describes three FOWT types with respect to the three methods of achieving static stability. In this study, the spar-buoy concept of a floating support platform was chosen to conduct the effects of the aerodynamic performance because of the platform motion. This concept was determined because of the simplicity in design, suitability to modeling, and propinquity to commercialization. Fundamental engineering properties of the spar-buoy design are given in Table 2.

#### 3.2. Computation modeling

The three-bladed rotor with the hub configuration was considered ignoring the tower and nacelle configurations of a wind turbine system. The presence of those configurations might cause the effects of the aerodynamic loading on a wind turbine due to the flow interference between them and turbine rotors. Particularly, the aerodynamic loading of the tower and tower dam can be important in higher wind speeds due to its drag and wake interaction which can be significant because of the relative velocity for the survival cases.

The full three-bladed rotor with an unstructured grid topology is explicitly modeled as shown in Fig. 8. The cylindrical

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**Table 1** Properties of the NREL 5 MW baseline wind turbine.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating</td>
<td>5 MW</td>
</tr>
<tr>
<td>Rotor Orientation, Configuration</td>
<td>Upwind, 3 blades</td>
</tr>
<tr>
<td>Control</td>
<td>Variable Speed, Collective Pitch</td>
</tr>
<tr>
<td>Drivetrain</td>
<td>High Speed, Multiple-state Gearbox</td>
</tr>
<tr>
<td>Rotor, Hub Diameter (m)</td>
<td>126, 3</td>
</tr>
<tr>
<td>Hub Height (m)</td>
<td>90</td>
</tr>
<tr>
<td>Cut-In, Rated, Cut-out Wind Speed (m/s)</td>
<td>3, 11.4, 25</td>
</tr>
<tr>
<td>Cut-In (rpm)</td>
<td>6.9, 12.1</td>
</tr>
<tr>
<td>Rated Tip Speed (m/s)</td>
<td>80</td>
</tr>
<tr>
<td>Overhang, Shaft Tilt, Precone (m-degree)</td>
<td>5, 2.5</td>
</tr>
<tr>
<td>Rotor Mass (kg)</td>
<td>110,000</td>
</tr>
<tr>
<td>Nacelle Mass (kg)</td>
<td>240,000</td>
</tr>
<tr>
<td>Tower Mass (kg)</td>
<td>347,000</td>
</tr>
<tr>
<td>Coordinate location of overall CM (m)</td>
<td>(−0.2, 0.0, 64.0)</td>
</tr>
</tbody>
</table>

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**Fig. 7.** Floating platform concepts for offshore wind turbines.
computational domain is applied with a radius of 400 m, and extends 5.5- and 15.0- time of the rotor radius in negative (upstream) and positive (downstream) z-direction, respectively. Refine mesh was generated behind the wind turbine rotor to capture wake behavior. For blade surfaces, a sub-map triangular mesh pattern was generated with 40 $\times$ 550 elements along chordwise and spanwise directions, respectively. Near the rotor surface as shown in Fig. 8, we generated 6 layers of refined mesh with first layer thickness of 1 cm and a progression factor of 1.1. This mesh structure for the rotor surface and adjacent mesh layer can be seen by Bazilevs et al. (2011). The total number of cells in the numerical grid was approximately 6.0 million, consisting of pentahedral at near wall surfaces and tetrahedral meshes over the total domain. The blade completed one cycle of revolution in 5 s with a time step size of 0.02778 s that corresponded to a blade rotation of 2.0°. All the computations were effectively carried out on personal server-clustered parallel machines with Intel(R) Core (TM) i7-3970X CPU @ 3.5 GHz (6 core) and 64GB RAM. For 20 sub-iterations of each global time step, the computational cost approximately took 4 min using 12 CPUs parallel processing.

At the upstream boundary of the inlet, an axial flow was specified with a velocity and static pressure assumed to be the sea level at the downstream boundary of the outlet. The turbulent intensity and turbulent viscosity at inlet and outlet boundaries were also assumed to model freestream turbulence condition. On the surface of the wind turbine blades, a non-slip condition was defined. The symmetric boundary condition which assumes zero normal gradients of all variables at symmetry plane was imposed on the far field boundary of a computational domain. The multiple moving reference frames (MRFs) technique was utilized to simulate the artificial moving rotor blade. Additionally, the shear-stress transport (SST) $k-\omega$ turbulence model was applied to account for the turbulence flow effects.

The pitching motion of a wind turbine rotor due to the pitching DOF mode of a platform is given as the following equation which

| Table 2 Floating platform structural properties of OC3 platform configuration. |
|-----------------|--------------------------|
| Platform Diameter Above Taper (m) | 6.5 |
| Platform Diameter Below Taper (m) | 9.4 |
| Draft (m) | 120 |
| Displaced volume of water (m$^3$) | 8029.21 |
| Mass (kg) | 7466.33e3 |
| CM Location below SWL (m) | 89.9155 |
| Rolling inertia about CM (kg m$^2$) | 4229.23e6 |
| Pitch inertia about CM (kg m$^2$) | 4229.33e6 |
| Yaw inertia about CM (kg m$^2$) | 164.23e6 |

Fig. 8. (a) A full computational domain. (b) A closed-view of the refined grid regime. (c) A closed-view of boundary layer on a blade surface.
assumes as a sine function with an amplitude (Amp) and frequency (Freq). In order to impose prescribed platform pitching motion, user defined functions (UDFs) code were originally developed to practically define the transient motion of a floating wind turbine. The user defined function, DEFINE_CG_MOTION, was compiled into CFD code so that it can fully model 6-DOFs rigid modes of the floating platform motion about the rotating center (mass center) of the full floating wind turbine system (turbine plus platform). This mass center which usually depends on platform types can be located below or above the seawater lever (SWL).

\[ \theta_{\text{pitch}} = \text{Amp} \cdot \sin(2\pi \cdot \text{Freq} \cdot t) \]  

(8)

4. Result and discussions

4.1. Unsteady aerodynamic analysis using averaged equivalent method

The current CFD and UBEM analyses for uniform, axial flow have been verified for the different wind velocities by the author (Tran et al., 2013). In this study, the NREL 5-MW offshore wind turbine was considered for a freestream velocity of 8 m/s and 11 m/s with reference to a rotating speed of 9.16 rpm and 12 rpm, respectively. It should be noted that the additional velocity contribution due to the platform motion was added to inlet velocity, simultaneously. Therefore, the blade locations are only varied with respect to the rotating axis (the low-speed shaft axis of a wind turbine). They are not changed with regard to the rotation center or the center gravity (CG) of a full FOWT system. The non-axial flow due to the platform motion was also considered as a yaw angle error at given pitching amplitude motion. Additionally, the control algorithm for both the blade pitch and low-speed shaft of a wind turbine was not considered. It means that the blade pitch and rotating speed remained as a constant during the unsteady simulation. Frequency and amplitude of the supporting platform motion were assumed in order to model the similarity behavior of a real platform motion that usually has a small rotating angle and low frequency or high frequency. In the reality, the frequency and amplitude of the motion depend on the coupled hydro–aero–elasticity of the full FOWT. In this study, different frequencies and amplitudes were assumed as 0.2–0.033 Hz and 1–4°, respectively. It should be noted that the frequencies chosen fall in the range of typical sea states, which have peak spectral periods in the range of 5–20 sec (Jonkman et al., 2007; Schlipf et al., 2013) corresponding to frequencies in the range of 0.05–0.2 Hz (i.e., 0.314–1.257 rad/s).

The supporting platform will tend to oscillate at the excitation frequency of the incident waves (Jonkman, 2008). Furthermore, the aerodynamic effect due to the different rotating center (center of gravity) positions, which depends on the designs of the platform types, has been performed.

Fig. 9(a) shows the relative vertical position responses of the middle blade span with respect to time or azimuth angle. Under a sine function of the pitching motion with an amplitude of 4° and frequency of 0.1 Hz, the relative vertical position responses of the different blades harmonically vary. As mentioned above, the additional velocity contribution on the blade sections along its span due to the pitching motion is different as shown in Fig. 9(b). The additional velocity contribution at the blade tip location achieves a maximum value due to a maximum distance from the rotating center of a platform to its location, whereas it is smallest at the blade root location. They achieve this status when the angular velocity of the pitching motion becomes the maximum magnitude. It can be clearly seen at the time of 0 s, 5 s, 10 s, and 15 s when the blade number 1 is located at 0 o’clock position as shown in Fig. 9(a). It is noted that the sign of the additional velocity contribution indicates the movement forward and backward of an FOWT. At middle point along spanwise direction of the different blades, the additional velocity contributions also vary the different magnitudes as shown in Fig. 9(c). From non-uniform distributed additional velocity along the spanwise direction of turbine blades (known as direct local relative method), we changed it to the uniform distributed additional velocity along the blade spanwise (known as equivalent averaged velocity method) as shown in Fig. 4. In fact, this assumption still conserves the total mass flow across the plane rotation of a wind turbine. As shown in Fig. 9(d), the average relative velocity contribution of three blades is consistent with the additional velocity contribution at the hub position due to the pitching motion of the supporting platform.

Fig. 10 shows the unsteady aerodynamic comparison between the direct local relative velocity (DLRM) and equivalent averaged relative method (EqAM) due to the prescribed pitching motion of the supporting platform. The unsteady blade element momentum method (UBEM) was performed to compare both approaches. The platform motion was assumed as the pitching DOFs only with 4° amplitude and 0.1 Hz frequency. The rotating center was located at intersection point between the center line of tower and water sea level. Generally, both DLRM and EqAM have good agreement for the aerodynamic power and thrust. At peak curves, DRLM predicted higher load than EqAM which assumes uniform distributed velocity along a blade span. The relative velocity must be different value at the different blade sections in a real wind turbine. The different relative velocities along each blade span can be taken into account by applying DLRM. This leads to the effect of the aerodynamic lift and drag force on each blade section along its span. It is a reasonable explanation to explain why there are somewhat differences between two methods in the present study.

In order to fully verify the current EqAM, we also applied this approach for the modified FAST solver. It means that the additional velocity contribution from the average relative velocity of three blades or relative velocity at the hub position in Fig. 9(d) was performed. The modified FAST’s AeroDyn with the general dynamic wake (FAST-GDW) and blade element momentum (FAST-BEM) aerodynamic theory were considered herein. For current FAST’s AeroDyn code, the wind profile input was only changed to model the average relative velocity of three blades and time-dependent yaw error. Beddoes–Leishman’s dynamic stall was switched on to account for the effects of a dynamic stall response due to the rapid changes in an angle attack. It should be also noted that there was no control algorithm for the unsteady simulation by current FAST solver. The structures DOFs of a wind turbine system were all disabled to model the rigid rotor turbine system. Additionally, the unsteady CFD with multiple reference frames and the dynamic mesh was applied to solve an FOWT simulation. Fig. 11 shows the aerodynamic power and thrust comparison among the unsteady CFD, DRLM by UBEM, and EqAM by modified FAST-GDW and FAST-BEM. The amplitude pitching motion was assumed as a very small value so that its effects of FOWT can be neglected. Fundamentally, the unsteady aerodynamic power and thrust obtained by the different approaches, which model relative velocity contribution due to the platform pitching motion, are slightly different. Aerodynamic power by UBEM approach tends to be highest prediction due to excluding the dynamic wake model. Both unsteady CFD and FAST–BEM predictions were well compared with each other. On the other hand, the aerodynamic load by FAST-GDW tends to predict higher that of FAST-BEM. This was also appeared in previous study (Meng et al., 2009). As Meng and his coauthors mentioned, the standard released version of AeroDyn does not include enough finite states to provide a good prediction of induced velocity at blade tip and root. In the view point of wind turbine designer, better prediction of the aerodynamic load has significant effect on optimism design. On the contrary, higher
prediction of aerodynamic load tends to give a more conservative choice. In summary, this result gives us confidence that our computational approaches are accurate enough and can be applied to simulate further cases.

Under a small pitching motion with an amplitude 0.01° and frequency 0.1 Hz, a maximum additional velocity contribution due to the pitching motion is approximately 0.017 m/s at the blade tip when it locates at 0 o'clock position. This wind speed at hub position which is approximately 0.010 m/s seems to be very small as compared to the freestream velocity of 11 m/s. Fig. 11 clearly shows slight aerodynamic load variation when the small amplitude of the pitching motion is applied. On the other hand, the aerodynamic power and thrust becomes bigger variation under the pitching condition. At the first time of the pitching motion, some discrepancy at the maximum peak area in which the aerodynamic load is large variation although the normal pitching condition occurs under the normal wind and wave condition.

4.2. Unsteady aerodynamic effect due to platform pitching motion with different frequencies and amplitudes

As we mentioned above, the aerodynamic load tends to be largely varied although there is small pitching motion amplitude under a normal wind and wave condition. In this part, the different amplitudes and frequencies of the pitching motion have been carried out. The freestream wind speed and rotating speed are similar to above case. It should be noted that DRLM and EqAM were used for UBE, FAST with GDW and BEM, respectively. The results obtained by these numerical approaches will be compared to the unsteady CFD approach.

Fig. 12 shows the comparison of the unsteady aerodynamic power and thrust responses among CFD, UBE, and FAST solvers for different frequencies and the same amplitude of the pitching motion. Generally, the current numerical approaches predicted well the trend of the aerodynamic power and thrust of an FOWT under the pitching conditions. The aerodynamic power and thrust respond as a sine function. In Fig. 12, it is shown that predicted aerodynamic responses are similar to the frequency of the pitching motion of the FOWT. At the first time of the pitching motion, somewhat numerical error exist due to abrupt change of wind condition. After that, the dynamic responses become regular trend. UBEM approach over-predicted rather than other approaches. FAST with BEM tends to underestimate as compared to FAST with GDW, especially the peak area of the additional velocity contribution. The current result obtained by CFD clearly shows some discrepancy at the maximum peak area in which the pitching motion achieves a maximum motion velocity. At that point, the relative wind velocity contribution also achieves the maximum magnitude. It should be noted that UBEM code did not account for the effects of the wake interference between a rotor blade and windmill in the present study, whereas FAST solver can take into account for the wake dynamic, particularly GDW aerodynamic theory. Both the axial and tangential induction factors.
were applied by FAST solver, simultaneously. Theoretically, the blade element momentum method is not preferred for unsteady or highly skewed flows because of skewed wake correction model and decoupling approach between the dynamic stall routines and wake correction model (Moriarty and Hansen, 2005). The GDW aerodynamic theory which is based on the potential flow solution to Laplace’s equation can be modeled with more flow states and a fully nonlinear implementation to account for the turbulence and spatial variation of the inflow (Suzuki, 2000). Moriarty and Hansen, 2005 also mentioned that the main advantages of GDW method over BEM theory includes inherent modeling of the dynamic wake effect, tip losses, and skewed wake aerodynamics. The dynamic wake effect is the time lag in the induced velocities created by vorticity being shed from the blades and being convected downstream. However, it should be noted that the current wake model of GDW approach has not been developed to account for blade tip-wake interaction at interference regimes when a wind turbine is moving to downstream region because of the pitching motion. On the other hand, the unsteady CFD is able to account for the blade tip-wake interaction at the interference regimes. Therefore, the current results, which were obtained by several numerical tools, showed somewhat different of predicted unsteady aerodynamic power and thrust for a wind

![Fig. 10. Unsteady aerodynamic comparison by the direct local relative velocity method (DLRM) and equivalent averaged method (EqAM) due to the prescribed platform pitching motion.](image-url)

![Fig. 11. Unsteady aerodynamic comparison by the current UBEM and FAST (NREL) due to the prescribed platform pitching motion.](image-url)
turbine experiencing the pitching motion. As shown in Fig. 12, aerodynamic power and thrust increase with respect to a frequency increment of the pitching motion. The amplitude motion of 4° was considered for different frequencies. At a maximum peak of the aerodynamic power curves, the unsteady CFD approximately predicted 6.0 MW and 7.2 MW on the subject of the frequency motion of 1/33 Hz and 1/20 Hz, respectively. Compared to the normal operating condition of a wind turbine without the wave effects, the aerodynamic power approximately rises up 25% and 50%, respectively. Theoretically, these are significant increments for a large wind turbine system when the control system is not activated either because of failure system or does not work properly. On the other hand, the aerodynamic thrusts obtained by the unsteady CFD at the maximum peak zone tend to be slightly different. For UBEM simulation, the big variation of the aerodynamic load responses also appears for different frequencies. Compared to the frequency motion of 0.1 Hz in Fig. 10, the aerodynamic power and thrust also decreased at the different frequencies in Fig. 12. It is concluded that the aerodynamic power and thrust responses are dominated by the frequency motion of the FOWT.

Fig. 13 shows the unsteady aerodynamic power and thrust comparison among CFD, UBEM and FAST solver for different amplitudes and the same frequency of the pitching motion. As mentioned above, the aerodynamic power and thrust also responded the similar frequency to prescribed pitching frequency of FOWT motion in this analysis. Even though small rotation angle due to the pitching motion of an FOWT appears, there is large variation of the aerodynamic load responses. Under the pitching motion with the frequency 0.1 Hz, the aerodynamic power and thrust obtained by unsteady CFD approach raise up to a maximum 4.8–9.4 MW and 697–944 kN since the motion amplitude increases from 0.01 to 4°, respectively. Furthermore, they decrease to a minimum 4.8–0.9 MW and 696–355 kN with respect to 0.01–4° range of the pitching motion amplitude. When the pitching motion amplitude is small, it leads to the small effect of the additional velocity contribution to the FOWT operating. Thus, the aerodynamic performance responses of FOWT are also slightly changed as compared to fixed wind turbine. It is clearly seen in Fig. 13 when the range of the pitching motion is from 0.01 to 0.5°. They become big variation as a sine function since the pitching motion amplitude increases from 1.0 to 4.0°. It should be noted that the range of these motion amplitudes tends to normally exist for the real FOWT. Like previous simulation, FAST with BEM predicted well with the unsteady CFD, whereas FAST with GDW tends to slightly over-predicted. However, this situation is only right since the effect of the additional velocity contribution is small enough. It is clearly shown in Fig. 14 which compares relative error among the numerical approaches respecting the CFD results. The different percentages between FAST with BEM and unsteady CFD are below 5% since motion amplitude range is from 0.05 to 1°. In this range, the effects of the additional velocity contribution are fairly small as compared to freestream velocity. When the additional velocity contribution is large (approximately 3.95 m/s at hub or maximum 6.70 m/s at blade tip since blade is located at 0 o’clock position), the different percentage rise up to 12% and 6% with respect to the aerodynamic power and thrust, respectively. The different percentage between the FAST-GDW and unsteady CFD is almost above 6% and below 4% in relation to the aerodynamic power and thrust, respectively. They exist when the pitching motion amplitude range is from 0.01 to 1.0°. As the pitching motion amplitude increases up to 4°, they rise up to 9.0% and 5.6% with respect to the
Fig. 13. Aerodynamic comparison by present UBEM, CFD and FAST (NREL) for the different amplitudes of the pitching motion of an FOWT (Freq = 0.1 Hz).

Fig. 14. Relative error comparison (CFD-based) by the present UBEM and FAST (NREL) for the different amplitudes of the pitching motion of an FOWT (Freq = 0.1 Hz).
The aerodynamic power and thrust, respectively. Aerodynamic loads obtained by UBEM still over-predicted with the maximum difference of 18%. It can be concluded that traditional analysis tools such as BEM, GDW are still available for the FOWT analysis if the pitching motion amplitude is small enough. In the other word, the unsteady CFD should apply for large pitching motion of the FOWT.

Fig. 15 shows the comparison of the aerodynamic power and thrust responses obtained from different amplitudes and the same frequency. It should be noted that the amplitude of the motion can be much more different depending on the floating types. The amplitude motions, herein, was relatively selected so that the aerodynamic performance simulation of the FOWT can be clearly compared by the different numerical approaches. As shown in Fig. 15, the trend of predicted aerodynamic responses among solvers seems to predict well. They also behave as a sine function with the similar frequency of the pitching motion. The aerodynamic performances are significantly changed even when small motion amplitude of 1.0° exists. In this case, the additional velocity contributions at hub and blade tip are 2.0 m/s and 3.4 m/s, respectively. In fact, these additional velocity contributions are fairly large magnitude as compared to the freestream velocity. That leads to big variation of the aerodynamic power and thrust responses. Unlike other numerical approaches for the case of 4° motion amplitude, UBEM tend to predict the different trend at the maximum peak area. Wake interaction between rotor blade and windmill is not taken into account for the UBEM approaches, whereas the unsteady CFD and FAST do. Because the rotor blade quickly moves away the wake regime as rotor blade move forward, the aerodynamic power and thrust responses tend to be an unsymmetrical pattern as shown in Fig. 15. As shown in Fig. 16, the different percentage of the maximum aerodynamic power and thrust obtained by FAST-GDW achieve to approximately 24% and 16%, respectively. In the other hand, FAST-BEM approach predicted approximately 15.5% different percentage of both aerodynamic power and thrust. This different percentage is significantly changed compare to the pitching motion with the same magnitude of 4° and the different frequency of 0.1 Hz in previous case. Compare to previous case, UBEM tend to be good prediction with maximum different percentage of 16% for the aerodynamic thrust as shown in Fig. 16. For current assumption of EqAM method, the additional energy which is basically transmitted to the rotor due to the platform pitching motion is uniformly distributed along spanwise direction on turbine blade. This energy moderately increases with the increments of magnitude and frequency pitching motion. Therefore, the aerodynamic load of local blade sections obtained by EqAM approach tends to be somewhat difference with that of DRLM approach. It is a proper reason there are somewhat discrepancies of aerodynamic power and thrust on current study.

4.3 Unsteady aerodynamic effect due to platform pitching motion with different rotating center locations

Platform designs can generally be classified into three “stability classes” according to a primary way in which they achieve static stability: via ballast, buoyancy, or mooring lines. Ballast-stabilized designs rely on a deep draft and heavy ballast to make the center of gravity (CG) of a platform lie below its center of buoyancy, thus ensuring hydrostatic stability in all circumstances. Buoyancy-stabilized
designs rely on a large water plane area to raise the platform’s metacenter above its center of gravity. These designs are generally shallow-drafted with a center of mass near the waterline. Mooring-stabilized platforms often called tension leg platforms (TLPs) make use of tensioned usually vertical mooring lines to hold the platform below the waterline. In the present study, the center mass location of a full floating offshore wind turbine system has been considered to address the unsteady aerodynamic effect of a rotor blade. For example, the mass center is located about 77.77 m below the seawater lever (SWL) for the OC3-Hywind spar-buoy platform.

Fig. 17 shows the unsteady aerodynamic comparison of the different center mass location of a full FOWT system. Those results were obtained by the unsteady CFD analysis. One can be seen that the aerodynamic load responses largely vary with respect to the CG location. The aerodynamic power and thrust increase as the CG location moves down from the sea water level. For pitching motion with an amplitude of 4° and frequency of 0.1 Hz, a maximum aerodynamic power achieves 9.0 MW and 11.4 MW with respect to the CG location at the sea water level of 0 m and below the sea water level of 77.77 m, respectively. Both CG location conditions have the similar aerodynamic power when an angular velocity is equal zero as shown in Fig. 16. At zero angular velocity, a rotor blade rotates 180° or 540° with respect to 2.5 s and 7.5 s in the pitching motion period. Although small amplitude motion of 1° and normal frequency of 0.1 Hz, large variation of the aerodynamic responses happen in this simulation. The aerodynamic thrust
responses seem to be lower variation than the aerodynamic power. However, it largely varies with respect to the different CG locations.

Fig. 18 shows typical the pitching amplitude of the platform motion with reference to a time or azimuth angle of rotor blade.

The instantaneously turbine rotor position due to this pitching motion is illustrated in Fig. 19. The computed iso-surfaces clearly show instantaneous vortices beyond a wind turbine rotor experiencing prescribed pitching motion in Fig. 18. Both side-view and iso-view of vortices visualization have introduced. The blade tip vortices are strong and stable as the platform motion does not exist as shown in the left-hand side figures of Fig. 19. Strong vortices also detach from the roots of the blades where the geometry changes quickly from the DU40 airfoil profile to the cylindrical posts attached to the hub. Notice that the vortical structures dissipate quickly away from the regions covered by the grid refinements, downstream of the rotor plane and at tower below 1 blade length as shown in Fig. 8. The complex physical flow can be only captured using the advanced CFD method. When rotor blade moves backward and achieves maximum pitching amplitude motion or zero value of motion angular velocity at time $T_1 = T/4$ s, it tends to deeply move in interference regime of its wake, subsequently. Thus, it results in the disappearing of vortices behind rotor blade. Its length also decreases as shown in the iso-view of Fig. 19(c). Then, the rotor blade moderately moves forward. Therefore, motion angular velocity regularly increases to the maximum magnitude at $T_2 = 2T/4$ s and subsequently decreases to minimum value at time $T_3 = 3T/4$ s. The vortices visualization at time $T_3$ and $T_4$ clearly shows the effects of the wake interference regime between the rotor and blade. The fully attached flows on

![Fig. 18. Platform pitching angle profile (Amp=4.0°, Freq=0.1 Hz).](image1)

![Fig. 19. The instantaneous computed vortices visualization for the unsteady FOWT simulation represented by an isosurface of magnitude velocity contour (Amp=4°, Freq=0.1 Hz).](image2)
the blade surfaces and hub surface increase as wind speed concurrently increases with the motion angular velocity. The different attached flows behind the trailing edges of the rotor blade may indicate that the additional velocity contribution on each rotor blade is the different magnitude. Additionally, the gap distance between two vortices cycles tend to increase as the rotor blade move forward. Again, tip vortices disappear when rotor blade move backward as shown in last right-hand side figures of Fig. 19. It is concluded that the unsteady CFD simulation tool is the best approach to highlight a complex flow-field behind the FOWT. The physical flow patterns can be impressively captured through unsteady CFD method.

5. Conclusions

The flow-field around a rotor blade of the floating offshore wind turbine is a complex behavior under the influences of the aerodynamic, ocean waves, current sea, hydrodynamic and so on since the support platform of a wind turbine system has six rigid-body modes of motion. It is believed that there are large aerodynamic effects on the floating wind turbine, even in a small amount of the floating motions of the support platform since the tower is very high. In this study, the unsteady aerodynamic analysis for the rotating rotor blades with the floating motion have been successfully performed using both unsteady blade element momentum (UBEM) theory and the unsteady computational fluid dynamics including the moving reference frame and deformable grid techniques. A direct local relative velocity method (DLRM) and proposed equivalent averaged velocity method (EqAM) which have been incorporated with a developed in-house UBEM code have been successfully applied for the complex aerodynamic simulation of the rotating blades with oscillating motions. Proposed equivalent averaged velocity method had a good consistent with the direct local relative velocity method. Three numerical approaches including UBEM, FAST with BEM and GDW have been applied the proposed method to compare the predicted unsteady aerodynamic performance each other. The predicted aerodynamic power and thrust obtained by CFD, UBEM, and modified FAST’s AeroDyn showed overall good agreement in case of small pitching motion amplitude such as 1°–2°. It is however importantly found for the present model that there are about 24% differences among predicted results for increased amplitude pitching motions such as 4°. These traditional numerical approaches, which still have some theoretical limitations for the full unsteady aerodynamic calculations comparing to the advanced unsteady CFD approach, need to be improved to much more accurately predict the complex aerodynamic interaction phenomena due to FOWT motions. However, using the advanced CFD method with transient turbulent model, the generation of instantaneous blade-tip vortices behind the rotating blades during the platform pitching motion have been successfully captured and visualized, and physically investigated in detail. It is suspected that strong wake interactions between the rotating blades and generated wake due to relatively large amplitude platform pitching motion yield somewhat different prediction of aerodynamic performances. The existence of different gap distance for blade-tip vortices depending on time is one of evidences to show strong interactions between the rotating blades of an FOWT and its generated wakes. It becomes decreased and increased as the wind turbine moves downward (downstream) and forward (upstream) zones, respectively. It is also importantly shown in this paper that the generated wake strength behind the rotating blades during the forward pitching motion is stronger than that during the backward pitching motion. Although blade pitch controller was not considered in this study to perfectly make the same analysis condition as an academic purpose, this effect deserves to be practically considered in the future works.

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