A Numerical Study of the Motion and Structural Responses of Interlinked Spars in Irregular Waves

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A numerical analysis has been made of the motion characteristics and structural responses of interlinked spars of three different arrays in irregular waves. The goal of the study is to clarify the behavior of the interlinked structure as a new type of platform for offshore wind turbines and to establish its design criteria. The numerical model used herein includes the connectors and taut/catenary mooring lines, but aerodynamics and rotor-dynamics are not considered. Both the connectors and the mooring lines are modeled by elastic beams. The minimum energy principle and Lagrange multiplier method are applied to formulate the governing equation for the dynamics of the connectors and mooring lines. Numerical solutions are obtained by using an in-house finite element method (FEM) code. Meanwhile, hydrodynamic coefficients are calculated by using an in-house code based on the nine-node higher-order boundary element method. The performances of three different arrays of the interlinked spars are evaluated and compared in terms of the motion of the structure and the tensile force and bending moment of the connectors. It is found that the three arrays considered in this work show motion behavior and structural responses similar to those of a single spar. Therefore, the arrayed structures can be considered positively as a new type of offshore wind farm, because the construction cost for mooring lines, power cables, and installation can be largely reduced, and the hydrodynamic and elastic behavior is favorable.

INTRODUCTION

The demand for renewable energy resources has steadily increased in response to concerns over the shortage of fossil fuel as well as the inherent impact on the environment. Offshore wind energy has emerged globally as one of the most promising forms of renewable energy. For example, EU countries such as the UK, Germany, and Norway have agreed to set a goal for making offshore wind energy 20% of the total domestic energy production in each country in 2015 (EWEA, 2008).

To access the region in which high energy density is available and to avoid noise pollution issues, the installation depth of offshore wind turbines tends to go deeper and deeper. However, it is less economical to build a fixed offshore foundation in deep water. Thus, a floating offshore wind turbine has been suggested as an alternative to deepwater application. The idea of floating offshore wind turbines was first introduced by Heronemus (1972). The installation depth of the fixed foundation for offshore wind turbines is normally limited to 30 m. Wind resources, however, are more plentiful across the globe in deep-sea areas in waters up to 600 m.

There have been a number of conceptual designs for floating wind turbine structures, such as those in Jonkman (2010), Robertson and Jonkman (2011), Myhr et al. (2011), and Shin (2011). Most of the studies favor the spar-type structures, such as the OC3-Hywind, with different mooring systems, although there are some studies on barge-type and semi-submersible structures. Recently, the concept of Windfloat was proposed based on a semi-submersible concept with a high damping plate (Rodddier et al., 2010).

Three different types of test floating structures for wind turbines were installed in 2011 (Wilkes et al., 2012). Blue H, an 80-kW floating wind turbine located 113 km off the coast of Italy, was first deployed in December 2007. The Blue H technology employed the tension leg platform design with a two-bladed turbine. The first high-capacity, 2.3-MW floating wind turbine, StatoilHydro’s Hywind, was installed 10 km southwest of Karmøy, Norway in September 2009 (Madslien, 2009). In October 2011, Principle Power’s WindFloat Prototype was installed 4 km offshore of Aguçadoura, Portugal in approximately 45 m of water. The WindFloat was equipped with a 2.0-MW wind turbine. This was the first offshore wind turbine installed in the open waters of the Atlantic Ocean, and adopted the semi-submersible-type floating base.

In September 2011, Japan announced a plan to build a pilot floating wind farm with six 2-MW turbines off the Fukushima coast of northeast Japan, where the recent nuclear reactor meltdown invoked a serious shortage of electricity. After the evaluation phase, the proto-structure will be completed in 2016, and then Japan intends to build as many as 80 floating wind turbines by 2020 (Kinoshita, 2012). Furthermore, the state of Maine in the U.S. solicited proposals to build the world’s first floating commercial wind farm in 2010. The U.S. government sought proposals for 25 MW of deepwater offshore wind capacity to supply power over a 20-year contract period by using grid-connected floating wind turbines in the Gulf of Maine.

The feasibility of deepwater floating wind turbines is theoretically possible because floating structures are a proven technology already practiced by offshore oil industries over the last decades. Recent studies demonstrated that floating turbines are becoming more feasible, both technologically and economically, in the global energy market. If offshore wind turbine farms are to be built commercially, the economics will be governed by the design and construction costs of the floating structures and their connection to the electrical grid. Thus, it is important to design economical and safe floating structures and mooring systems to ensure the economical operation of the floating wind farm. The
The basic concept of a floating wind farm is to maximize the economic benefits by grouping the turbines together and thus reducing the separate cost of installation, maintenance, and grid integration. Therefore, the concept of using a multi-unit floating offshore wind farm (MUFOW) is advantageous in terms of cost because MUFOW can save most of the mooring cost (Henderson, 2000).

Recently, Hong et al. (2012) conducted a fundamental study on offshore wind spar structures and obtained promising numerical results. The idea of interlinked structures with connectors was proposed as subsea power transmission ducts replacing the power cable in order to reduce CAPEX (CAPital EXPenditure). At the same time, the connectors could also function as mooring members. However, the connectors, used for linking floaters, were modeled as rigid simple circular cylinders. The study concluded that the connectors cannot be modeled as a rigid body but rather as elastic structural members, as the distance between floaters becomes long.

It is well-known that even though a spar is hardly able to store oil products, this structure has been regarded as one of the promising offshore structures because of its remarkable ability of station-keeping. The previous works indicate that a lot of wind farm projects are developing with the spar-type structure. Also, information about the OC3-Hywind is relatively easy to obtain, compared to obtaining information about other types. For this study, an OC3-Hywind type of floating structure is selected as the numerical model.

This study aims to investigate the performance of moored floating structures connected by elastic circular beam cylinders and mooring lines. This type of structure is a possible new type of platform for offshore wind farms. Elastic beam connectors and catenary mooring lines are modeled by using FEM beam elements. A numerical analysis is carried out for wave-induced motions and structural responses in some sea conditions. Again, aerodynamics and rotor-dynamics are not included in this study.

**MODELING OF ARRAYED FLOATING STRUCTURES**

**Basic Concept and Characteristics of Numerical Models**

In this paper, three different interlinked arrays of floaters are considered: a 5-by-1 horizontal array, a 2-by-2 square array, and a 3-by-3 square array. The separation distance is chosen based on the previous parametric study, namely 500 m between the centers of the neighboring two floaters (Hong et al., 2012). These floaters and mooring line properties are identical to those of the OC3-Hywind (Jonkman, 2010). The basic structural and hydrodynamic characteristics of the connectors are determined by a parameter study with respect to the unit weight, the axial stiffness, and the hydrodynamic coefficients. The schematic view of the integrated system of floating structures, connectors, and mooring lines is shown in Fig. 1. The principal dimensions of the connectors and the mooring lines are listed in Table 1. The floaters are modeled as rigid bodies, and the connectors are modeled as elastic beams. Elongation, bending, and torsion are regarded as negligible for the mooring lines, which act on the motion equation as the restoring force due to their weight. Each mooring line is discretized by 30 elements, and each connector by 40 elements.

**Table 1** Characteristics of connectors and mooring lines

<table>
<thead>
<tr>
<th>Connector</th>
<th>Mooring line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass per unit length [kg/m]</td>
<td>1985</td>
</tr>
<tr>
<td>Mass effective per unit length [kg/m]</td>
<td>49.95</td>
</tr>
<tr>
<td>Axial stiffness [kN]</td>
<td>4.92E+07</td>
</tr>
<tr>
<td>Bending stiffness [kN·m²]</td>
<td>1.28E+07</td>
</tr>
<tr>
<td>Torsional stiffness [kN·m²]</td>
<td>9.86E+06</td>
</tr>
<tr>
<td>Length of each element [m]</td>
<td>9.812</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>1</td>
</tr>
<tr>
<td>Mass coefficient</td>
<td>2</td>
</tr>
<tr>
<td>Diameter [m]</td>
<td>1.57</td>
</tr>
<tr>
<td>Cross-sectional area [m²]</td>
<td>0.239</td>
</tr>
<tr>
<td>Installation vertical position from still water level [m]</td>
<td>–70</td>
</tr>
</tbody>
</table>

Equation 1 can be converted to its counterpart in the time domain as follows:

\[
(-\omega^2[M_B + M_{add}])\{\ddot{u}_B(t)\} - i\omega[C_B]\{\dot{u}_B(t)\} + [K_B]\{u_B(t)\} = \{f_u(t)\}
\]

where \(\omega\) is the wave frequency, \(\{u_B\}\) and \(\{f_u\}\) are \(6n_B \times 1\) vectors of the body motion and the wave force, respectively, and \(n_B\) is the number of floating bodies. \([M_B]\), \([C_B]\), and \([K_B]\) are \(6n_B \times 6n_B\) matrices of mass, hydrodynamic damping, and hydrostatic stiffness, in this order. \([M_{add}]\) is the added mass matrix. In order to estimate the hydrodynamic coefficients, the Green’s function method is used. The discretized shape is represented by nine-node bi-quadratic elements. Through the adoption of higher-order schemes, the quadratic distribution of the physical values of each element is possible, and the convergence of second-order quantities is improved. Details of the boundary element method are well-described in Choi et al. (2001).

Equation 1 can be converted to its counterpart in the time domain by transformation, such as the convolution integral (Cummins, 1962). The external forces can be put to the right side. Then the motion equation in the time domain is arranged as:

\[
[M_B + M_{add}(\infty)]\{\ddot{u}_B(t)\} + \int_{t-\tau}^{t} R(t-\tau)\dot{u}_B(\tau)d\tau + [K_B]\{u_B(t)\} = \{f_u(t)\} + \{f_c(t)\} + \{f_v(t)\} + \{f_w(t)\}
\]

where \(R(t-\tau)\) is the matrix of the retardation function, which is calculated by the relation with the wave damping coefficient. \(M_{add}(\infty)\) is the added mass matrix at the infinite frequency. \(f_c(t)\) and \(f_v(t)\) are the first wave-induced force and the low-frequency wave drift force, respectively. \(\{f_u(t)\}\) and \(\{f_w(t)\}\) are the mooring line force and the connector force, separately. \(f_v(t)\) represents the viscous damping force vector of floating bodies. The i-th component of the viscous damping is expressed by:

\[
f_{vi} = C_{vi}\ddot{u}_{Bi}
\]
where $C_{ij}(i, j = 1, \ldots, n)$ is the viscous damping coefficient. In general, the damping is evaluated as a portion of the critical damping ($C_{ij} = 2 \sqrt{\text{inertia}_{ij} \times \text{stiffness}_{ij}}$), which takes the following form:

$$C_{ij} = 2 \xi_{ij} \sqrt{(M_{B,ij} + M_{add,ij})(K_{B,ij} + K_{m,ij})}$$ (4)

where $\xi_{ij}$ is the damping ratio. In this study, experiments for a single floater (KORDI, 2012) are utilized to determine this damping ratio.

The external force on and the behavior of the mooring lines and connectors are evaluated by using FEM. In the FEM formulation, the minimum energy principle is applied to derive the nonlinear equilibrium equations. Constraint equations due to mooring lines and elastic connectors are included in the potential energy formulation using the Lagrange multiplier method. The core part of the previous works (Kim et al., 2010, 2013) is cited briefly below:

In Fig. 2, $T$ denotes the axial tension in the local coordinate system. The $x$-axis of the local coordinates is defined along the element length, while the $y$-axis and $z$-axis follow the right-hand convection with the $x$-axis. The global coordinate system takes Cartesian coordinates, the origin of which is at the center of floater 1’s waterline area. $l$ is the element length of such a reference line, and $\bar{r}$ is the position vector by local directional displacements, $u_x$, $u_y$, and $u_z$, at $x$. The position vector and Jacobian are given by Eq. 5 and Eq. 6:

$$\bar{r} = (x + u_x, y + u_y, z + u_z)$$ (5)

$$J = \frac{ds}{dx} = \frac{|d\bar{r}|}{ds} = \sqrt{\left(1 + \frac{\partial u_x}{\partial x}\right)^2 + \left(\frac{\partial u_y}{\partial x}\right)^2 + \left(\frac{\partial u_z}{\partial x}\right)^2}$$ (6)

With these definitions, the element contains the potential energy, strain energy induced by bending and torsion, kinetic energy, and external work. Also, the constraint condition for the line length of an element is applied. The potential is rearranged in the matrix form by interpolating $u_x$, $u_y$, and $u_z$ with nodal displacements and the potential’s minimization. The motion equation of nodes and the constraint condition in the local coordinate system are induced by the minimization of the total potential:

$$[M_e][\ddot{u}_e] + [K_e][u_e] + [B] \lambda = -[R][f_{ex}] + [f_e(y_g, u_g)]$$ (7)

where $u_e$ is the displacement vector composed of elements, each term of which is described in Eq. 8:

$$[u_e] = [u_{x1}, u_{x2}, \theta_{x1}, \theta_{x2}, u_{z1}, u_{z2}, \theta_{z1}, \theta_{z2}]^T$$ (8)

$M_e$ and $K_e$ are the matrices for the inertia and the stiffness, respectively, which are explained in Kim et al. (2013). The term $[B]$ is described by Eqs. 9, 10, and 11:

$$[B] = [A] + [C][u_e]$$ (9)

$$[C] = \frac{1}{(J + 1)^2}$$

$$\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$ (10)

$$[A] = \frac{2}{J + 1} [-1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0]$$ (11)

After the minimum energy principle is applied, the terms containing the Lagrange multiplier, $\lambda$, are rearranged in $[B]$ for the sake of simplicity. $R$ is the orthogonal coordinate transform matrix, which satisfies Eq. 12:

$$[R]^T[R] = [I]$$ (12)

$[f_e]$ is the matrix of 6-DOF section forces acting at nodes 1 and 2, as illustrated in Eq. 13:

$$[f_e] = [f_{x1}, f_{y1}, M_{x1}, M_{y1}, f_{z1}, f_{y2}, f_{z2}, M_{z2}, M_{y2}, M_{z2}]^T$$ (13)

$f_{wx}$ is the weight force, as illustrated in Eq. 14:

$$f_{wx} = \frac{Jwl}{2} [0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0]^T$$ (14)

The constraint equation for each element length is as follows:

$$\int_{S} (ds - dx) = s - l$$ (15)

where $s$ is the element length in the equilibrium position. If a pure catenary is assumed, $s$ becomes:

$$s = s_0$$ (16)

If the effect of elastic deformation is considered as well as the catenary behavior, the length will be changed as follows:

$$s = s_0 \left(1 + \frac{T}{EA}\right)$$ (17)

A coupled solution is obtained by solving Eq. 2 and Eq. 7 iteratively by using a bisectional method. The Newmark–$\beta$ method for FEM analysis and the Hamming method for the higher-order boundary element method are used for time marching. Relative errors for convergence are set at 0.1% in the floater solver and 0.01% in the mooring and connector solvers.
VALIDATION OF DEVELOPED NUMERICAL SCHEME

Firstly, the line dynamics are examined. The static deformation of a connector is calculated and compared with the analytic solution given by Eq. 18 (DNV, 2011) and with a reliable commercial code (OrcaFlex), as shown in Fig. 3:

\[
x(s) = \left(1 + \frac{T_0}{EA}\right)s - \frac{1}{6}\left(\frac{w}{T_0}\right)^2 s^3 [m]
\]

\[
z(s) = -z_m + \frac{1}{2} \frac{w s^2}{T_0} \left(1 + \frac{T_0}{EA}\right) [m]
\]

(18)

where \(EA\) represents the axial stiffness, \(T_0\) is the pre-tension, \(w\) is the effective weight per unit length, and \(s\) is the horizontal distance from the origin. Connector ends are restrained in planar motions, while rotations are freely permitted. It was confirmed that the static equilibrium position can be predicted precisely.

Static pull-out tests in the surge direction are also made. The effective tension acting on the end of a connector is shown in Fig. 4. In the axial stiffness dominant region (0 ∼ 20 excursion), the present result shows good agreement with the commercial code. The forced oscillation of the right end in the vertical direction is conducted. The natural frequencies of a cantilever beam are described in Eq. 19 (Meirovitch, 1967):

\[
\omega_1 = 1.875^{2} \sqrt{\frac{EI}{mL^4}}; \quad \omega_2 = 4.694^{2} \sqrt{\frac{EI}{mL^4}}; \quad \omega_3 = 7.855^{2} \sqrt{\frac{EI}{mL^4}} (19)
\]

In this problem, the 1st, 2nd, and 3rd natural frequencies are 0.0747 rad/s, 0.4679 rad/s, and 1.3102 rad/s, respectively. The 3rd mode of the harmonically excited beam is illustrated in the upper part of Fig. 5, while the 2nd mode is described in the lower part of Fig. 5. The mode shapes are well-compared in both cases. Based on these results, it is believed that the present FEM module can predict well the static and dynamic behavior of line elements.

One floater case is then simulated. It is modeled the same as the OC3-Hywind project, a spar-type floater moored by 3 lines with 120-degree intervals. Mooring line properties are listed in Table 1. Regular wave conditions in head sea are taken for frequencies from 0.1 to 1.5 rad/s. The motion RAO of surge, heave, and pitch are illustrated in Figs. 6, 7, and 8 in this order. In these figures, “Exp-RW test” denotes the experimental data in regular waves, while “Exp-White noise test” denotes the experimental test with white-noise spectrum. These tests were conducted in the previous work by KORDI (2012). Small discrepancies are observed in the surge RAO in the low-frequency region and in the heave and pitch RAO in the vicinity of the natural frequency. However,
The horizontal acceleration at the nacelle is also checked in comparison with the experimental data, as represented in Fig. 9. The nacelle, which is referred to as the center of the blades and the rotor of the wind turbine, is located at +89.35 m from the still water level. The rigid tower is assumed in this calculation, so the local point acceleration is estimated by simple transformation. In experiments, the accelerometer was installed at the nacelle point. It may be concluded from Fig. 9 that the present results reflect the experiment quite well.

CALCULATION FOR INTERLINKED-SPAR ARRAYS

We consider three different deployments of the floating wind turbine. Firstly, the horizontal array with 5 floaters is modeled. Both of the end floaters are constrained by the same mooring configuration as the single floater. The floaters are connected by cylindrical steel pipes, whose properties are listed in Table 1. Hereinafter, this array is called “5-by-1 array.” In Fig. 10, ML means the mooring lines, CON denotes the connectors, and # (NUM) indicates the ID of the floaters. These abbreviations are also adopted in Figs. 11 and 12. Then, square arrays with four or nine floaters are modeled. Each floater is berthed to adjacent floaters with steel pipes, as in the case of the 5-by-1 array. Mooring lines are installed just at the edge floaters. Hereinafter, the four floaters’ array is called “2-by-2 array,” and the nine floaters’ array is called “3-by-3 array.”
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### Condition Sea state

<table>
<thead>
<tr>
<th>Condition</th>
<th>$H_s$ [m]</th>
<th>$T_p$ [s]</th>
<th>Heading [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational</td>
<td>5</td>
<td>2.4</td>
<td>10.0</td>
</tr>
<tr>
<td>Survival</td>
<td>8</td>
<td>13.5</td>
<td>17.0</td>
</tr>
</tbody>
</table>

#### Table 2 Environmental conditions

Two different sea states are considered. One is the operational condition and the other is the survival condition, as listed in Table 2. The wave heading is fixed to 180 degrees, namely head sea. The 5-by-1 array is considered for both the operational condition and the survival condition, while the 2-by-2 and the 3-by-3 arrays are considered only for the survival condition. Other incoming wave directions are also considered in order to examine the occurrence of severe yaw motions.

### 5-by-1 Horizontal Array

The surge response of floaters in the operational condition is shown in Fig. 13. The surge motion is confined to the range of $-1.0$ m to $1.0$ m, where drifted-off phenomena are rarely found. The allowable horizontal offset for offshore floating structures is in general 5% of the water depth (DNV, 2011). Viewed from this criterion, this system can be regarded as reliable in position-keeping ability. Phase differences among floaters, which were induced by gap distances, are also observed.

The corresponding bending moments on connector 3 are presented in Fig. 14. To check the structural reliability, the peak values of the tension and bending moment are counted, in order to calculate the maximum stress on connectors, which is shown in Eq. 20. To simplify this problem, the phase difference between the tension and bending moment on the connector is not accounted for; the maximum stress is estimated by simply adding two maxima, as shown in Eq. 20:

$$
\sigma_{\text{max}} = \frac{M_{\text{max}}}{I} \cdot \frac{z}{F_{\text{max}}} + A
$$

where $I$ is the second moment of area, $A$ is the cross-sectional area, and $z$ is the distance between the neutral axis and the stress point of application. The maximum stress values of each connector are evaluated and summarized in Table 3. The maximum stress acts on connector 1, while differences in magnitude are not significant. In the operational condition, the bending moment is most dominant. Generally, the ultimate breaking stress of ASTM steel is about 400 MPa. The minimum safety factor is found to be 3.81.

Next, the survival condition is considered. Figure 15 shows the statistical data of the surge, heave, and pitch motions with respect to the significant double amplitude. Floater 2 experiences the maximum motion in surge and pitch modes, while the heave motion of floater 1 is the largest. Due to interactions between the floaters and connectors, the surge motions of all the floaters are significantly reduced, while the heave and pitch motions show similar behavior in one floater case. Even though mooring lines are installed only for floaters 1 and 5, the station-keeping ability is
The structural reliability of the connectors is performed. The minimum safety factor is obtained for connector 1, which is 1.44. Reinforced connectors or other connecting mechanisms might be introduced according to offshore structure rules and regulations.

2-by-2 and 3-by-3 Square Arrays

The 2-by-2 and the 3-by-3 square arrays are calculated under the survival condition. The same connectors, which are used in the 5-by-1 array case, are introduced. However, the mooring lines are replaced by the equivalent linear springs to reduce the numerical burden. It is confirmed that the restoring forces are almost identical to the FE-modeled mooring lines or to the linear spring modeling, within 20 m offset.

The motion trajectory of the 2-by-2 array in the XY plane is shown in Fig. 16. One floater case is also illustrated for reference. The floaters in the 2-by-2 array are not drifted-off as seriously as one floater case in the x-direction. With respect to the position-keeping ability, this interlinked structure can be regarded as much improved compared to one floater. Small sway motions appear in the 2-by-2 array, which do not appear in one floater test. An imbalance in the global mooring force for each floater might trigger y-directional motions, while y-directional displacements are much smaller than x-directional displacements.

A statistical analysis of connector tensions is conducted, in which RMS means Root Mean Square (shortly, mean) and SDA denotes Significant Double Amplitude (also referred to as significant height), as shown in Fig. 17. SDA is obtained by averaging the motion height (crest to trough) of the highest third of the motion signals. This integrated system moves simultaneously along the y-axis. The connectors parallel to the x-axis (connectors 1 and 3) are affected by the relative motions of the floaters because of the phase difference due to their different x-axis locations. This causes a significant difference in tension at the connector ends between connectors 1, 3 and connectors 2, 4. The ratio of the significant height to the mean height is found to be approximately 1.6:1.0.

Next, the 3-by-3 array, which is composed of 9 floaters, 12 connectors, and 4 mooring lines, is investigated. Mooring lines are installed only at the edge floaters (2, 4, 7, and 9). The motion trajectory in the XY plane is shown in Fig. 18. A small number of sway motions are found along the sideline floaters (2, 3, 4, 7, 8, and 9), which are not seen in one floater case. The interaction between floaters and connectors causes this phenomenon, which is identical to the behavior of the 2-by-2 array. Traces of the midline floaters (1, 5, and 6) do not show any sway motions because the systems are symmetric along the midline. Also, the interaction with side floaters and the absence of mooring lines exaggerate surge motions. Even a certain number of positive displacements in the x-direction are observed.

Effective tensile forces at the ends of connectors are illustrated in Figs. 19 and 20. There are significant differences between connectors lying in the x-direction (in Fig. 19) and connectors lying in the y-direction (in Fig. 20). The relative motion along the x-axis is the primary cause for the tensile force; therefore, tensile forces acting on connectors parallel to the x-axis are enlarged much more than those acting on connectors parallel to the y-axis in head sea condition. Also, the connectors lying in the x-direction (in Fig. 19)
show the wave frequency motion, while higher frequency components appear in the connectors lying in the y-direction (in Fig. 20).

### Comparison Among Three Arrays

The mean and maximum surge offsets at the free surface and the maximum horizontal acceleration at the nacelle, for the three arrays under the survival condition, are listed in Table 5. The mean surge motions of the 2-by-2 array are the smallest among the arrays investigated herein. The average number of mooring lines for each floater is 1.0 in the 2-by-2 array, 0.4 in the 5-by-1 array, and 0.44 in the 3-by-3 array. More mooring lines naturally enhance the station-keeping ability. In the case of the 3-by-3 array, a huge deviation of surge motions occurs between the midline floaters (1, 5, and 6) and the other floaters. It is obviously induced by the unsymmetrical mooring installation. Even though the maximum surge motion is smaller than that in the one floater case, the problem caused by the unsymmetrical mooring configuration needs to be solved carefully.

With respect to the horizontal acceleration at the nacelle, the last floater (5) in the 5-by-1 array has the minimum value among the three systems. As the floater recedes from the wave-generating origin, the acceleration of the nacelle is decreased slightly in the 5-by-1 array. However, this tendency is not identical in the other arrays. In the 2-by-2 array, the rear side floaters (2 and 3) have larger acceleration values, while the nacelle accelerations of the 3-by-3 array are disordered. The mean value of the nacelle accelerations is similar for all three arrays, although the exact values are slightly different according to the connectors and mooring line deployment.

<table>
<thead>
<tr>
<th>Array</th>
<th>#</th>
<th>Mean surge offset at free surface [m]</th>
<th>Maximum surge offset at free surface [m]</th>
<th>Maximum horizontal acceleration at nacelle [m/s²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-by-1 horizontal array</td>
<td>1</td>
<td>-6.6820</td>
<td>-13.0888</td>
<td>2.2619</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-6.3195</td>
<td>-12.5594</td>
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<tr>
<td></td>
<td>3</td>
<td>-5.9745</td>
<td>-10.8261</td>
<td>1.9495</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-6.3350</td>
<td>-12.0747</td>
<td>1.8978</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-6.3220</td>
<td>-11.3297</td>
<td>1.8636</td>
</tr>
<tr>
<td>2-by-2 square array</td>
<td>1</td>
<td>-2.5248</td>
<td>-9.2127</td>
<td>2.3537</td>
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Table 5 Mean and maximum surge offsets at the free surface and maximum horizontal acceleration at the nacelle, for three arrays under the survival condition

### CONCLUSIONS

A series of nonlinear time-domain simulations for three interlinked-spar arrays were conducted. From the numerical results, the following conclusions are drawn:

1. For the horizontal array, the surge motions of all the floaters are considerably reduced due to the connectors. Under the operational condition, the maximum stress on the connectors is sufficiently low compared to the ultimate yielding stress of ASTM steel. However, under the survival condition, the stress exceeds the allowable yield stress with a safety factor of 2.0. Thus, the optimization of the design parameters needs to be conducted, depending on the environmental condition.

2. For the square array, the effective tensile forces are significantly affected by the wave phase difference due to the floaters’ positions, even though the sway, roll, and yaw motions also appear owing to the interaction between the connectors, mooring lines, and floaters. This is not the case for one floater.

3. Through a comparison of the statistical values of the motion responses of the three different arrays, the 3-by-3 array shows the largest deviation of the surge motion, while the horizontal acceleration at the nacelle, induced by connectors, shows the smallest. In this aspect, none of the arrays show a clear superiority in the SDA of motion responses.

4. A detailed structural analysis of connectors and mooring lines is required, if they satisfy the design criteria.

As shown in the numerical results, three types of interlinked spars show no significant differences in motion responses, which are similar to those of a single spar. Furthermore, the tension and bending stresses on the connectors are within the practical application. Therefore, the arrayed structures can be considered as the platform for offshore wind farms in deep water. Finally, such a system is economical in terms of the construction costs of the
mooring equipment and power cables, and is easier in terms of the installation and maintenance of the electronic cables. However, it is essential to confirm the numerical results by performing more experiments. So far, one floater case was validated by previous experimental results (Hong et al., 2012). Experiments for the 2-by-2 array are scheduled in the near future and will be reported thereafter.

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REFERENCES


