Dynamic response of floating substructure of spar-type offshore wind turbine with catenary mooring cables

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Abstract

The station keeping and the rotational oscillation control are important to secure the dynamic stability of spar-type floating offshore wind turbine subject to irregular wind and wave excitations. Those are usually evaluated in terms of rigid body dynamic response of floating substructure which supports whole offshore wind turbine. In this context, this paper addresses the numerical investigation of dynamic response of a spar-type hollow cylindrical floating substructure moored by three catenary cables to irregular wave excitation. The upper part of wind turbine above wind tower is simplified as a lumped mass and the incompressible irregular potential wave flow is generated according to the Pierson–Moskowitz spectrum. The wave-floating substructure and wave-mooring cable interactions are simulated by coupling BEM and FEM in the staggered iterative manner. Through the numerical experiments, the time- and frequency-responses of a rigid spar-type hollow cylindrical floating substructure and the tension of mooring cables are investigated with respect to the total length and the connection position of mooring cables.

1. Introduction

Wind turbines are only used to extract the renewable energy from the wind, and those were initially designed for installing on land and showed the rapid increase in both the total number of wind turbines installed and the maximum wind power capacity (Hansen and Hansen, 2007). However, this rapid increase encountered several obstacles such as the substantial environmental impact on people living in the vicinity of wind turbines, the limitation of being high-capacity and making large wind farm. This critical situation naturally turned the attention to the offshore sites, a less restrictive installation place. Offshore wind turbines are classified largely into two categories, fixed- and floating-type according to how the wind turbine tower is supported. Differing from the fixed-type, the floating-type wind turbine is under the concept design stage because several core technologies are not fully settled down (Karimirad et al., 2011), particularly the maintenance of dynamic stability against irregular wind, wave and current loads (Faltinsen, 1990).

In order to secure the dynamic stability of floating-type offshore wind turbine, the station keeping at sea and the rotational oscillation control becomes critical (Tong, 1998). Because of this essential requirement, the floating-type offshore wind turbine requires additional equipments like substructure, mooring lines or tension legs and anchors, when compared to the fixed-type. And, those are classified according to how is generated the righting moment or draft control, such as submerged-, TLP (tension-leg platform)- spar-types (Lee, 2008; Jonkman, 2009), and barge-type FOWT. However, all the types have some things in common from the fact that the station keeping and the vertical and rotational oscillation control of them are secured by a combined use of the buoyancy force and the tension of mooring lines or tension legs.

In case of spar-type floating wind turbine, the buoyancy force produced by a long hollow cylindrical substructure supports the whole offshore wind turbine and the tension of mooring lines keeps the station position of spar-type floating substructure. The pitch and roll stability can to a large extent be maintained by the pitch and roll stiffness of spar-type floating substructure which increases in proportional to the metacentric height (i.e., the vertical distance between the metacenter and the center of mass) (Koo et al., 2004) and the relative distance between the centers of gravity and buoyancy (Karimirad et al., 2011). In addition, it is also influenced by both the tension magnitude and the connection position of mooring lines, and it could be improved further when passive tuned liquid damper (TLD) or/and active control using water ballast are employed (Lee, 2005; Lee et al., 2006; Colwell and Basu, 2009; Seo et al., 2012). Here, the pitch and roll stiffness is meant by the pitching and rolling moments required to pitch and roll the substructure by unit angle.
The dynamic response of spar-type offshore wind turbine to wind and wave excitations is usually evaluated in terms of rigid body degrees of freedom of floating substructure. The station keeping referring to the horizontal degrees of freedom, surge and sway are largely influenced by the mooring system, while the other degrees of freedom are mainly affected by the floating platform characteristics.

This subject has been studied by experimentally using small-scale prototypes (Nielsen et al., 2006; Utsunomiya et al., 2010; Goopee et al., 2012), by analytically/numerically with the simplified wind turbine geometry and the analytically derived wind/wave loads (Tracy, 2007; Lee, 2005; Karimirad, 2010; Dodaran and Park, 2012), or by the combined use of CFD, hydro, FSI (fluid-structure interaction) or/and MBD (multibody dynamics) codes (Zambrano et al., 2006; Jonkman, 2009; Jonkman and Musial, 2010). In case of numerical simulation, 3-D full Navier–Stokes equations are rarely used because extremely long slender mooring lines not only require a large simulation domain but cause highly turbulence flow around them. Because of this numerical difficulty, water flow around substructure and mooring lines is usually assumed to be potential flow (Ansys, 2012).

The purpose of the current study is to numerically investigate the dynamic response of spar-type floating substructure to wave-induced excitation. The upper part composed of wind blades, hub and nacelle is simplified as a lumped mass, and three catenary mooring cables are considered. Sea water is assumed to be potential flow by neglecting the viscosity and compressibility, and the time histories of irregular wave are generated using the Pierson–Moskowitz spectrum (1964). The wave–floating substructure and wave–mooring cable interactions are simulated by the coupled BEM–FEM methods in the staggered iterative approach (Cho et al., 2008). Through the numerical experiments, dynamic responses of cylindrical floating substructure and mooring cables are investigated with respect to the length and connection position of mooring cables and to location of the center of mass of floating substructure.

2. Problem description

2.1. Spar-type floating offshore wind turbine

The most important requirement for renewable energies is the efficiency and capacity, and in this regard wind energy draws an intensive attention because of its potential to generate a huge amount of electricity from plenty of wind around us (Hansen and Hansen, 2007). In particular, floating offshore wind turbines are currently drawing a worldwide attention because the wind power capacity and efficiency can be maximized by constructing wind farm with such next generation wind turbines at deep sea providing stable wind energy. However, for the floating offshore wind turbine, the design of floating substructure becomes a critical subject because it not only supports the whole wind turbine system and but also influences the dynamic stability. Currently, most concerns focus on three types of floating substructures, barge, tension leg (TLP) and spar types.

A typical spar-type floating offshore wind turbine is represented in Fig. 1, where the whole wind turbine is supported by the buoyancy force and the amplitude of rotational oscillations could be reduced by the bottom weight, tuned liquid damper and hydraulic control. Regarding the dynamic displacement of wind turbine which is caused by wind, wave and current loads, only surge and sway displacements are counteracted by the mooring lines when a catenary mooring system is adopted while the displacements in all DOFs are counteracted by tension lines if a TLP system is adopted (Lefebvre and Collu, 2012). The dynamic stability of floating-type wind turbine is evaluated in terms of three translational motions (i.e., surge, sway and heave) and three rotational motions (i.e., pitch, roll and yaw). These six components of the rigid body motion are coupled to each other, and the surge and pitch motions are the most significant factors in the evaluation of the dynamic stability of wind turbine. The dynamic stability of floating-type wind turbine is influenced by gust, wave and current, so most research efforts have been focused on the effects of such aero and hydro excitations.

In general, the pitch stiffness is proportional to the metacentric height, composed of different elements, not only to the distance between the center of buoyancy (CB) and the center of gravity (CG) (Karimirad et al., 2011). Furthermore, if the CG is above the CB, then the more distance theses points are the less stable in the floating structure. As well as, the connection position and tension of mooring lines do also influence the pitch stiffness of the floating substructure. Among available mooring systems, catenary mooring composed of fabric ropes and steel chains is widely adopted because of its topological simplicity and cost effectiveness (Wu, 1995). Catenary mooring cables are anchored at seabed and connected to the floating substructure, and they have small flexural stiffness so that external loads are resisted by the in-line tension. Here, the external loads include the self weight, the hydrodynamic drag forces in the normal, tangential and bi-normal directions, and the added inertia force stemming from surrounding sea water (Vaz and Patel, 2000). The extremely small diameter of catenary cables easily causes large-eddy turbulent flow around cables, so that the equilibrium configuration is usually computed by the geometrically nonlinear cable dynamics.

2.2. Wave model

A wave spectrum is the distribution of wave energy in function of frequency which describes the total energy transmitted by a wave-field at a specific time. As one of the simplest spectra which are widely used, the Pierson–Moskowitz (Pierson and Moskowitz, 1964) is an empirical relationship between the energy distribution and frequency of irregular wave at sea. It is suitable for decomposing a sea-state into several sinusoidal wave components. It is based upon the assumption that wave reaches the equilibrium state, known as a fully developed sea wave, if wind blows steadily for a long time over a large area. The energy density \( S(\omega) \) \((m^2/Hz)\) of wave in the Pierson–Moskowitz spectrum is defined by (Pillai and Prasad, 2000)

\[
S(\omega) = \frac{2H_s}{T_z^2} \frac{1}{\omega^5} \exp\left(-\frac{2}{3} \frac{2}{T_z \omega}\right)
\]

where, \( \omega \) \((rad/s)\) is the wave frequency, \( H_s \) \((m)\) the significant wave height, and \( T_z \) \((s)\) the zero crossing period. Fig. 2(a) shows a typical energy density distribution when the significant wave height \( H_s \) and the zero crossing period \( T_z \) are 1.0 m and 10 s, respectively.

For a given wave spectrum, the time history of irregular wave can be generated by linear superposition of harmonic wave components (Kim, 2001), as represented in Fig. 2(b). Then, the wave height \( \eta(x,t) \) is expressed by

\[
\eta(x, t) = \frac{1}{2} \sum_{n=1}^{N} A_n \cos(k_n x - 2\pi f_n t + \phi_n)
\]

with the wave number \( k_n \), the wave frequency \( f_n \), the wave amplitude \( A_n \), and the phase angle \( \phi_n \). And, the relationship between the energy density \( S(\omega) \) and the wave amplitude \( A_j \) for
the $j$-th wave component is given by (Faltinsen, 1990)
\[
\frac{\alpha_j^2}{2} = \frac{S(\omega_j) (\omega_{\text{max}} - \omega_{\text{min}})}{N}
\]
In which, the frequency range is divided by the number of $N$, and the maximum and minimum frequencies $\omega_{\text{max}} = 0.1$ Hz and $\omega_{\text{min}} = 0.01$ Hz are determined from the Pierson–Moskowitz spectrum.

3. Fluid–rigid body interaction problem

Referring to Fig. 3(a), let $\Omega_\text{F} \in \mathbb{R}^3$ be a semi-infinite unbounded flow domain with the boundary $\partial \Omega_\text{F} = S_F \cup S_B \cup \Gamma_I$ and $\mathbf{V}$ denotes a continuous triple-vector water velocity field, where $S_F$, $S_B$ and $\Gamma_I$ indicate the free surface, seabed and flow-structure interface respectively. Water is assumed to be inviscid and incompressible and water flow is irrotational so that there exists a velocity potential function $\phi(x; t)$ satisfying
\[
\phi(x; t) : \mathbf{V} = \nabla \phi
\]
The velocity potential function $\phi(x; t)$ is defined by
\[
\phi(x; t) = \sum_{j=1}^{6} \phi_j + \phi_w + \phi_d
\]
with $\phi_j$ due to the rigid body motion of structure, $\phi_w$ due to undisturbed incoming wave and $\phi_d$ due to diffraction of the undisturbed incoming wave, respectively. Then, the flow field is governed by the continuity equation
\[
\nabla^2 \phi = 0, \quad \text{in} \quad \Omega_\text{F} \times (0, \tilde{t})
\]
and the boundary conditions given by
\[
\frac{\partial \phi}{\partial n} = \mathbf{u} \cdot \mathbf{n}, \quad \text{on} \quad \Gamma_I
\]
\[
\frac{g}{\partial z} \frac{\partial \phi}{\partial t} + \frac{\partial^2 \phi}{\partial t^2} = 0, \quad \text{on} \quad S_F
\]
\[
\frac{\partial \phi}{\partial z} = 0, \quad \text{on} \quad S_B
\]
with $\tilde{t}$ being the time period of observation, $\mathbf{u}$ the displacement vector of the rigid body, $g$ the gravity acceleration, $\mathbf{n}$ the outward unit vector normal to the structure boundary. Eq. (8) is a unified free surface condition derived from the linearized dynamic and kinematic conditions on $S_F$ by neglecting the surface tension (Cho and Song, 2001; Cho et al., 2005). In addition, the potential function satisfies the radiation condition: $\phi \to 0$ as $r \to \infty$ at the far field.

The substructure occupying the material domain $\Omega_S \in \mathbb{R}^3$ with the boundary $\partial \Omega_S = T_D \cup T_N \cup \Gamma_I$ is assumed to be a rigid body. By denoting $[\mathbf{d}, \vartheta]$ be its rigid body translation and rotation at the
center of mass, the dynamic motion of the substructure is governed by the conservation of linear and angular momentums
\( (i = x, y, z) \)

\[
m \ddot{d}_i + c \dot{d}_i + k d_i = F_i, \quad \text{in } \Omega_5 \times (0, \tilde{t})
\]

\[
I \dddot{\theta}_i + c_i \dot{\theta}_i + k_i \theta_i = M_i, \quad \text{in } \Omega_5 \times (0, \tilde{t})
\]

and the initial conditions given by

\[
|d, \theta|_{t=0} = |d_0, \theta_0|, \quad |d, \theta|_{t=0} = |d_0, \theta_0|
\]

In which, \( m, c_i, k_i, c_i^t \) and \( k_i^t \) denote the total mass and the damping and stiffness coefficients for the translational and rotational degrees of freedom, respectively. Meanwhile, \( \gamma_i \) indicate the mass moments of inertia with respect to the center of mass, and \( \mathbf{F} \) and \( \mathbf{M} \) are the external force and moment vectors, respectively, which are calculated by

\[
\mathbf{F} = \int_{\Gamma} \mathbf{p} \mathbf{n} \, ds
\]

\[
\mathbf{M} = \int_{\Gamma} \mathbf{p} \times \mathbf{n} \, ds
\]

Here, \( \mathbf{p} \) and \( \mathbf{r} \) are the hydrodynamic pressure and the position vector from the center of mass, respectively.

Meanwhile, catenary mooring cable of length \( l \) is a slender flexible structure subject to hydrodynamic pressure, self weight, inertia force and drag force. Referring to Fig. 3(b), the nonlinear differential equations of motion \( (\text{Goodman and Breslin, 1976; Aamo and Fossen, 2000}) \) for the differential cable element \( d' \) are governed by the equilibrium equations in translation and rotation,

\[
(m_c + m_a) \frac{\partial \dot{\mathbf{u}}_c}{\partial t} + \frac{\partial T_c}{\partial s} + (1 + \gamma)\mathbf{F}_c
\]

\[
\frac{\partial M_c}{\partial s} = -\mathbf{r}_c \times (1 + \gamma)\mathbf{T}_c
\]

and the compatibility equation

\[
\frac{\partial \mathbf{u}_c}{\partial t} = \frac{\partial}{\partial t}((1 + \gamma)\mathbf{r}_c)
\]

with the boundary conditions given by

\[
\mathbf{u}_c = 0, \quad \dot{\mathbf{r}}_c = \dot{\theta}_c^B \quad \text{at } s = 0 \quad (\text{at seabed})
\]

\[
\mathbf{u}_c = \mathbf{d}_p, \quad \dot{\mathbf{r}}_c = \dot{\theta}_c^B \quad \text{at } s = L \quad (\text{at connecting point})
\]

In which, \( m_c \) indicates the mass per unit arc length, \( m_a \) the added mass of water, \( \mathbf{u}_c \) the velocity vector, \( s \) the arc length of unstressed cable, and \( \gamma \) is the engineering strain. In addition, \( \mathbf{r}_c \) is the vector tangent to the cable center line, \( \mathbf{M}_c \) the resultant internal moment, and \( \mathbf{F}_c \) the external loading per unit arc length due to the self weight \( \rho_c g \), and \( \mathbf{F}_n \), \( \mathbf{F}_t \) and \( \mathbf{F}_b \) the normal, tangential and binormal

\[
\text{drag forces (Morison et al., 1950). Here, the unit vector } \mathbf{q} \text{ in the bi-normal direction is defined by } \mathbf{q} = \mathbf{u}_c \times \mathbf{r}/|\mathbf{u}_c \times \mathbf{r}| \text{ with } \mathbf{r} \text{ being the tangential unit vector. Eq. (16) and the associated boundary conditions are excluded when the flexural stiffness of catenary cables is neglected.}

The potential flow governed by Eqs. (6)–(9) is interpolated by the boundary element method while the dynamic motions of the rigid floating substructure and mooring cables are approximated by the finite element method. For the rigid body dynamic motion analysis, only the surface of rigid floating substructure is discretized with 2-D finite elements and each mooring line is divided into a finite number of line elements. A two-step predictor–corrector method \( (\text{Cong, 1996; Kim and Kim, 2001}) \) is used for the time integration of the equations of motion. The Euler–Lagrange-type coupling method is employed to deal with the interaction between the rigid body structure motion and the water flow, and it with the lapse of time is numerically implemented in a staggered iterative manner \( (\text{Sigrist and Abouri, 2006; Cho et al., 2008}) \). The hydrodynamic pressure of water flow acts as the external force and moment for both the floating substructure and mooring cables, and then the rigid body movement of floating substructure relocates the flow-structure interface. This staggered computation iterates up to the preset time period of observation.

### 4. Parametric sensitivity study

A spar-type floating offshore wind turbine with three equal catenary mooring cables is taken for the parametric numerical experiments of dynamic responses of the cylindrical floating substructure and mooring cables. The geometry dimensions and total masses of the major components are recorded in Table 1. Referring to Fig. 4(a), three rotor blades, hub and nacelle assembly are simplified as a lumped mass, and the whole rigid body composed of the top lumped mass, tower and substructure is discretized with the total of 2,920 10-node hexahedron elements. The center of buoyancy (CB) and the center of mass (CM) are
measured from the free surface of water and the relative vertical distance between two centers is set by 10.0 m.

The section dimensions of the water pool are set by $500 \times 500$ m$^2$ and the depth from seabed is set by 200 m, respectively. The free surface coincides with the interface between tower and floating substructure, and the significant wave height $H_s$ and the zero crossing period $T_z$ in the Pierson–Moskowitz spectrum are set by 1.0 m and 10 s respectively. The water depth is chosen from the fact that floating offshore wind turbines are typically installed at sea of water depth 100–300 m, and the section dimensions of the water pool are chosen so as to sufficiently cover three mooring cables by considering the CPU time required for the numerical simulation. Two parameters $H_s$ and $T_z$ in the Pierson–Moskowitz spectrum are chosen referring to the sea state between 2 and 3 (Wayman et al., 2006). The total length of all three catenary mooring cables is taken variable and the angles between two adjacent catenary cables are 120°, while the horizontal distance $d_c$ between anchor and the substructure is always kept by 200 m.

Three equal catenary mooring lines are aligned as represented in Fig. 4(b) where the wave direction opposes to the x-direction. The directions of six components of the rigid body motion of floating offshore wind turbine follow the convention shown in Fig. 1(b). The fluid–rigid body interaction simulation was carried out by the commercial FEM software ANSYS AQWA (Ansys, 2012). The time and frequency responses of rigid floating substructure and the cable tension are parametrically investigated with respect to the total length and connection position of three mooring cables.

4.1. To the total length of mooring cables

Figs. 5 and 6 represent the time and frequency responses of surge and pitch motions when three mooring cables with the total length $L$ of 290 m are connected to the center of buoyancy. Considering the cable installation position at the center of buoyancy and the horizontal distance $d_c$ of anchor, there is always a fraction of the mooring cables laying on the seabed when the total cable length is longer than 260 m. And, such a fraction does not have any influence on the cable tension because its weight is counteracted by the seabed reaction. The surge motion at the center of mass shows the sine-wave-like time history with the peak amplitude of 2.1 m. Meanwhile, the substructure shows a small pitch motion with the peak amplitude near 0.5° at the beginning and then it exhibits a beating-like pitch motion with the peak amplitude greater than 2.2°, implying that the rotational inertia of floating substructure is remarkable. One can see two apparent surge resonance frequencies from Fig. 5(a), the lowest one of 0.0029 Hz and the other one of 0.0324 Hz, where the latter is identical to the first pitch resonance frequency, showing the coupling between surge and pitch motions. Thus, it has been confirmed from the frequency response that the natural
frequencies of rigid body motion of spar-type floating substructure are remarkably low (Tracy, 2007; Lee, 2008).

Fig. 7(a) represents the dependence of the peak amplitude in the frequency response of surge motion on the total length $L$ of catenary cables, for which the total length was increased by 10 m from 260 m to 350 m. The peak amplitude of surge motion decreases in proportional to the total length, which can be also observed from Fig. 7(b) showing the variation of the peak amplitude in the frequency response of pitch motion. The dynamic system of floating substructure and catenary cables becomes more sensitive to the external wave excitation as the cable length decreases, because the cable tension increases when the catenary cables becomes tightened. But, it is observed that the peak amplitudes in both surge and pitch motions approach certain values, implying that an appropriate cable length which can prevent the excessive rigid body dynamic motion of floating substructure could be chosen.

The variation of cable tension to the cable length is evaluated in terms of the peak value and RMS (root mean square) in its time responses. It is observed from Fig. 8 that the tensions of three catenary cables do commonly drop abruptly from $L = 260$ m to $L = 270$ m but the decrease significantly slows down thereafter. The laying of mooring cables on the seabed starts when the total cable length becomes longer than 260 m as addressed in the previous paragraph, and such a fraction of the mooring cables becomes significant when the total cable length is longer than 270 mm. Since the cable tension is influenced by only the suspended fraction of mooring cables, the cable tension abruptly drops up to the total cable length of $L = 270$ m and then the
influence of the total cable length on the cable tension becomes insignificant. This tendency is consistent well with the variation of peak amplitudes shown in Fig. 7 to the cable length, where the peak surge amplitude steeply decreases at such a critical interval of cable length and vise versa for the peak pitch amplitude.

Cables 1 and 3 exhibit almost the same cable tension but cable 2 produces the cable tension smaller than cables 1 and 3 at the critical interval of cable length, but three cables show almost the same magnitude beyond such a critical length interval. Considering the relative orientation of three mooring cables to the wave direction, cables 1 and 2 experience the similar remarkable extension and relaxation but cable 3 does not experience the remarkable extension. Thus, cable 3 shows the relatively lower tension than cables 1 and 2 in the critical interval of cable length. Beyond such a critical interval, the significant decrease in both the suspended fraction of mooring cables and the surge and pitch amplitudes lead to almost the same magnitude in three cable tensions. As well as, such a difference in the cable tensions of three cables becomes negligible when the cable tension is measured in RMS, because cables 1 and 2 experience larger fluctuation in time responses of cable tension than cable 3.

4.2. To the connection position of mooring cables

Next, the effects of the cable connection position on the surge and pitch motions of the spar-type floating substructure and the cable tension are investigated. The total cable length is set by \( L = 300 \, \text{m} \) where the peak surge amplitude is lowest. The connection position is measured from the free surface of sea water as represented in Fig. 9 and five different positions are considered. The detailed connection positions are 22.5 m for case I, 27.5 m for case II, 32.5 m for case III, 37.5 m for case IV and 42.5 m for case V respectively, and the connection positions for each case are kept same for all three mooring cables.

It is observed from Fig. 10(a) that the peak amplitude in the frequency response of surge motion slightly decreases until the cable connection position reaches the center of buoyancy (CB). But, it dramatically increases as the connection position becomes lower from such a critical position. It is because the horizontal dynamic motion of the center of mass becomes more sensitive to the cable tension as the cable connection position approaches to the center of mass. On the other hand, the cable tension tends to increase the surge motion while suppressing the pitch motion as the cable connection position goes up above the center of buoyancy. Thus, in aspect of surge motion, the dynamic stability is the best when mooring cables are connected to the center of buoyancy. On the other hand, it is found from Fig. 10(b) that the peak amplitude in the frequency response of pitch motion monotonically increases as the connection position goes down from the free surface of sea water. But, the slope of increase is different whether the connection position is above or below the center of buoyancy. It is because the moment resisting to the pitch motion by the cable tension increases in proportional to the distance (i.e., the length of moment arm) between the cable connection position and the center of mass. Thus, it is convinced that the surge and pitch motions could be minimized when mooring cables are connected to the center of buoyancy or slightly above the center of buoyancy.

The variation of cable tension to the cable connection position is also investigated in terms of the peak value and RMS (root mean square) in the time responses of each mooring cable. It is observed from Fig. 11 that the peak and RMS tensions of all three mooring cables show the uniform decrease as the cable connection position goes down. It is generally consistent with the trend shown in Fig. 10 that both the peak amplitudes in pitch and surge motions increase as the cable connection position goes down. Referring to Fig. 9, the suspended length of mooring line becomes shorter as the cable connection position goes down if both the total cable length and the anchor position at seabed are kept the same. Thus, such a decrease of the cable suspended length makes the cable tension lower as the cable connection position goes down, resulting in the increase of the peak amplitudes in pitch and surge motions of the floating substructure to the cable connection position. This trend is clearly distinguished from one with respect to the total cable length shown in Fig. 8, where the cable tension approaches a certain limit as the total cable length increases beyond a critical length.

![Fig. 9. The connection position of mooring cables.](image)

![Fig. 10. Variation of the peak amplitudes in frequency responses to the cable connection position: (a) surge and (b) pitch.](image)
5. Conclusion

In this paper, the dynamic responses of a rigid cylindrical floating substructure moored by three catenary cables to one-dimensional irregular wave have been investigated by the fluid–rigid body interaction simulation. The upper part of offshore floating-type wind turbine above wind tower is simplified as a lumped mass and both the wind tower and floating substructure was assumed to be rigid. The incompressible potential wave flow in Eulerian domain was generated by the Pierson–Moskowitz spectrum, and the wave-floating substructure and wave-mooring cable interactions were simulated by the coupled iterative BEM–FEM methods. The time and frequency responses of the rigid floating substructure and the cable tension were parametrically investigated with respect to the total length and connection position of catenary cables. According to the parametric numerical results the following main observations are drawn.

1. The moored cylindrical floating substructure exhibits the sine-wave-like surge response and the beating-like pitch response, and it shows two apparent resonance frequencies, one by the excitation wave and the other by the extensional vibration of mooring cables.

2. The surge and pitch motions of floating substructure become less sensitive to the external wave excitation such that the peak amplitudes in surge and pitch motions generally decrease as the total cable length increases. Meanwhile, the peak cable tension drops abruptly from $L = 260$ m to $L = 270$ m but it approaches a certain limit whereafter.

3. To the connection position of catenary cables, the peak amplitude in surge motion slightly decreases until the connection position reaches the center of buoyancy, but it dramatically increases as the connection position becomes lower than such a critical position. Meanwhile, the peak amplitude in pitch motion monotonically increases as the connection position goes down. The peak cable tension shows the uniform decrease as the cable connection position goes down.

4. Restricted to the current cylindrical floating substructure dealt with in this paper, it has been found that the surge and pitch motions could be minimized when three catenary cables with the total length $L$ larger than 270 m are connected to the center of buoyancy or slightly above the center of buoyancy.

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