Time-domain coupling analysis of semi-submersible floating foundation with four buoys for offshore wind turbine and its mooring system

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Abstract: Taking OC4 semi-submersible floating foundation design of offshore wind turbine as the research object, the mooring system of OC4 semi-submersible floating foundation with four buoys is designed according to its structural parameters. The calculation model is established by AQWA software to analyze the time domain coupling analysis results of the floating foundation and its mooring system under the action of wind, wave, and current to determine its mooring system. The results show that for the four buoy semi-submersible floating foundation, the catenary mooring system has more advantages in the positioning and motion control of the floating fan.

1. Introduction
In order to cope with climate change and achieve the goal of carbon peak and carbon neutralization as soon as possible, researchers have accelerated the development and utilization of clean energy. As a kind of clean energy, offshore wind power has been widely studied in academic circles. With the continuous development of wind power technology, offshore wind power is developing towards deep water and large capacity of the single wind turbine. A fixed offshore wind turbine faces high construction difficulty and a sharp increase in economical cost. Floating offshore wind turbine has apparent advantages. At present, the common floating foundation structures are mainly divided into three categories: spar floating foundation, semi-submersible floating foundation and tension leg floating foundation\cite{1}. OC4 semi-submersible floating foundation equipped with a 5MW wind turbine in a US renewable energy laboratory is a typical semi-submersible floating foundation.

With the development of wind turbine capacity towards large scale, wind turbine manufacturers worldwide have launched their research and development of 10MW wind turbine. Dtu10mw wind turbine\cite{2} proposed by the Danish University of science and technology has become one of the mainstream 10MW wind turbines in the market. With the increase of wind turbine capacity, the overall structure increases, and the corresponding floating foundation needs further structural adjustment to meet its user’s needs. The mooring system is a traditional passive positioning system\cite{3}. The base equipment is placed on the bottom of the sea, and the floating body is connected with the base by mooring lines to limit the range of motion of the floating body. At the same time, the strength of the mooring lines should be ensured, especially in extreme sea conditions, because the floating fan system...
cannot sail like a ship; in order to ensure the safety of the floating fan system, the material, quantity and arrangement of mooring lines are particularly critical, which has an important impact on the reliability and safety of the mooring system. In this paper, based on the OC4 semi-submersible floating foundation design of Renewable Energy Laboratory of the United States with 5MW wind turbine, a four buoy semi-submersible floating fan foundation and its mooring system are established. The time-domain coupling results of the floating foundation and its mooring system under the action of wind, wave and current are calculated by AQWA software to determine the mooring system scheme of the floating foundation.

2. Mathematical model

2.1 Basic parameters of floating fan foundation

The structure of this paper refers to OC4 semi-submersible floating foundation, and on this basis, a floating foundation. The design draft is 15m, and the pontoon spacing is 80m. It is mainly composed of the main pontoon, 16 struts and a tower. The specific parameters of the floating foundation are shown in Table 1.

| Parameter                                | Numerical value |
|------------------------------------------|-----------------|
| Height of main buoy (m)                  | 30              |
| The outside diameter of the main buoy (m)| 10              |
| Upper height of auxiliary buoy (m)       | 10              |
| The outer diameter of the upper part of the auxiliary buoy (m) | 10 |
| Height of lower part of the auxiliary buoy (m) | 20 |
| The outer diameter of the lower part of the auxiliary buoy (m) | 20 |
| External diameter of the strut (m)       | 4               |
| Tower height (m)                         | 115.63          |
| Tower quality(kg)                        | 628442          |
| Equivalent density(kg/m³)                | 7850            |
| Tower top outer diameter(wall thickness)  | 5.5m,20mm       |
| The outer diameter of the tower bottom (wall thickness) | 8.3m,38mm |

2.2 Mooring system design

Combined with the sea conditions of the working area of the floating fan, two different mooring systems are designed: catenary mooring and tension mooring. Since the mooring system of the floating fan is required to have a good motion control effect, and the multi-point mooring mode can effectively control the plane motion and rotation motion of the floating body, the multi-point mooring mode is adopted. At the same time, the floating fan designed in this paper has four symmetrical pontoons, so the mooring scheme of four groups of eight mooring lines and anchor points is designed. The mooring line material of the catenary mooring system is steel cable. In contrast, the mooring line of tension mooring system adopts a three-section structure. That is, the upper and lower ends are made of anchor chain material. The middle part is made of polyester cable material. The top ends of the four groups of mooring lines are respectively connected with the connecting code at the bottom centre of the four buoys. The four groups of mooring lines form a 90° The arrangement is shown in Figure 1 for the catenary mooring system and tension mooring system, respectively. The specific time-domain calculation model and the coordinates of mooring line endpoints are shown in the figure below.

In the time domain analysis of the two mooring modes, the water depth is set at 200m. Table 2 and Table 3 are the coordinates of the mooring line fairlead and anchor point, and table 4 is the physical parameters of the mooring line.
Catenary mooring system                Taut mooring system

Fig 1. Two mooring systems

Table 2. Coordinates of fairlead and anchor points of the catenary mooring system

| Cable number | Fairlead coordinate | Anchor coordinate |
|--------------|---------------------|-------------------|
|              | x(m) | y(m) | z(m) | x(m) | y(m) | z(m) |
| Mooring line 1 | 40   | 40   | -10  | 700  | 40   | -200 |
| Mooring line 2 | 40   | 40   | -10  | 40   | 700  | -200 |
| Mooring line 3 | -40  | 40   | -10  | -40  | 700  | -200 |
| Mooring line 4 | -40  | 40   | -10  | -700 | 40   | -200 |
| Mooring line 5 | -40  | -40  | -10  | -700 | -40  | -200 |
| Mooring line 6 | -40  | -40  | -10  | -40  | -700 | -200 |
| Mooring line 7 | 40   | -40  | -10  | 40   | -700 | -200 |
| Mooring line 8 | 40   | -40  | -10  | 700  | -40  | -200 |

Table 3. Coordinates of fairleads and anchorages for tensioned mooring systems

| Cable number | Fairlead coordinate | Anchor coordinate |
|--------------|---------------------|-------------------|
|              | x(m) | y(m) | z(m) | x(m) | y(m) | z(m) |
| Mooring line 1 | 40   | 40   | -10  | 230  | 40   | -200 |
| Mooring line 2 | 40   | 40   | -10  | 40   | 230  | -200 |
| Mooring line 3 | -40  | 40   | -10  | -40  | 230  | -200 |
| Mooring line 4 | -40  | 40   | -10  | -230 | 40   | -200 |
| Mooring line 5 | -40  | -40  | -10  | -230 | -40  | -200 |
| Mooring line 6 | -40  | -40  | -10  | -40  | -230 | -200 |
| Mooring line 7 | 40   | -40  | -10  | 40   | -230 | -200 |
| Mooring line 8 | 40   | -40  | -10  | 230  | -40  | -200 |

Table 4. Physical parameters of mooring line

| Mooring line | Diameter (mm) | Axial stiffness (MN) | Breaking load (KN) | Unit weight (kg/m) | length (m) |
|--------------|---------------|----------------------|--------------------|-------------------|-----------|
| Anchor chain | 127           | 1340                 | 13591              | 353.23            | 810       |
| Polyester cable | 178         | Nonlinearity         | 10268              | 11.00             | 268       |
3. Analysis of calculation results

3.1 Working condition selection
When selecting the working conditions of the floating fan system in this paper, considering that the rated wind speed, cut-off wind speed, and limit wind speed of the 10 MW fan are 4/11.4/25 m/s[4], respectively. The target sea area is the South China Sea, the three typical working conditions selected in this paper are shown in table 5.

| Working condition | Wave direction (°) | Hs(m) | Tp(s) | Wind speed (m/s) | Wind direction (°) | Current speed (m/s) |
|-------------------|-------------------|-------|-------|------------------|-------------------|---------------------|
| Rated condition   | P-M               | 0°    | 4.50  | 7.00             | API               | 11.40               | 0°                  | 1.55                |
| Stall condition   | P-M               | 0°    | 7.10  | 9.80             | API               | 25.00               | 0°                  | 1.88                |
| Limiting condition| P-M               | 0°    | 12.00 | 13.40            | API               | 40.00               | 0°                  | 2.82                |

3.2 Calculation results of different degrees of freedom
After the calculation, the motion responses of the two mooring modes are compared 0°; therefore, this paper only lists the calculation results of the three degrees of freedom of Pitch, Heave and Pitch. The results are as follows.

(Surge)

(Heave)
Fig 2. Comparison of time history curves of different degrees of freedom

Table 6. Motion response statistics of each degree of freedom under two mooring modes

|                      | Catenary type | Tension type | Difference |
|----------------------|---------------|--------------|------------|
| Surge motion statistics |               |              |            |
| Maximum (m)          | 18.480        | 34.700       | -16.220    |
| Minimum (m)          | -3.859        | 3.170        | -7.029     |
| Average (m)          | 5.980         | 15.340       | -9.360     |
| Maximum (m)          | 3.410         | 3.663        | -0.253     |
| Heave motion statistics |               |              |            |
| Minimum (m)          | -1.832        | -3.255       | 1.423      |
| Average (m)          | 0.943         | 0.701        | 0.242      |
| Maximum (°)          | 2.928         | 2.763        | 0.165      |
| Pitch motion statistics |              |              |            |
| Minimum (°)          | -2.138        | -2.164       | 0.026      |
| Average (°)          | 0.3566        | 0.2082       | 0.1484     |

From Figure 2 and Table 6, we can find that:

a) According to the relevant specifications, the horizontal displacement of the floating platform is not more than 5% - 6% of the water depth. The heave motion amplitude is not more than 5% ± (0 ~ 3.0) m. As there is no inhabitant on the floating fan platform, the horizontal and heave motions can be relaxed appropriately[5]. From Table 5, it can be seen that the longitudinal motion amplitude of tension mooring is greater than that of catenary mooring in three aspects of maximum, minimum and average. Therefore, from the aspect of longitudinal degree of freedom, catenary mooring is better than tension mooring.

b) The heave motion range of the floating fan platform is -1.832m ~ 3.410m in catenary mooring mode and -3.255m ~ 3.663m in tension mooring mode. The differences between the maximum, minimum, and average motion responses of the two platforms under heave degrees of freedom are -0.253m, 1.423m and 0.242m. In general, there is little difference in heave displacement between the two mooring modes.

c) The motion response of the floating wind turbine platform under catenary mooring is -2.138°~2.928°. The results show that the motion response of the platform is -2.164°~2.763°. The difference between the maximum, minimum and average of the motion response in pitch degrees of freedom is
0.165°, 0.026° and 0.1484°. The pitching motion difference of the two mooring modes is slight. The motion response is in a reasonable range, so they meet the operation requirements.

3.3 Comparative analysis of mooring line tension
When analyzing the mooring line tension characteristics of the floating wind turbine, the same sea conditions are ensured. The tension characteristics of the floating wind turbine with catenary mooring and tension mooring are analyzed. The magnitude of the mooring line tension and the change of the time history curve is mainly compared. The time-domain simulation of 10800s for 3 hours is carried out to analyze and count the maximum, minimum and average values of the mooring line tension. Considering that the structure of the floating fan and the arrangement of the mooring system are symmetrical about the x-axis, and the wind, wave and current are all along the 0° It acts on the floating wind turbine and its mooring system, so the figure below only lists the 4# mooring line and 5# mooring line on the wave side. Fig 3, are the tension time history curves of 4# and 5# mooring lines under the two mooring modes, respectively, and Table 7 shows the statistical results of the tension of the two mooring lines.

![Fig 3. Comparison of tension time history curves of 4# and 5# mooring lines of two mooring systems](image)

| Response type Mooring line tension (N) | Mooring mode | Mooring line number | Maximum        | Minimum        | Average         |
|---------------------------------------|--------------|---------------------|----------------|----------------|-----------------|
| Catenary type                          | 4#           | 3.567E+06           | 1.884E+06      | 2.531E+06      |
|                                       | 5#           | 3.585E+06           | 1.896E+06      | 2.558E+06      |
| Tension type                           | 4#           | 2.601E+06           | 2.840E+05      | 1.161E+06      |
|                                       | 5#           | 2.584E+06           | 2.763E+05      | 1.180E+06      |

It can be seen from Figure 10 and Table 11 that under rated conditions, the mooring line tension of the tension mooring system is less than that of the catenary mooring system. The maximum tension of the catenary mooring system occurs on the 5# mooring line, which is 3.585e + 06n, with an average of 2.558e + 06n. The maximum tension of the tensioned mooring system is 2.601e + 06n, and the average tension is 1.161e + 06n. Through comparative analysis, the value of mooring line tension of catenary mooring mode is greater than that of tension mooring mode. However, the maximum tension of the mooring line of the two mooring modes is far less than the breaking load of the mooring line. Hence, the floating fan has good mooring performance under the two mooring modes, which can effectively ensure the safe operation of the floating fan.

4. Conclusions
By comparing and analyzing the motion response time history curve, mooring line tension time history curve and statistical results of the two mooring modes, it can be concluded that: in terms of the motion
response of the floating fan, the motion response of the tension mooring mode in the degree of freedom of Surge and sway is significantly greater than that of the catenary mooring system; in the heave degree of freedom, the motion response of the tension mooring system is smaller than that of the catenary mooring system, but there is little difference between them; However, in rolling, Pitch and yaw degrees of freedom, the motion responses of the two mooring modes are relatively small and have little influence. In terms of the mooring line tension of the floating fan, the maximum mooring line tension of the two mooring modes is far less than the breaking load of the mooring line, which meets the operational requirements of the floating fan system. In general, the catenary mooring system has more advantages in the positioning and motion control of the floating fan, and the motion amplitude of the tensioned mooring system in the surge degree of freedom is too large, which has exceeded the relevant standards. Therefore, the advantages and disadvantages of the two mooring methods are comprehensively analyzed. Considering that the floating fan requires the mooring system to have good motion control ability, the Catenary mooring system is more suitable for the semi-submersible floating foundation with four buoys.

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