Numerical investigation of the gyro effects on a 10 MW floating offshore wind turbine

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Abstract. In this study, the gyro effects on a floating offshore wind turbine (FOWT) is investigated. For the DTU 10 MW wind turbine, the ITI Energy Barge platform is adopted. The ANSYS software has been used to study various mechanical properties related to the wind turbine, such as natural frequency, vibration mode as well as the critical speed of the wind turbine, based on which the speed in working condition is designed. The transient dynamic analysis is then carried out and the maximum displacements are found to occur at the place located at the top and bottom of the tower. A comparison between the maximum displacements in working condition and non-working condition has been performed. In addition, the gyro effects on the mechanical properties caused by the gyro torque have been analysed and the dangerous area has been discovered. Furthermore, the stress on the top and the bottom of the wind turbine is analysed and it appears to be one of the obvious results affected by gyro effects. Present study can provide valuable reference for the design of the FOWT.

1. Introduction

Nowadays, worldwide energy demand continuously growth and global environmental problem increasingly aggravates [1]. He Ocean is broad and powerful, taking the advantage of marine renewable is a significant energy supply in the future. The development of new and clean energy in China is an inevitable trend in the future. Offshore wind energy has many advantages, such as high wind speed, stable wind condition, no restriction on site selection, and so on. FOWT has become an inevitable choice for the development and utilization of wind energy [2]. Compared with onshore wind energy, offshore wind energy has the advantages of high wind speed, small wind shear and saving land resources. Compared with the traditional land wind turbine, the floating wind turbine is faced with complex marine environment [3]. Under the combined action of the large scale motion of the floating platform and the rotation on the wind turbine blade, a torque which named the gyro moment will be produced.

Nielsen et al. [4] studied the pitching and pitching characteristics of spar floating support system under the combined action of wind and wave through numerical simulation and model experiments, and clearly pointed out that the gyro effect caused by hub rotation has an important influence on the response of floating support system. Matsukuma et al. [5] developed a program for motion analysis in still water according to the theory of multibody system dynamics. The results show that under the influence of
gyro effect, the floating body appears the phenomenon of swinging, rolling and yawing at the same time. Therefore, it is suggested that the gyro effect of the blade should be considered when analyzing the motion characteristics of the floating body. Christian Jensen [6] analyzed the NREL 5MW wind turbine and built an equivalent model through ANSYS to simulate the condition when the rotor is operating. However, there are some shortcomings in modal analysis. Instead of building a complex model with rotors, towers, and floating platforms, only a simple model of the rotor is built for modal analysis in Christian Jensen’s paper. Therefore, it is necessary to establish a model and analyze it as a whole, and further explore the influence of its rotor speed on the FOWT.

The present study aims to study the influence of the gyro effects on the mechanical properties of the FOWT. Based on the Multibody System Dynamics and the Theory of Finite Element Analysis, the frequency and the vibration mode of the 10 MW FOWT are analyzed by using ANSYS. The working condition and the non-working condition are compared to study the influence of the gyro effect on the working condition of the FOWT. By drawing the Campbell diagram, the critical speed of the wind turbine is discovered, and the rationality of the working speed of the FOWT is verified. In addition, the transient analysis is carried out to investigate the gyro effects on the mechanical properties of the wind turbine.

2. Parameters of floating offshore wind turbine
The gyro effects of FOWT on the whole deformation and the inner force of tower under a pitch motion and a rotor speed are investigated for the 10MW DTU wind turbine. The wind acts on the rotor and it produces forces which leads to a bending of the blades and the tower, and it produces a rotation of the rotor. The generator moment counteracts this rotation. And I neglect the thrust of the wind (bending around z-axis) and the wind moment (moment around x-axis). The ITI Energy Barge platform [7] is adopted as the supporting foundation for the wind turbine. The parameters of the superstructure and supporting platform of the 10MW DTU wind turbine are listed in Table 1.

| Table 1. Main parameters of the structure [8] |
|-----------------------------------------------|
| **Superstructure parameter**                      | **Supporting platform parameters**                   |
| 3 blades                                        | Size                                              | 40 m × 40 m × 10 m |
| Cutting speed 6 (r·min⁻¹)                        | Waterline                                        | 4 m                   |
| Rated speed 9.6 (r·min⁻¹)                        | Displacement                                     | 6000 m³               |
| Power rating 10 MW                              | Total platform mass                               | 5452000 kg           |
| Hub height 119 m                                | Center of mass                                   | 0.2818m               |
| Tower height 115.63 m                           | Rolling inertia                                   | 7.269×10⁸ kg·m²     |
| Overhang 7.1 m                                  | Pitch inertia                                     | 7.269×10⁸ kg·m²     |
| Rotor diameter 178.3 m                          | Yawing inertia                                    | 1.4539×10⁹ kg·m²   |
| Hub diameter 5.6 m                              | Number of mooring cables                          | 8                    |
| Rotor mass 230.7 t                              | Cable length                                      | 564.5m               |
| Cabin mass 446.0 t                              | Cable diameter                                    | 0.0809 m             |
| Tower mass 628.4 t                              | Cable mass                                        | 130.4 kg/m           |
| Total mass 1305.1 t                             | Cable stiffness                                   | 5.89×10⁸N/m          |

| Table 2. Element types of the structure |
|-----------------------------------------|
| **Structure**                           | **Element types**                                 |
| Shaft                                   | Beam188                                           |
| Tower                                   | Beam188                                           |
| Hub and blade                           | Mass21                                             |
| Nacelle                                 | Mass21                                             |
| Platform                                | Shell181                                           |
| Anchor chain                            | Combin14                                           |
3. Theory of gyro effects of floating offshore wind turbine

A rotating object, such as the wind turbine, has the inertia to maintain the direction of its axis of rotation, which can lead to the gyro effects. For a structure that rotates around the axis, if a disturbance is applied perpendicular to the axis, there will exist a reverse moment, which is the gyro moment [9]. Gyro has two characteristics: precession and orientation stability. The axis of the gyro moment is perpendicular to both the axis of rotation and the axis of precession. The gyro effects can be equivalent to be an additional gyro matrix [G] implemented in the motion equation of the wind turbine.

The general dynamic equation of the wind turbine is [10]

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

In Equation (1), [M], [C] and [K] are the mass, damping and stiffness matrices, respectively; {F} is the external force vector. In the process of rotor rotation, the above equation should include gyro effects and rotation damping, then the dynamic equation becomes

\[ [M]\ddot{U} + ([C] + [G])\dot{U} + ([K] + [B])U = F \]  

The gyro matrix [G] depends on the rotational speed and can affect the analysis of the dynamics about the wind turbine. This matrix is necessary in the analysis of rotor dynamics. The rotational damping matrix [B] also depends on the rotational speed, and it can obviously change the stiffness of the structure and cause unstable motion of the structure [11].

As the gyro effects are mainly affected by rotor speed and wind turbine pitching, the effects of buoyancy and stability are not taken into account here. The movement of FOWT due to the combined action of wind, wave and current load is simplified as simple harmonic motions. Spring damping element Combin14 has been used in the modeling. A Combine 14 element with enough stiffness between the shaft and the tower is established to simulate the bearing. In the present analysis, the element is applied to the corner of the floating platform. The provided vertical force can balance the gravity. In the meantime, the drag force in the horizontal direction can be used to simulate the spring force due to the anchor chain. The model established by ANSYS is shown in Fig.1. The element types of the structure in ANSYS are shown in Table 2.

![Figure 1. The model established by ANSYS](image1.png)

![Figure 2. Campbell diagram](image2.png)

In order to simulate the movement of the FOWT under the combined action of the wind and wave, harmonic load in the form of \( z = A \sin \omega t \) is applied at the corner of the floating platform. When the maximum amplitude acts on the platform, \( A \) is 1.743 m, the floating wind turbine can produce a large
pitching under the action of waves. In the meantime, a wave period of 6s, which is the common in the South China Sea, is adopted in this study.

4. Modal Analysis of wind turbine and determination of critical Speed

Modal analysis is used to determine various vibration characteristics of structures, i.e., the natural frequencies and vibration modes, which are important parameters in the design of structures subjected to dynamic loads. The frequency and vibration modes are analyzed for the wind turbine with the rotation speeds of 0 and 9.6 rpm, respectively. The effect of the pitching and the rotor speed on the dynamic behavior of the wind turbine can be examined.

| Order | Natural frequency/Hz | Mode description                  |
|-------|----------------------|-----------------------------------|
| 1     | 0.24217              | tower bends about x-axis          |
| 2     | 0.24259              | tower bends around z-axis         |
| 3     | 1.6209               | torsion of transmission system    |

Table 3. Frequency when the rotational speed is 0

| Order | Natural frequency/Hz | Mode description                  |
|-------|----------------------|-----------------------------------|
| 1     | 0.21954              | tower bends around z-axis         |
| 2     | 0.24376              | tower bends about x-axis          |
| 3     | 1.6159               | tower bends around z-axis         |

Table 4. Frequency when the rotational speed is 9.6 rpm

The natural frequencies of each order in Table 3 and Table 4 have changed. The change is due to the change of the gyro matrix [G] and the rotational damping matrix [B] in Equation (2) because of the simultaneous rotation of the rotor and the pitching of the wind turbine. It will significantly change the stiffness of the structure and can cause unstable motion in the structure. The natural frequency varies with the rotational speed of the rotor.

The rotation of the rotor can affect the gyro matrix [G] and the rotational damping matrix [B] in Equation (2) will be changed. Then, the stiffness of the structure as well as the natural frequency of each vibration mode can be changed. In addition, in specific conditions, the rotation of the hub can make the motion of the whole structure unstable. By observing the Campbell diagram, it can be found that in the process of increasing the rotational speed of the rotor, the original first-order natural frequency is decreased, and the second-order natural frequency is increased. When the rotational speed is 9.6 rpm, first-order natural frequency has been changed from 0.24217 Hz to 0.24376 Hz, second-order natural frequency has been changed from 0.24259Hz to 0.21954Hz, so the second-order mode is obtained by the change of the original first-order mode and the first-order mode is obtained by the change of the original second-order mode.

The rotor of the rotating system will vibrate in operation. With the critical speed, resonant motion of the rotating system can be happened, at which vibration of the rotating system reaches the maximum. As the rotation speed increases further and exceeds the critical speed, the vibration of the rotating system decreases gradually and then maintain stable within a certain range. In order to ensure that the rotating system does not resonate in the range of working, the critical speed should deviate from the working speed of 9.6 rpm. It can be seen from the Campbell diagram that the prediction from the ANSYS. The line of rotation speed intersects the frequency of first mode near 12 rpm and intersects the frequency of second mode near 14 rpm. It suggests that the first critical speed is 12 rpm and the second critical speed is 14 rpm, which are both far from the wind turbine’s working speed. The resonance effect is avoided well, which provides a precondition for the safe operation of the wind turbine.
5. Transient Analysis of wind turbine

It is not possible to define the same damping coefficient for different modes of vibration in the process of transient analysis. As a result, a weighted stiffness damping is required [12]

\[
[C] = \beta[K]
\tag{3}
\]

In Equation (3), \([C]\) is the damping matrix, \([K]\) is a stiffness matrix, \(\beta\) is a power coefficient and defined by

\[
\beta = \frac{2 \xi}{\omega}
\tag{4}
\]

In which, \(\omega\) is a circular frequency, corresponding to the minimum natural frequency of the first mode \(f = 0.21954\) Hz, \(\xi\) is a damping ratio of 1%. It can be calculated that

\[
\beta = \frac{2 \xi}{2 \pi f} = \frac{0.01}{3.14 \times 0.24217} = 0.1315
\tag{5}
\]

There are six forces of the node on the tower: \(N\) is the axial force, \(T\) is the gyro torque, \(M_x\) is the bending moment about the x-axis, \(M_z\) is the bending moment about the z-axis, \(F_x\) is the shearing force about the x-axis, and \(F_z\) is the shearing force about the z-axis.

The internal force curve of the bottom node is as shown in Fig. 3.

After comparison, it can be found that when the wind turbine is working, that is, rotating at 9.6 rpm, the gyro moment about the bottom node of the wind turbine is \(6.2 \times 10^6\) N·m, and the gyro moment causes an angle of torsion around the y-axis. In turn, a shear force \(F_z\) of \(1.4 \times 10^6\) N and a bending moment \(M_x\) of \(1.8 \times 10^8\) N·m. The is calculated \(\frac{F_z}{F_x} = 11.2\%\), \(\frac{M_x}{M_z} = 13.8\%\). At the same time, it affects the range of the axial force \(F_y\).

It can be seen that the gyro effects will have an influence on the internal force at the bottom of the tower, which in turn affects the Von Mises stress. The following is a comprehensive consideration of the situation in which the wind turbine is in non-working condition or in working condition. The minimum and the maximum inclination of the platform, and the influence of the gyro effect on the Von Mises stress at the bottom of the tower has also been considered.
Figure 3. Internal force of the bottom node

Figure 4. Von Mises stress at the bottom of tower
In the Fig. 4, at time of 69.1 s, the angle of inclination that the FOWT under the action of the wave is the smallest, and the 73.6 s is the time when the maximum angle that the FOWT under the action of the wave. The gyro effects are the strongest when the inclination angle is the smallest, and the comparison between Fig. 4(a) and Fig. 4(b) is a good illustration of this view. The maximum Von Mises stress at the bottom is 46.3 MPa when the wind turbine isn’t working, and the maximum Von Mises stress at the bottom is 114 MPa when the wind turbine is working, which is 2.5 times as much as the value when the wind turbine is not working. The gyro effect of the FOWT at the maximum inclination is the weakest, and the comparison between Fig. 4(c) and Fig. 4(d) is a good illustration of this view. The maximum Von Mises stress at the bottom is 339 MPa when the wind turbine isn’t working, and the maximum Von Mises stress at the bottom is 343 MPa when the wind turbine is working, which is only 4 MPa more than that when the wind turbine is not working. Thus, the maximum stress is increased by 1.18% because of the gyroscopic force. Because of neglecting the thrust of the wind and the wind moment, the wind forces would lead to a higher stress level and thus the effect of the addition stress due to the gyro effect would be smaller than 1.18%.

Similarly, the values of the maximum von Mises stress at the top is 48.2 MPa when the wind turbine isn’t working, and the values of the maximum Von Mises stress at the top is 63.3 MPa when the wind turbine is working, which is 1.3 times as much as the value when the wind turbine is not working. The gyro effect of the FOWT at the maximum inclination is the weakest. The values of the maximum Von Mises stress at the top is 204 MPa when in non-working condition, and the maximum Mises stress at the top is 217 MPa when the wind turbine isn’t working, which is only 13 MPa more than that when the wind turbine is not working. Thus, the values of the maximum stress is increased by 6.3% because of the gyroscopic force. Because of neglect the thrust of the wind and the wind moment, the wind forces would lead to a higher stress level and thus the effect of the addition stress due to the gyro effect would be smaller than 6.3%.

6. Conclusion
In this paper, the gyro effects on an FOWT, DTU 10 MW wind turbine, is investigated. The coupling effect of the simple harmonic wave motion and the hub rotation of the FOWT are considered. The modal analysis and transient analysis of the FOWT were carried out, and the natural frequency and vibration mode were studied. The critical speed of the wind turbine, the value of the internal force at the bottom and top of the tower changing with time are also been studied. The gyro effects on the natural frequency, the mode shape, the various internal forces at the bottom and the top of the tower are studied by comparing the working state with non-working state. At the same time, the influence of the gyro effect on the strength of the wind turbine was determined, and the following conclusions were obtained:

The natural frequency whose mode causes a change of the rotor axis is affected by the gyroscopic effect. The frequency of the first mode increases with increasing rotational speed, and the frequency of the second mode decreases with increasing rotational speed. This frequency change has to be considered in the design of FOWT. The first-order critical speed of the FOWT is 12 rpm, and the second-order critical speed is 14 rpm. To ensure safe and stable operation of the wind turbine, the speed should be kept away from the critical speed. The 10 MW DTU wind turbine works at 9.6 rpm, which is away from the critical speeds of different motion modes.

The gyroscopic force is significant, but, fortunately, the maximum of the gyroscopic forces and the maximum of the inertia forces do not occur at the same time. As the inertia forces are significantly higher, the gyroscopic force do not significantly affect the maximum stresses in the tower in this example. Nevertheless, the gyroscopic force should not be neglected in general as there might be cases, where the gyroscopic force may be considerable for the structural design and the motion response.

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