A Study on the Dynamic Responses of a Semi-Submersible Floating Offshore Wind Turbine System

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Introduction of this research project

(Wind Power Monthly, February 2006)

- Joint research project
  - Tokyo Electric Power Company and the University of Tokyo
  - Test the feasibility of two type of floating wind turbine systems

- Cooperative companies
  - Shimizu Cooperation
  - Penta-Ocean Cooperation
  - Mitsubishi Heavy Industries

who are responsible for the design of the floaters and the wind turbine respectively.
Outline of this project

- **Phase 1: Preliminary design**
  - Definition of design basis
  - Selection of floater concept and turbine configuration

- **Phase 2: Model test program**
  - Test of 1:150 scale model in collinear wind and wave
  - Investigation of dynamic behavior of the floater
  - Validation of the developed numerical model

- **Phase 3: Optimization of design**
  - Optimization of floaters
  - Review of fabrication and installation
  - Cost analysis
What we expect to see
What we expect to see
Outline of this presentation

- Motivation and concept of the floater
- Experimental setup and results
  - using a wind tunnel with water tank
- Development of a numerical model
  - for the analysis of response behavior of the floater
- Conclusions
Motivation and concept of the floater
Floater concepts in Oil&Gas industry

- Floating wind turbine technologies are derived from well known floater concepts in Oil&Gas Industry such as
  - Semi-submersible
  - Spar
  - TLP (Tension leg platform)

- Some points are different from those in Oil&Gas Industry, that is
  - Need to reduce cost for the mass production
  - Not need to consider the safety factor of human station and oil spillage

Develop effective designs to reduce cost
Achieve the stability of floater for reduction of the turbine and tower loading
Floater concepts for wind turbine

Several concepts of the floating wind turbine have been proposed after FLOAT project.

**Single turbine systems**

- TU Delft, ECN & Other, Netherlands, 2001
- H. Suzuki, Japan, 2005
- NREL, U.S. 2004

**Multi turbine systems**


The advantage of the multi turbine systems are

- less floater motion due to the low thrust height to floater ratio
- common mooring system for a set of turbines.

However, they have disadvantages of

- high loads by current and wave,
- the turbine wakes.

The single turbine systems have opposite characteristics.
In this project, both single and multi turbine systems are investigated. The detail of the single turbine system is presented in the poster session.
Proposed multi turbine system

The float support system includes the tower, the floater hull, and the moorings to the seabed.

Turbines would be positioned at each of the platform’s corners while cables would tether platform to a central floater to increase stability and to reduce wave loading at the corners of the platform.

It was decided to set the hub height at 70m, for the 92m diameter rotor. The machine was rated at 2.4MW at 14m/s hub wind speed.

The final platform design has 23200 ton displacement and has weight of 16000 ton.
Design conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Max. operating</th>
<th>Max. survival</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub height wind speed (m/s)</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Significant wave height (m)</td>
<td>7.1</td>
<td>12.0</td>
</tr>
<tr>
<td>Significant wave period (s)</td>
<td>9.8</td>
<td>13.4</td>
</tr>
<tr>
<td>Current speed (m/s)</td>
<td>1.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

A collinear wind and wave model was used in this study
Experimental setup
The proposed structure was scaled 1:150 and tests were carried out under Froude similarity law. This does not perfectly apply in this study because of the restrictions on the material.

The model structures were manufactured using acryl glass. Model parameters were summarized as follows.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Target model</th>
<th>Experimental model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (m³ × 10⁻³)</td>
<td>4.858</td>
<td>5.540</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>4.932</td>
<td>5.540</td>
</tr>
<tr>
<td>Inertia moment Ix, Iy (kgm²)</td>
<td>0.770</td>
<td>0.930</td>
</tr>
<tr>
<td>Metacentric height GM (cm)</td>
<td>20</td>
<td>16.6</td>
</tr>
<tr>
<td>Stiffness Kx of mooring (g/mm)</td>
<td>4</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Linearization of mooring lines

- Since the external force acting on the mooring was caused mainly by the strong current, catenary mooring lines were simplified by two sets of horizontal and vertical linear moorings.

- The mooring lines were reproduced using very fine Kevlar wires attached to calibrated springs which reproduce the horizontal component of elasticity of mooring.

- Vertical sets of mooring lines were ignored, because stiffness of vertical components are much smaller than horizontal those.
Modeling of wind load

- Operating case (thrust coefficient 0.33)
- Survival case (in feathering status)

\[ \frac{L_m}{L_p} = 1:150 \quad \Rightarrow \quad \frac{V_m}{V_p} = \frac{T_m}{T_p} = \sqrt{\frac{L_m}{L_p}} = 1:12.2 \]

<table>
<thead>
<tr>
<th>Wind turbine condition</th>
<th>Prototype</th>
<th>Model (1:150)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wave height (m)</td>
<td>Wave Period (s)</td>
</tr>
<tr>
<td>Operating</td>
<td>3.9-7.1</td>
<td>7.4-9.8</td>
</tr>
<tr>
<td>Survival</td>
<td>12.0</td>
<td>13.4</td>
</tr>
</tbody>
</table>
## Wind tunnel with water tank

**Upstream (wind)**

(Wave generator)

### National Maritime Research Institute

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water tank</td>
<td>L17.6m × W3m × H1.8m (Still water depth 1.5m)</td>
</tr>
<tr>
<td>Wind tunnel</td>
<td>Laminar wind speed: 1~32m/s</td>
</tr>
<tr>
<td>Wave generator</td>
<td>Regular wave</td>
</tr>
<tr>
<td></td>
<td>Max. wave height: 0.3m</td>
</tr>
<tr>
<td></td>
<td>Period: 0.6~4.0sec</td>
</tr>
<tr>
<td>Wave absorption</td>
<td>Absorbing beach</td>
</tr>
</tbody>
</table>

**Downstream (Absorbing beach)**
Model on the floater

The model is set at the 6.6m downstream of the wave generator.
Six independent components of displacement of the floater were measured by means of three CCD cameras. The optical target with four LEDs were mounted on the center floater and were used to measure the surge, heave and pitch motions of the floater.
Experiment results
Free vibration tests

To examine the natural periods of the floating wind turbine system, the free vibration test was carried out in the still water. From the measured displacement, the acceleration of the surge, heave and pitch was calculated.

Natural periods for surge, heave and pitch are 2.75s, 2.92s and 2.73s, respectively.
Video for the operating case

H=2cm, T=0.6s, U=2m/s

This video shows the dynamic response of floater in the operating case
1) First only the wind is blowing from right to left. The floater is almost stationary
2) When the wave comes from the right, you can see fairly large amplitude of surge.
This video shows the dynamic response of floater in the survival case
1) You can see the water surface is rough due to the high wind speed.
2) When the wave comes, the response of the floater shows larger amplitude.
Variation of surge with the wave periods

The peak of the surge can be found at the period near 2.7s, corresponding to the natural frequency of surge. Around this period, the larger wave height case shows lower amplitude. The reason is that near the resonant point, the larger wave height causes higher velocity of the floater, which results in the increase of the hydrodynamic dumping. On the other hand, when the wave period is far from the resonant point, the normalized surge does not depend on the wave height, which means that the relationship between the surge and the wave height is linear.
For heave and pitch motion, the resonance was not observed, which indicates that the damping of those motions might be very large.
As expected, the peak responses at the wind speed $U=2\text{m/s}$ are less than those at the wind speed $U=0\text{m/s}$, due to the aerodynamic damping around the resonant point, and the effect of the aerodynamic damping is more significant for the lower wave height, that is, lower hydrodynamic damping case.
In this cases, there is little dependency on the wind speed. This is because the aerodynamic damping from the blade is much smaller than the hydrodynamic damping from the floater.
Development of a numerical model
### Previous studies

<table>
<thead>
<tr>
<th>Concept</th>
<th>Dutch 2001</th>
<th>Henderson 2000</th>
<th>GH 1993</th>
<th>Suzuki 2005</th>
<th>This study 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave load model</td>
<td>Potential</td>
<td>Morison</td>
<td>Morison</td>
<td>Potential</td>
<td>Morison</td>
</tr>
<tr>
<td>Floater structure</td>
<td>Rigid</td>
<td>Rigid</td>
<td>Rigid</td>
<td>Elastic</td>
<td>Elastic</td>
</tr>
<tr>
<td>Hydrodynamic damping</td>
<td>×</td>
<td>×</td>
<td>△</td>
<td>△</td>
<td>○</td>
</tr>
<tr>
<td>Interaction between wind turbine and floater</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>○</td>
</tr>
<tr>
<td>Solution domain</td>
<td>Freq.</td>
<td>Freq.</td>
<td>Freq.</td>
<td>Freq.</td>
<td>Time</td>
</tr>
</tbody>
</table>

The interaction between the wind turbine and the floater is not considered, which might lead some error. In this study, we developed a FEM code for the analysis of dynamic response of the floater and wind turbines, in which:

1. Floater structure is constructed by beam elements to describe elastic behavior.
2. Interaction between wind turbine and floater is considered
3. Equations are solved in the time domain to accurately simulate non-linearity of the hydrodynamic and aerodynamic damping terms
Equation of motions for the floater

\[
[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{F_M\} + \{F_R\} + \{F_H\} + \{F_W\}
\]

\{\chi\}, \{\chi\}, \{\chi\} : Acceleration, velocity, displacement

[M] : Mass matrix
[C] : Damping matrix
[K] : Stiffness matrix

\{\psi^M\} : Mooring force
\{\psi^R\} : Restoring force
\{\psi^H\} : Hydrodynamic force
\{\psi^A\} : Aerodynamic force (Aerodynamic damping)

- The dynamic responses of the floater are predicted by solving this equation, where both of structures of the floater and the wind turbines are included.
- The mooring force, restoring force, hydrodynamic force and aerodynamic force are considered.
The Floating wind turbine system was constructed by 188 beam elements, which was used in the dynamic response analysis.

Each wind turbine with 46 elements.

Floater with 50 elements.
The dependencies of the peak response on the wave height can be simulated well by the proposed numerical model, which means accurate modeling of the hydrodynamic damping is very important.
Predicted and measured pitch

On the other hand, the peak response of pitch is overestimated around the resonant point. This is because the assumption of the hydrostatic restoring force is violated as for the pitch motion and will be improved in the further study.
Predicted and measured surge in operating case

As we have seen in the experiment, around the resonant point, the predicted peak responses at the wind speed $U=2\text{m/s}$ are also less than those at the wind speed $U=0\text{m/s}$ due to aerodynamic damping which is more significant for the lower wave height cases. This indicates that the effect of the aerodynamic damping can be demonstrated well by the proposed numerical model.
Conclusions

1. The dynamic behaviors of the semi-submersible floater were investigated by using a wind tunnel with water tank. The results indicate that the proposed floater gives small response during the operation and is stable enough in the survival condition.

2. The dependency of the peak surge on the wave height was observed, indicating that the hydrodynamic damping is very important during the resonance. In the operating case, the dependency of the peak surge on the wind speed was also observed due to the aerodynamic damping from the wind turbine, but not in the survival case.

3. A FEM code for the analysis of dynamic response of the floater and the wind turbines was developed, considering the interaction between the wind turbines and the floater. The predicted surge shows a good agreement with the experiment, while the pitch is overestimated around the resonant point, which should be improved in the further study.
Thank you for your attention!