ABSTRACT
A mooring and anchoring concept for floating offshore wind turbines is introduced in which each anchor moors multiple floating platforms. Several possible geometries are identified and it is shown that the number of anchors for a wind farm can be reduced by factors of at least 3. Dynamic simulation of turbine dynamics for one of the candidate geometries and for two directions of wind and wave loading allows estimation of multiline anchor forces the preview the types of loads that a multiline anchor will need to resist. Preliminary findings indicate that the peak demand on the anchor may be reduced by as much as 30% but that anchors used in such a system will need to be able to resist multi-directional loading.

INTRODUCTION
Offshore wind energy has an acknowledged and important role to play in meeting the renewable energy needs of the United States and the world. For example, the United States has identified targets of 10GW and 54GW of offshore wind energy by the years 2020 and 2030 [5]. Although the nearest of these goals is unlikely to be met, the first commercial offshore wind installation is proceeding in US waters (Deepwater Wind off the coast of the State of Rhode Island) [10], and additional leases have recently been purchased for offshore wind areas along the US Atlantic coast [3].

Offshore wind energy generation in waters deeper than approximately 50m invites consideration of floating platform systems, and floating systems may be favorable to US conditions for two particular reasons: The experience of the CapeWind project has shown that significant objection by a small number of shoreline landowners can successfully derail a project in which the turbines are visible from shore and the waters of the Pacific coast are suitable for fixed-bottom solutions for only a very short distance from shore. Floating systems, therefore, have the potential to mitigate objections from shoreline landholders along the Atlantic Coast, and open up for potential development a large percentage of US waters along the Pacific coast.

Despite advances in floating technology and the relative success of demonstration projects in Europe, Japan, and the United States, energy generated from floating platforms remains significantly more expensive than that generated from fixed-bottom offshore wind turbines OWTs. Reducing the number of expensive geotechnical site investigations and anchors is the focus of this paper.
Here, a concept for multiline mooring systems is introduced and preliminary analysis of the potential economies of such a system and the impact of such a system on anchor loads is presented. The key concept of the system is that floating offshore wind turbine (FOWT) platforms could share anchors, resulting in each anchor in a FOWT wind farm serving multiple platforms and generating economies in the number of site investigations required and the number of anchors required. The work presented here is informed by earlier work by one of the authors (Landon) on double line loading of suction caissons [1,2,4]. Four candidate geometries based on standard lattice topologies are presented, and from this geometric information alone a first order estimate of efficiency in terms of the number of anchors and site investigations is obtained. For the simplest of these geometries, and the one most similar to current mooring systems, dynamic analysis is performed to illustrate, in a preliminary fashion, key ways in which loading on a multiline anchor may differ from that on a single-line anchor.

The remainder of the paper is organized as follows: First, the geometric design of FOWT wind farms using the multiline concept is analyzed to show the degree to which anchorage efficiencies may be achieved; Next, a discussion of FOWT dynamics and the tools used to model FOWT dynamics is presented; Finally, approximations to the combined, time-varying loading applied to a multiline anchor are presented for one of the candidate geometries and two different wind/wave directions. The paper closes with conclusions and suggestions for further work.

**GEOMETRIC DESIGN OF OFFSHORE WIND FARMS**

The geometric design of offshore wind farms, that is, the determination of the positions of OWTs within a wind farm area, is typically driven by economic considerations related to power production. Specifically, turbine layout might be optimized to minimize wake effects for prevailing wind directions and turbine spacing would be minimized, above a lower bound, to maximize the number of turbines within a given wind farm. For floating systems, the geometric design is complicated by the need to determine the number of anchors per FOWT and site those anchors.

For the purposes of this paper the geometric design of a wind farm composed of FOWTs consists of the plan layout of the FOWT platforms, their mooring lines, and anchors. The designs shown here are schematic and therefore do not include length scales. It is assumed that the designs can be scaled such that appropriate inter-turbine spacing is achieved. Also neglected here is the role that water depth will play in determining the feasibility of candidate designs and the complicated interplay between water depth, anchor type, mooring line geometry, and inter-turbine spacing. This interplay, and determination of the feasibility of different designs for different anchor types, mooring line geometries and water depths is the subject of ongoing research by the authors.

The candidate designs are evaluated in terms of two quantities, both of which are given for the limiting case of an infinitely large wind farm in which the presence of anchors at the boundary that cannot be shared is neglected. This is equivalent to considering a unit cell for layouts that contain a periodic unit. The two quantities considered are \( n_{\text{TA}} \), the number of FOWTs (or mooring lines) per anchor, and \( n_{\text{AT}} \), the number of anchors per FOWT (or mooring line).

In assessing the efficiency of a design, \( n_{\text{TA}} \) is inversely proportional to the number of anchors needed for a multiline wind farm when compared to a farm designed with the same FOWT layout but without using the multiline concept. For example, for a wind farm with \( n_{\text{TA}} = 3 \), use of the multiline concept would result in a 67% reduction in the number of anchors required. While estimating the impact of such a reduction of the capital cost of the wind farm is complicated by possible increased anchor size due to increased demands from the multiline concept and possible decreased geotechnical site characterization costs, the reduction in the number of anchors constitutes a first order measure of the efficiency and economy generated by the multiline concept.

The number of anchors per FOWT, \( n_{\text{AT}} \), has the opposite effect on the total number of anchors in a wind farm, meaning that increasing \( n_{\text{AT}} \) increases the number of anchors. General practice is to use 3 anchors per FOWT, but it should be noted that this arrangement provides the minimum number of mooring forces needed to maintain equilibrium of the system with respect to station keeping and it may eventually be desirable to provide additional (but smaller) anchors to a FOWT to increase the reliability of the system. In the limit of an infinitely large wind farm, i.e. neglecting boundary effects on the number of anchors, the total number of anchors needed for a FOWT wind farm is

\[
 n_A = n_T \frac{n_{\text{AT}}}{n_{\text{TA}}} \tag{1}
\]

where \( n_T \) is the number of FOWTs in the wind farm. Therefore, farms with low values of \( n_{\text{AT}}/n_{\text{TA}} \) will minimize the number of anchors needed for a given number of FOWTs. Note that consideration of the capital expense of a given mooring system is complex, and consists of anchor production and installation costs and the cost of mooring line. Although the ratio \( n_{\text{AT}}/n_{\text{TA}} \) gives an indication of potential efficiency and economy gained through reduction of anchor numbers, a more thorough cost accounting is needed.

Figure 1 shows a set of candidate geometric designs, and Table 1 shows potential efficiencies of these multiline geometries. The table uses a hypothetical 100 turbine wind farm and neglects boundary effects which, since perimeter anchors cannot be shared, would cause the total number of anchors to rise modestly. This effect is neglected because it diminishes with size of the wind farm and the multiline concept is therefore expected to be most applicable to large, industrial scale developments. The table compares the number of turbines required for 100 turbine wind farms using the multiline concept and using standard single line anchors and defines the efficiency as the ratio of the number anchors needed for single line anchoring to the number of anchors needed for multiline anchoring. The efficiency gives, therefore, the factor by which
the number of anchors can be reduced using the multiline concept.

The candidate designs were generated by the authors based on well-known lattice structures based on hexagonal and square unit cells and were selected for this paper to cover a range of potentially feasible geometric designs for FOWT wind farms. The authors, as part of ongoing research, are investigating the generation of multiline mooring geometries based on network topology optimization approaches. Candidate designs cover a broad range of the design space (i.e. $n_{AT}$, $n_{TA}$) and present a variety of FOWT layout patterns that will require further investigation with respect to wake effects and power production consideration as well as variety in the number and geometry of the multiline attachments to individual anchors that will require determination of the resultant, time-varying demands on the anchors.

Though this paper presents preliminary findings regarding possible multiline efficiencies, it is important to note further areas of needed investigation, including: water depth considerations on mooring line geometry, anchor forces, and FOWT spacing; relative costs/benefits of reducing anchor numbers and possibly increasing mooring line lengths; effect of designs based on the multiline concept on power production; sensitivity of FOWT dynamics to anchor placement tolerances; design of anchors for multi-directional loading.

**PLATFORM DYNAMICS AND MOORING LINE FORCES**

In order to provide a preliminary evaluation of the anchor forces developed in a wind farm using the multiline concept simulations of floating platform dynamics that provide estimates of mooring line tensions at the anchor are performed. This section describes the example platform used here, the models used for the simulation, and some key characteristics of the response to a particular set of environmental conditions. In the following section approximations are introduced that allow estimation of the resultant forces at an anchor connected to multiple mooring lines.

The example platform used here is a semi-submersible based on the OC4 / DeepCWind design [11] that supports the NREL 5 MW tower and turbine [9]. Although design of an actual multiline wind farm would have to rely on the actual platform and turbine characteristics to be used in that farm, the OC4 / DeepCWind design is used here as an illustration because documentation of the platform and turbine characteristics are publicly available. The platform is moored in 200m of water by three lines spaced evenly such that the line labeled $L_1$ is oriented at 180° and lines labeled $L_2$ and $L_3$ are oriented at +60° and -60° with all directions given relative to a fictitious North that points upward on the page. The mooring lines are catenary with unstretched length of 835m, a seafloor lay length of 243m and a radial distance from the fairleads to the anchors of 797m. The fairleads are themselves located 41m radially from the center of the platform. The anchor points are assumed to be at the seafloor and to provide a fully fixed condition to the ends of the mooring lines.

![Figure 1: Candidate geometric designs. Solid circles represent anchors and tripod shapes represent FOWTs. FOWTs and anchors at the boundary of the geometries may not depict the full FOWT-anchor connectivity. Part A of the figure also shows the line nomenclature and wind/wave direction nomenclature used in the analysis section of the paper.](image)

![Table 1: Number of turbines per anchor ($n_{TA}$), number of anchors per turbine ($n_{AT}$), and efficiency gain in a 100 turbine wind farm for multiline geometries of Fig. 1. Note that the efficiency gains neglect edge effects in the multiline geometries.](table)

<table>
<thead>
<tr>
<th>Design</th>
<th>$n_{AT}$</th>
<th>$n_{TA}$</th>
<th>Anchors per 100 turbines</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3</td>
<td>3</td>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>4</td>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>3</td>
<td>200</td>
<td>1.5</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>6</td>
<td>50</td>
<td>6</td>
</tr>
</tbody>
</table>

Platform dynamics for the turbine in an operating state are simulated using FAST version 8 [8,9] for a turbulent wind field with a mean wind speed of 11.4 m/s (the rated wind speed of the turbine) and turbulence intensity of 0.11. An irregular sea state with significant wave height of 4m with peak spectral period of 7.1s is considered. Wind and wave fields are assumed to be co-directional and to originate from 180° or 90°.

FAST 8 makes three mooring line models available and MOORDYN is the option used in the simulations shown here [8,9]. MOORDYN is a lumped-mass mooring line model that accounts for internal axial stiffness and damping forces, weight and buoyancy forces, hydrodynamic forces from Morison's equation, and vertical spring damper forces from contact with the seabed (wave kinematics are not yet included in the hydrodynamic force calculations, which assumes still water).
MOORDYN first uses dynamic relaxation to determine the initial equilibrium state of the mooring system, then couples with fairlead kinematics to determine mooring kinematics and returns mooring forces on the fairlead. MOORDYN supports different line and connection properties (i.e. line axial stiffness, mooring geometry) and outputs mooring kinematics at any line node. All hydrodynamic properties are in accordance with FAST certification tests for the OC4 Semisubmersible [8] as available for public download from the NREL website, including drag and added mass hydrodynamic coefficients of the mooring lines and member-based hydrodynamic coefficients of the platform. Also contained in the certification tests are the linear potential-flow model data from the wave interaction analysis software WAMIT. WAMIT uses a three-dimensional numerical-panel method in the frequency domain to solve the linearized potential-flow hydrodynamic radiation and diffraction problems in the interaction between the platform and surface waves. The WAMIT output files in the OC4 Semisubmersible certification tests include the linear, non-dimensionalized, hydrostatic restoring matrix, frequency-dependent hydrodynamic added mass matrix and damping matrix, and frequency-and-direction-dependent wave excitation force vector per unit wave amplitude. Details on these properties and how to calculate them can be found in [6,11]. Seabed friction is neglected in the current implementation and incorporation of this effect will be an important addition to improve the realism of the simulations.

Figure 3 shows a one-hour time history (the first 50 seconds is not shown due to transients associated with analysis startup) for each of the three anchor tensions \( T_1, T_2, \) and \( T_3 \) for each wind/wave direction. For comparison the anchor tension generated equally at each anchor under the static condition with no wind and no wave action (907 kN) is also shown. For 180° wind/wave the tension \( T_1 \) is significantly higher (mean tension = 1520 KN) than \( T_2 \) (mean tension = 722KN) and \( T_3 \) (mean tension = 725KKN). Tensions \( T_2 \) and \( T_3 \) are approximately equal and \( T_1 \) is larger because it is generated in the only line that is oriented in the upwind/upstream direction. Tension \( T_3 \) also has a significantly larger coefficient of variation (0.13) than do \( T_2 \) (0.05) and \( T_3 \) (0.05). For 90° wind/wave the upstream \( T_2 \), which is at an angle to the wind/wave direction, see Fig. 1) and perpendicular \( T_3 \) tensions are comparable and larger than the downstream \( T_3 \) tension because the downstream line participates only minimally in providing station-keeping equilibrium. For 90° wind/wave all force magnitudes are lower than for 180° and the coefficients of variation of the more heavily loaded lines, \( T_2 \) (0.10) and \( T_3 \) (0.13) are comparable to that of the downstream line \( T_1 \) (0.10).

Although this paper is focused on anchor tensions it is worthwhile to note a few characteristics of key platform response quantities to provide context to the dynamic behavior of the system. The mean surge of the platform for 180° wind/wave is 9.4m with an associated standard deviation of 1.7m and the mean pitch angle is 3.1° with a standard deviation of 0.64°. Platform response for 90° wind/wave is comparable. If one considers that the wind could come from any direction during the course of the FOWT lifetime, these results indicate that the platform station-keeping is likely to be maintained within a circle of roughly 10m radius. In comparison to the nearly 800m radius of the mooring system in this example, this degree of surge is quite small, 1.25%, and indicates small changes in mooring line geometry during platform motion. The platform pitch of approximately 3° corresponds to a tower top displacement due to rigid rotation of approximately 5m, a displacement which is much larger than would be allowed for a fixed-bottom turbine, and one that could lead to significant added moment due to the eccentricity of the tower top mass of the rotor-nacelle-assembly. These to quantities are selected for discussion here because the surge is the largest of the platform translations and will have the greatest effect on mooring line geometry and the pitch is the largest of the platform rotations and will have the greatest effect on motion of the rotor and added tower base bending moments.
APPROXIMATION TO MULTILINE ANCHOR FORCES

In this section a simple approximation is developed to give initial insights into the loads that arrive at an anchor in a multiline wind farm. An example is constructed for an anchor arranged as in geometric design A shown in Fig. 1, characterized by \( n_{Ti} = n_{AT} = 3 \). It is assumed that each FOWT is subject to independent wind and wave fields that share direction (180° or 90°) and intensity characteristics (\( V_w = 11.4 \text{m/s}, T_l = 0.11, H_s = 4 \text{m}, T_p = 7.1 \text{s} \)). This is an approximation to the actual conditions prevailing in a wind farm, in which the fluctuations in the wind and wave field may be spatially correlated. Investigation of such wind/wave/load correlation is a current topic of study by the authors and it should be noted that while calculating the arrival time delay for a wave between two platforms is straightforward, estimation of the actual load correlation is complicated by wind field turbulence, wave field dispersion, and time constants associated with the platform dynamics. The assumption of independence, therefore, has been implemented here to simplify preliminary calculations.

Denote by \( T_{i} \) the anchor tension at anchor \( i \) generated by a line connected to FOWT \( j \) such that in the arrangement shown \( T_{i1} \) has the characteristics of \( T_1 \) from Fig. 3, \( T_{i2} \) has the characteristics of \( T_2 \) and \( T_{i3} \) has the characteristics of \( T_3 \). The resultant forces at the anchor in the 0° (parallel to wind-wave field) and 90° (perpendicular to wind-wave field) directions are

\[
F_{r,0} = T_{i1} - [T_{i2} \cos(60°)+T_{i3} \cos(60°)]
\]

(2)

and

\[
F_{r,90} = T_{i2} \sin(60°)-T_{i3} \sin(60°),
\]

(3)

and the total resultant force

\[
F_r = \sqrt{F_{r,0}^2 + F_{r,90}^2},
\]

(4)

acts in the direction

\[
r = \tan^{-1} \left( \frac{F_{r,90}}{F_{r,0}} \right).
\]

(5)

Note that in the above all of the quantities are functions of time and mooring line tensions are assumed always to act along a line connecting the anchor position to the undisplaced fairlead position. This is a reasonable assumption since platform motions are small relative to the fairlead to anchor distance.

Each estimate of the anchor forces by Monte Carlo simulation requires three independent realizations of FOWT dynamic time histories that deliver realizations of \( T_{i1} \), \( T_{i2} \), and \( T_{i3} \). In keeping with the practice recommended by the IEC specification [7], 6 independent one-hour realizations of \( F_r \) and \( F_{r0} \) are generated from 18 independent FOWT realizations.

Time histories of the components of the resultant anchor force in the 0° (parallel to wind-wave direction) and 90° (perpendicular to wind-wave direction) are shown in Fig. 4 for each of the wind/wave directions. Forces perpendicular to the wind/wave direction are smaller than those parallel to the wind/wave direction in each case, though the difference is much greater in for the 180° wind/wave direction. In both cases the perpendicular anchor force crosses 0KN, reinforcing the need for anchor systems that can resist loading from multiple directions.

For the 180° wind/wave case, due to the small magnitude of \( F_{r90} \), the total resultant force on the anchor is nearly equal to \( F_{r0} \), as shown in Fig. 5, which also shows that the resultant force magnitude is intermediate to the anchor forces \( T_1 \), \( T_2 \), and \( T_3 \) from the isolated platform analysis shown in the previous section. The coefficient of variation of \( F_r \) is 0.23, which is significantly larger than those for the individual mooring lines. This increased coefficient of variation may have implications for anchor design that incorporates cyclic loading considerations.

For the 90° wind/wave case (also shown in Fig. 5), the mean resultant anchor force is smaller than for the 180° case and the coefficient of variation of 0.18 is also significantly smaller.

Mean values, coefficients of variation and time histories are important to anchor design, particularly so in the multiline case, but maximum loads remain of significant importance. The standard estimator for the maximum load is the mean of the maxima of six independent realizations of the time history of the response of interest. Here, the estimates for \( T_1 \) and \( F_r \), as given by

\[
T_{1,\text{max}} = \frac{1}{6} \sum_{i=1}^{6} \max_{t} T_{1,(i)}
\]

(6)

and

\[
F_{r,\text{max}} = \frac{1}{6} \sum_{i=1}^{6} \max_{t} F_{r,(i)}
\]

(7)

where the superscript \((i)\) is the index number of the realization. In the current example, \( F_{r,\text{max}} = 2400\text{KN} \) for the 180° wind/wave case, \( F_{r,\text{max}} = 1700\text{KN} \) for 180° wind/wave, and \( F_{r,\text{max}} = 1000\text{KN} \) for 90° wind/wave. Note that \( F_{r,\text{max}} \) is larger than the largest values shown in Fig. 5 since it is the result of averaging the maxima from six realizations, some of which have much higher peak values than does the realization shown in Fig. 5. \( T_{1,\text{max}} \) is reported only for the 180° wind/wave case since that represents the worst case single line loading that an anchor would be designed for in a standard design. Using that value allows comparison of the multiline loads to the worst case design loads for a single line per anchor design. For this example, then, multiline action reduces the maximum demand on the anchor by 30% for 180° wind/wave and 58% for 90° wind/wave loading.

The question of loading directionality is of crucial importance to the design of a multiline anchor system since certain types of anchors (e.g. certain drag anchors) may have little or no capacity in other than a single direction while others (e.g. piles, suction caissons) may have nearly equal capacity in all directions. By examining the multiline concept for two perpendicular loading directions, this paper demonstrates quantitatively that multiline anchors will, as expected, have to resist significant loads from multiple directions, but that the characteristics of those loads (mean and coefficient of
variation) may not be consistent across all directions. Certainly the details of the directional dependence of loading will depend on the particular multiline geometry used (e.g. A-D in Fig. 1) and models for spatial load correlation. Both of those topics are subject to ongoing research by the authors. To finally illustrate the importance of designing a multiline anchor for multi-direction loading, Fig 6. shows wind and wave direction distributions for a site off the coast of Nantucket Island in the US state of Massachusetts. Significant variability in the wind and wave direction is typical. Therefore, preliminary indications are that multiline anchors may be able to be designed for reduced overall capacity, but must be able to retain that capacity through a range of loading directions.

CONCLUSIONS
This paper has described a mooring and anchoring concept for floating offshore wind farms in which anchors are shared among multiple platforms. This networked approach to the mooring systems results in multiple lines being attached to the anchor delivering loads of different magnitudes and acting in different directions. Candidate geometric designs (turbine and anchor layouts) are shown along with preliminary quantifications of the net gains in efficiency and redundancy of the mooring system relative to systems in which each anchor is connected to only one turbine. These efficiencies, of up to a factor of 6, reflect only the number of anchors needed for a given number of turbines, and neglect production and installation cost and line cost. Dynamic time history analysis of an example semi-submersible floating platform for one of the candidate geometries allows estimation of the net forces that reach a multiline anchor for one of the candidate geometries and two cases of directional wind/wave loading and the results indicate that the multiline concept may result in reduced loads on the anchor but that those loads may come from unpredictable directions, necessitating anchor designs that

Figure 4: Multiline anchor force components.

Figure 5: Multiline total resultant anchor force compared to anchor forces generated by an isolated platform without multiline mooring.
This preliminary study has addressed only co-directional wind and wave loading approaching the wind farm from two orthogonal directions for a single platform type and has assumed independence of the wind and wave fields at the locations of different turbines within the wind farm. Further research is needed to address issues of directionality, further candidate designs, cyclic and directional design of anchors and to arrive at well supported estimates of the effect of the multiline concept on overall wind farm capital costs.

ACKNOWLEDGMENTS

The authors wish to thank the US National Science Foundation for its support through grants IGERT-1068864, CMMI-1463273, CMMI-1463431, and CMMI-1462600, the Massachusetts Clean Energy Center for its support and Andrew Goupee and Matt Hall of the University of Maine for their advice and consultation on technical aspects of the simulation of floating platform dynamics.

REFERENCES


