Development of offshore wind farms can ensure a sustainable source of renewable energy. In deep sea wind turbines need to be placed on floating structures to improve economy. In this study, a nonlinear finite element model has been developed for dynamic response prediction of floating offshore wind turbine system. A water tank experiment has been used to verify performance of developed model. The model is also verified for modeling Catenary, seabed contact and pretension using experiments. A comparison of linear and nonlinear model for Catenary mooring system is presented and limitation of linear model have been identified. It is observed that linear model can only provide reasonable response prediction if wave period is less than half the natural period of floating system.

**Keywords**: Floating wind turbine system, Water tank experiment, Mooring system, FEM.

**INTRODUCTION**

Wind energy is one of the most renowned sources of renewable energy. Offshore wind energy offers obvious advantage of no land usage and more reliable wind resource. Offshore wind energy development is thus a great prospect for renewable power generation. In shallow waters, bottom-mounted support is economically feasible; however floating support structures are essential in deep waters around Tokyo, Japan. The station-keeping of such structures is accomplished through mooring systems. To improve economy, structural reliability analysis of these systems is essential, which require accurate response prediction over entire range of wave period. Use of experiment, is very expensive and is not completely helpful because similarity laws do not allow proper modeling of all system components. Development of numerical tool is therefore essential for response prediction. Current design approach considers linear approximation of mooring force, which may not be appropriate for this purpose.

In this study a fully coupled nonlinear FEM model for dynamic response prediction of floating wind turbines has been developed and each of its components is verified through comparison with respective experiment. The model is then used to compare linear and nonlinear model for estimation of mooring force and identify limitation of the linear model.

**NUMERICAL MODEL**

**Equation of Motion**

The equation of motion for the floating wind turbine system can be written as

$$
[M]{\ddot{X}} + [C]{\dot{X}} + [K]{X} = {F}
$$

(1)

$$
{F} = \{F_n\} + \{F_r\} + \{F_h\} + \{F_w\}
$$

(2)

In equation (1) \([M]\), \([C]\), \([K]\) are mass, damping and stiffness matrices and \(\{X\}, \{\dot{X}\}, \{\ddot{X}\}\) are displacement, velocity and acceleration vectors respectively. The external force vector \({F}\) can be divided in four parts as shown in equation (2). \(\{F_n\}\) is wave exciting force, \(\{F_r\}\) is hydrostatic restoring force, \(\{F_h\}\) is mooring force and \(\{F_w\}\) is wind force. As this paper concentrates on mooring systems, wind force is not considered in this study.

The wave exciting force is estimated using Morison's equation [1] along with Srinivasan's model [2] with 15% linear hydrodynamic damping. The restoring force is estimated using non-hydrostatic model. The detail of how these models are incorporated in the current numerical scheme is available in Ishihara et al. [3]. Here only model for mooring force is discussed.

**Mooring Force Model**

**Linear Model**

In this method, mooring system is modeled as linear springs having constant stiffness \([K]\); the force is estimated from fairlead displacement \(\{x\}\) as follows:

$$
\{F_m\} = -[K]\{x\}
$$

(3)

**Nonlinear Model**

A complete finite element model of mooring system is considered to include the effect of mooring inertia and damping. The mooring force can then be defined as:

$$
[m]{\ddot{x}} + [c]{\dot{x}} + [k]{x} + \{F_m\} = 0.0
$$

(4)

In equation (4) \([m]\), \([c]\), \([k]\) are mass, damping and stiffness matrices and \(\{x\}, \{\dot{x}\}, \{\ddot{x}\}\) are displacement, velocity and acceleration of the mooring system. In the present model, this equation is directly coupled with equation (1), which eliminates the need for separate estimation of mooring force \(\{F_m\}\). The nonlinear model, can consider the seabed interaction, which is done using contact model presented by Ju et al. [4]. The pretension of the tension leg tether is based on Cook et al. [5].
Numerical Scheme

A fully coupled finite element model is developed in this study. Its salient features are summarized in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Summary of FEM Code</th>
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<tr>
<td><strong>Dynamic Analysis</strong></td>
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<td><strong>Element Type</strong></td>
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<td><strong>Formulation</strong></td>
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<td><strong>Damping Estimation</strong></td>
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<td><strong>Hydrodynamic Force</strong></td>
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<td><strong>Restoring Force</strong></td>
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<tr>
<td><strong>Mooring Force</strong></td>
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</tbody>
</table>

WATER TANK EXPERIMENT

![Model and Experimental Layout](image)

The experiment is performed in the water tank facility at National Marine Research Institute, Japan [6]. Figure 1 shows the 1:100 scaled model of floating wind turbine system and its layout in water tank experiment. The model is placed at center of the tank. Kevlar thread is used to connect the model with elastic bands and elastic band to tension meter at front and weight-pulley assembly at rear. An initial tension of 2.95 N is setup in elastic bands using weight-pulley assembly to obtain required linear mooring stiffness of 45.0 N/m in surge direction. Since the experiment is unidirectional, mooring stiffness in other directions is ignored. Displacements are measured from a four-legged LED target fixed to the wind turbine tower using CCD camera. The experiment is performed under regular wave for the wave heights and period range listed in Table 2. Data collection is done at 30 fps for 60 sec. Since the experiment does not consider wind, blades have been ignored and their weight is included in the nacelle.

<table>
<thead>
<tr>
<th>Table 2 Experiment Condition</th>
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<tr>
<td><strong>Sea State</strong></td>
</tr>
<tr>
<td>Prototype</td>
</tr>
<tr>
<td>Rated</td>
</tr>
<tr>
<td>Extreme</td>
</tr>
</tbody>
</table>

VALIDATION OF DEVELOPED MODEL

Hydrodynamic Model

The FEM model for the wind turbine system is developed having 142 nodes and 150 elements. The floater is modeled using 122 beam elements with 114 nodes. Elastic bands are modeled as 4 linear spring elements and Kevlar thread is modeled using 24 truss elements. The hydrodynamic drag and inertia coefficients for use in Morison equation have been considered as functions of Kevlegan-Carpenter number as recommended by Offshore Standard DNV-OS-J101 [7]. Free vibration tests are used to verify the accuracy of the FEM model. A comparison of the measured and predicted natural periods is given in Table 3. The FEM model can therefore suitably represent the experiment model.

Surge and heave response amplitudes from experiment and simulation are compared in Figure 2. The response amplitudes have been normalized with respect to wave amplitude ‘H/2’. The wave period has been reverted to prototype scale. Simulation shows good agreement with experiment and is able to consider influence of hydrodynamic damping due to increase in wave height. The resonance peak for surge and heave modes can be clearly defined, which is because of linear mooring system. The experiment results at long periods (26~30 sec) are affected by reflected wave and wave disturbances, which reduce agreement with simulation.

Figure 3 provides the comparison of dynamic line tension from experiment and simulation, acceptable agreement can be observed verifying that the developed model can provide realistic prediction of element forces.

<table>
<thead>
<tr>
<th>Table 3 Natural period of Floater System</th>
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<tbody>
<tr>
<td><strong>Mode</strong></td>
</tr>
<tr>
<td>Surge</td>
</tr>
<tr>
<td>Heave</td>
</tr>
</tbody>
</table>

![Comparison of Dynamic Line Tension](image)
Catenary and Contact Model

In order to verify the modeling of mooring Catenary and its interaction with seabed, a static experiment on Catenary chain is carried out. A chain having length of 2.0 m is suspended between supports 1.5 m apart. The chain forms a Catenary with mid-span sag of $0.6 \approx 0.6$ m. A horizontal plate is raised from underneath the hanging Catenary chain to obtain contact length for a given plate elevation. Free Catenary and Four plate elevation of 0.55, 0.50, 0.45 and 0.403 m are considered. 80 truss elements are used to model the Catenary chain. Comparison of Catenary profile with and without contact and measured and predicated contact lengths is shown in Figure 4. The developed model can correctly model Catenary shape as well as the seabed interaction of mooring lines as it can correctly predict the contact length.

Tether Pre-tension Model

For response prediction of tension legged mooring system, modeling of tether pretension is very important. The model developed in this study can consider element pretension and its performance has been verified using experimental data from Kanda et al. [8]. The reference experiment was performed on a 1:100 scaled submerged tether model having length of 4.391 m and initial pre-tension of 21.6 N. The FEM model is prepared using 20 pre-tensioned beam elements is verified with the experimental model using Eigen-value analysis. The tether is subjected to a forced vibration of 100 mm amplitude at 1.28 sec, which is the first mode of vibration. The comparison of tether profiles over a cycle of vibration at interval of 0.133 sec is shown in Figure 5. It can be observed that developed model shows good agreement with experiment. The developed model is therefore completely verified and can be used for the response prediction of fully coupled floating offshore wind turbine systems.

INFLUENCE OF MOORING FORCE ESTIMATION

An initial application of the developed code is done to discuss the influence of mooring force estimation on dynamic response of floating wind turbine systems using linear and nonlinear models for Catenary mooring. The response prediction for linear model has already been verified using the experiment. The stiffness of 45.0 N/m used in this model is based on an arbitrary four mooring line system with two lines in front and back each, separated by 40 degrees as shown in Figure 6. Length of each mooring line is 4.6 m and it weighs 11.6 g/m on model scale. A nonlinear model considering this mooring arrangement is prepared and response prediction from the two models is compared. The model scale is used to be consistent in the comparison of the two methods of mooring force estimation.
Figure 7 shows comparison of the two methods at wave height of 4.0 cm. In order to clarify the effect of resonance on linear model, the wave period is normalized w.r.t respective natural frequency for surge and heave modes. It can be observed that the surge response using linear model is very sensitive to resonance period while for nonlinear model it is insensitive. This is because of the nonlinear nature of the mooring force. The linear model overestimates the surge response in wave period range from \(0.5 T_0 \sim 1.5 T_0\). It shows good agreement before 0.5 \(T_0\) while underestimates the response after 1.5 \(T_0\). This indicates that the linear model can only be used if wave spectrum falls within the 0.5 \(T_0\) range of the floating system natural period, otherwise its use will result in a conservative design.

CONCLUSIONS

A sophisticated numerical model has been developed that considers Morison equation with Srinivasan’s model for hydrodynamic force and a non-hydrostatic model for restoring force. The model can use either linear or nonlinear model to estimate mooring system contribution. The seabed contact and element pretension can also be considered. Each component of the model has been verified through comparison with experiment and is found to provide good agreement. The influence of considering actual mooring system instead of linear mooring stiffness is discussed and it is observed that the linear model overestimates surge response near resonance peak and can only provide realistic results if wave period is less than half the natural period of the system. Use of linear model outside this limit shall result in a conservative thus uneconomical design.

References


