EAI Endorsed Transactions
on Energy Web

Research Article **EAI.EU**

Study on Dynamic Response Characteristics of Offshore Floating Wind Turbine Pitch System

Xin Guan[1,2,*a], Shiwei Wu[1,b], Mingyang Li[1,c], Yuqi Xie[1d]

[1]College of New Energy, Shenyang Institute of Engineering, Shenyang, China
[2]Shenyang Key Laboratory of Refined Comprehensive Utilization and Scheduling Energy Storage of Clean Energy, Shenyang, China

Abstract

Due to its special working conditions, offshore wind turbine will bear large direct and indirect loads under the combined action of air flow and wave flow. In this paper, a variable pitch system composed of variablepitch motorand variable pitch bearing is improved, and the characteristics of system's bending moment, torque, vibration and other physical quantities under the action of multiple physical loads are verified, and the mechanical response characteristics of floating wind turbine under the control of unified variable pitch and independent variable pitch are studied under the running conditions at sea. The results show that mechanical structure of uniform pitch is compared with that of independent pitch, the independent variable pitch structure can effectively reduce the mean oscillation value of wind turbine tower in the parallel direction of air flow by optimizing control strategy, and reduce the thrust at the hub of wind turbine and the bending moment at the root of tower, but increase the vibration frequency and fatigue load of offshore wind turbine tower along parallel direction of air flow. Reduce the fatigue life of equipment. The research results can be used as a reference to reduce the variable pitch control and vibration suppression of offshore wind turbines and improve the reliability of wind turbines.

Keywords: Offshore wind turbines, Simulation test, Vibration suppression, Dynamic characteristics, Reliability

Received on 15 November 2023, accepted on 09 April 2024, published on 16 April 2024

doi: 10.4108/ew.5800

1. Introduction

Wind turbine is the main power generation equipment of new energy. Onshore wind power equipment has entered the stable running stage, and their running reliability is basically guaranteed. The construction of smart wind farm is gradually advancing, but the disadvantages of poor stability of onshore wind resources and low quality of wind power are still unavoidable. The corresponding offshore wind resources has the advantages of relatively stable wind power, high wind power quality andutilization, small transformation of natural environment and small impact on human living environment, so it is favored by domestic and foreign power construction units.

Variable pitch system plays an important role in offshore wind turbines, which has been identified as the future development and research direction of wind power equipment by experts and scholars at home and abroad, and it is considered as the core technology for large-scale development and utilization of offshore wind power. However, offshore wind turbines are subjected to the combined effects of uncertain environmental loads such as air flow and wave flow, especially under the cut-out wind speed. There are some practical problems such as poor system stability, large structural load and unstable driving power, which pose new challenges to the running stability and equipment reliability of offshore wind turbines.

Aiming at the problem of structural overload of offshore wind turbines, many researchers have been carried out by domestic and foreign scholars for a long time, and blade pitch control method has been proposed. The research shows that variable pitch control can effectively stabilize power output and reduce structural load at high wind speed. Bossanyi et al. [1] proposed a basic variable pitch controller based on PI or PID algorithm. By measuring a single signal such as generator speed or output power, the blade pitch angle required by the system under different running

[a*]Corresponding author. Email: xin.guan@sina.com
[b]2312782286@qq.com, [c]549431996@qq.com, [d]yuqi_xie7725@163.com

conditions was obtained. However, the traditional PI variable pitch control has some shortcomings in the floating wind turbine. Nilsen et al. [2] pointed out that if the variable pitch controller of wind turbine is activated above the rated wind speed, the thrust coefficient will decrease with the increase of wind speed, and negative damping effect may be introduced, resulting in large resonant motion of the floating wind turbine. At the same time, Larsen et al.[3] found that due to the low-frequency characteristics of floating foundation, tower vibration and aerodynamic load would produce significant coupling effect, leading to the decrease of pitch angle control ability and possibly negative damping effect. To this end, they studied the motion and load response of floating wind turbines under different controller natural frequencies, and optimized the PI controller parameters. Later, Jonkman[4] redesigned the variable pitch controller by reducing controller PI parameters, which could suppress the platform pitch motion caused by negative damping effect to a certain extent, but the control effect was not significant.

Therefore, based on the disadvantages of traditional unified pitch control, scholars further proposed an independent pitch control strategy, that is, according to the changes of external environment and wind turbine state, different pitch angles are implemented on three blades to suppress the floating body motion and structural load of floating wind turbine to a certain extent. Namik et al. [5] studied the independent variable pitch control of three floating wind turbines (barge type, single column type and tension-leg type) based on state-space method. The results show that the independent pitch can effectively reduce the load distribution inequality caused by wind shear and tower shadow effect. In addition, they added an anti-interference controller to reduce the impact of wind speed perturbations on floating wind turbine system. Zhang et al.[6] proposed an independent blade varying strategy based on proportional resonance. This strategy does not need to measure blade azimuths or carry out multiple Coleman transformations between rotating coordinate system and stationary coordinate system, and can reduce 1P load of blades and 3P load of rotors without filtering. Han et al.[7] focused on the fuzzy controller with independent variable pitch. By optimizing the balance between multiple control objectives (such as root bending moment and generator torque), fatigue load could be effectively reduced and power output regulated. Aiming at the nonlinear problem of floating wind turbine, Lu Xiaoping et al.[8] designed PID variable pitch controller with expert system and realized independent variable pitch control with d-q coordinate transformation, which effectively reduced the pitch motion of the platform without affecting output power. Zhou Lawu et al.[9] proposed an independent variable pitch control method based on radial basis function neural network, which realized the comprehensive effect of stabilizing power output, reducing load fluctuation and pitch oscillation. Bottrell[10] has studied the different characteristics of two-blade wind turbines under periodic pitch variation, and the results show that periodic pitch variation can effectively reduce the asymmetric load and unstable yaw error of wind turbine. Larsen et al.[11] found that periodic variable pitch could improve the wind performance of two-blade wind turbines without affecting the power output and load. Bottasso et al.[12] found that periodic variable pitch control can effectively reduce the average load of wind turbine tower, spindle and other core components. Then, Li Qingan et al.[13] carried out numerical simulation and wind tunnel test of two-blade wind turbine with periodic pitch variation to study the influence rule of various factors of periodic pitch variation on wind turbine performance.

The above work effectively promotes the development of floating wind power and independent pitch control technology, and proves its effectiveness in improving wind turbine stability and reducing structural load. However, although the independent pitch can effectively improve load asymmetry of floating wind turbine, it can stabilize power output and reduce platform motion. But it is undeniable that, first of all, independent pitch varying is highly dependent on the reliability of wind turbine pitch system, and it is difficult for three blades to independent blade varying in real time in complex environment. Secondly, the variable pitch motion depends on precise running state of the wind turbine, so higher requirements are put forward for the sensor carried by wind turbine. Therefore, the existing independent pitch control is mainly based on simulation analysis and simple verification test. The integrated test of floating wind turbine including independent pitch control has not been reported, and its control effect on the stability of floating wind turbine system and structural load has not been fully verified by the test. In order to fill this gap, based on the developed scale model of floating wind turbine[14], this paper further builds an independent pitch, and compares and analyzes the influence laws of unified and independent pitch control on the motion and structural load of floating wind turbine under complex working conditions, providing valuable data support for the research on independent pitch control of floating wind turbine .

2. Test Overview

2.1 Floating wind turbine model

In order to study the effect of independent pitch control on dynamic response of floating wind turbine, an integrated floating wind turbine test system with independent pitch control is designed and manufactured. This test object is a three-column semi-submersible floating wind turbine with a design draft of 50m. The system mainly consists of three parts: wind turbine model, floating platform and mooring system. The wind turbine model used in this paper is based on DTU 10MW wind turbine, which is designed and manufactured according to the scale ratio of 1:64. According to Froude's law of similitude, the thrust similarity is satisfied, and the model wind turbine blade is equivalent reconstructed based on the station load matching algorithm. The model blades are made of carbon fiber, and the diameter of wind turbine rotor is 279cm. The tower model ofwind turbine is made of aluminum alloy, and the first-order natural frequency meets corresponding relationship with prototype wind turbine. There is a six-component force balance at the top and bottom of tower, and the height of wind turbine hub is 1.86m.

The floating platform is the main part of wind turbine model. The test object is a semi-submersible three-column platform with good motion performance and stability. The platform draft is 20m and the displacement is 15,000t. Mooring system is an important part to limit the movement of floating platform. In this experiment, a three-point combined catenary mooring system was adopted, which was composed of three groups of mooring cables, each group of mooring cables was 120° apart, and each group of mooring cables was composed of three cables. Wind turbine, floating platform and mooring system constitute the whole floating wind turbine system.

2.2 Independent variable pitch control mechanism

In order to explore the influence of independent variable pitch on the motion and load of floating wind turbine, a set of independent variable pitch control mechanism based on space linkage mechanism is developed and designed in this paper, as shown in Figure 1, which mainly includes three parts: variable pitch drive module, transmission module and executive module. The variable pitch drive module is composed of three electric push rods. It adopts 120° circular distribution in the vertical plane. The weight is light and it is easier to achieve the goal of similar mass at the top of the wind turbine. The variable pitch drive module is composed of a non-rotating disc and a rotating disc, which are connected by bearings as transmission part to convey information sent by variable pitch drive module to executive module; The executive module is composed of three variable blade pusher rods and blade root discs. The three variable blade pusher rods are connected with the three blade root discs respectively through bearings and are evenly distributed in the space of 120°.

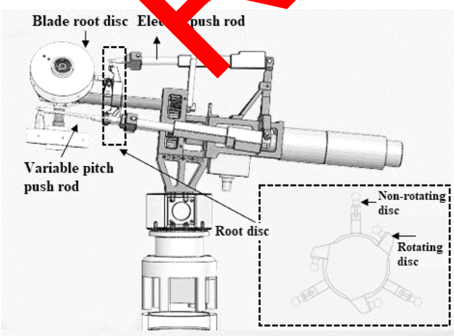

Figure 1. Independent variable pitch control mechanism

Figure 2 shows the principle diagram of developed independent pitch control mechanism. When variable pitch control is carried out, first of all, the mapping relationship between the formation of electric pusher and blade pitch angle is established, and the stroke of electric pusher is calculated inversely according to the required pitch angle. Then, the command is sent from remote control system to variable pitch drive module, and the electric pusher receives command and moves to specified stroke. The different combinations of three electric push rod strokes will make variable pitch drive module in different positions and attitudes. At this time, the position and attitude of non-rotating disc always remain unchanged, and rotating disc will rotate with wind turbine rotor, but always keep parallel with non-rotating disc; Finally, the rotary disc transmits travel information of electric pusher to variable pitch pusher, and the variable pitch pusher is connected to root disc through ball bolt. By moving back and forth to drive the rotation of root disc, the purpose of changing pitch angle is finally achieved. Different pitch needs correspond to different electric push rod stroke. The three electric push rods need to move the same distance when pitch is changed uniformly. Independent pitch change, according to the change of external environment, real-time determine the three electric push rod different travel information; Periodic variable pitch only need to adjust the position of transmission module and tilt attitude, the rotating disc will take the variable pitch push rod in the wind turbine rotor rotation to periodically change the stroke, to achieve the purpose of periodic variable pitch. As a preliminary exploration of integrated independent pitch control of floating wind turbine, this paper only tests and analyzes the simple independent pitch control of periodic pitch.

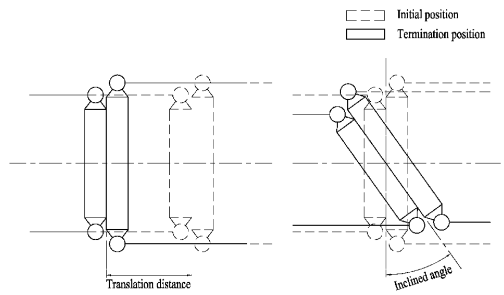

Figure 2. Principle diagram of independent variable pitch mechanism

In the test, the periodic pitch angle of blade is shown in Formula (1) :

$$\beta = a + b * \cos(\varphi + \zeta) \quad (1)$$

Where, β is blade pitch angle, a is average blade pitch angle, b is blade pitch angle amplitude, φ is blade azimuth angle, and ζ is phase difference. When the phase difference is 0, the relationship between pitch angle and azimuth angle is shown in Figure 3.

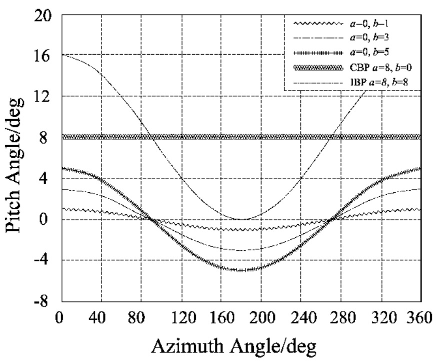

Figure 3. Relation between pitch angle and azimuth angle

In order to obtain the accurate control model of independent pitch control mechanism, it is necessary to calibrate and test the pitch control mechanism. Figure 4 shows the corresponding relationship between stroke of the electric push rod and pitch angle. As can be seen from the Figure, the theoretical calculated values are in good agreement with the experimental measured values, indicating that the independent pitch variable mechanism designed and developed has reliable accuracy and can realize relatively accurate pitch angle control. The pitch angle of system can be adjusted from -40° to 90°, which meets the requirements of variable angle of floating wind turbine under all running conditions.

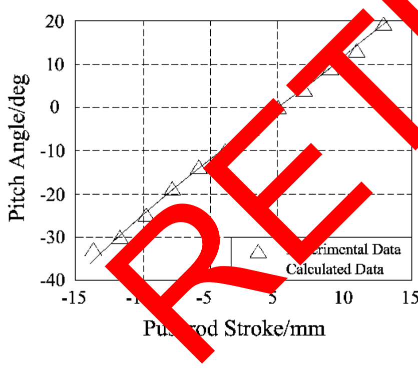

Figure 4. Relationship between pitch angle pitch and electric pushrod stroke

2.3 Test environment and running condition

The experiment was carried out in Shenyang Key Laboratory of Refined Comprehensive Utilization and Scheduling Energy Storage of Clean Energy. The above floating wind turbine model is placed in marine wind, wave and current simulation environment to construct integrated floating wind turbine test system with independent variable pitch. The air generating system used in the test is composed of 16 axial flow wind turbines arranged in 4×4 to form a wind turbine array. The 16 axial flow wind turbines can be operated and controlled independently to realize spatial-spatial distribution and uniform wind field simulation. The air generating area is 3m×3m, and the front side is equipped with fairing to reduce the turbulence of wind field, which can realize a good simulation of ocean wind environment. The marine wave environment is realized by wave making system. The laboratory wave making machine can generate two-dimensional long peak wave and three-dimensional short peak wave. The maximum meaningful wave height can reach 0.3m under model scale, and the wave period is between 0.3 and 3.0s.

The main purpose of this experiment is to explore the effects of uniform and periodic variable pitch on the performance of a floating wind turbine system. The test conditions are divided into four categories: basic performance test, static water condition, regular wave condition and irregular wave condition. The basic performance tests mainly to verify the inherent properties of floating wind turbine. It only needs to keep the wind turbine rotor speed at 0m/s, which is introduced in the following part. The effects of different pitch changing strategies in pure wind environment on the dynamic characteristics of wind turbine system are studied in still water condition. In the case of regular and irregular wave conditions, the changes of independent pitch changing strategy on the performance of floating wind turbine under waves are further studied.

3. Results and discussion

In the marine environment, the motion and load of floating wind turbine are quite complicated, which depends not only on the pitch controller of wind turbine, but also on the speed controller of wind turbine, wind field and wave field parameters. Therefore, this section mainly studies the dynamic response behavior of floating wind turbine under unified and independent pitch varying conditions under different environments and running conditions based on the developed independent pitch varying controller.

It should be noted that the wind and waves are always in the same direction during the test. In addition, the response parameters of floating wind turbine are numerous. In this paper, only the pitch motion of floating platform, the thrust FTx at the top of wind turbine tower and the bending moment at the bottom of the tower are taken as the main evaluation indexes to systematically study the control performance of independent variable pitch on floating wind turbine system.

3.1 Basic performance test of floating wind turbine

In order to obtain the natural period and other basic mechanical properties of the floating wind turbine system, the attenuation test of floating wind turbine under mooring conditions was carried out. During the test, the floating wind turbine system is in static water and no wind environment. An initial pitch angle is applied to floating wind turbine system, and then released freely. Attenuation curves of platform pitch angle, tower top thrust and tower bottom bending moment are recorded, and relevant dynamic attribute parameters are extracted from them, as shown in figure 5. Two peaks of 0.3Hz and 2.2Hz can be observed in the figure, corresponding to the natural frequency f_p of platform pitching and the first natural frequency f_t of tower, respectively. It can be seen that both of them well avoid the wave frequency in actual environment and reduce the possibility of structural resonance.

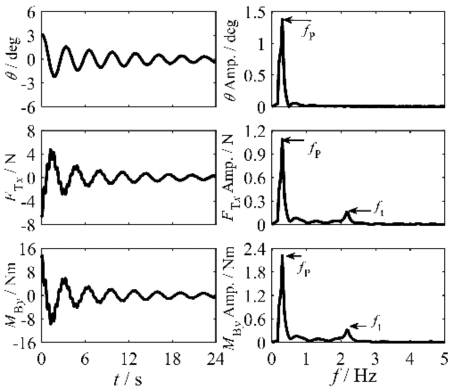

Figure 5. The response of θ,F_{Tx} and M_{By} in decay test

In order to further reveal the natural mechanical properties of floating wind turbine system, the real-time measurement and data analysis of system response of floating wind turbine under shutdown condition were carried out. During the test, the wind field was a uniform wind with speed of 1.425m/s without wave, the blades were in state of smooth paddling (blade pitch angle β=90°), and the wind turbine rotor speed was 0m/s. The test results are shown in figure 6. In the figure, the pitch angle, the top thrust and the bottom bending moment fluctuate up and down at 0.55°, 1.2N and 1.7Nm respectively and remain relatively stable, indicating that the quality of wind field and the accuracy of model making are good, which can better ensure the accuracy of test results of kinematic and dynamic characteristics of wind turbine system in further tests. In figure 8, it can also be obviously observed that some response components with frequencies lower than the natural frequency f_p of the platform pitch, which is mainly caused by wind load of low frequency pulsation. In addition, nonlinear wave loads such as difference frequency are also one of reasons for low-frequency response of floating platforms [15].

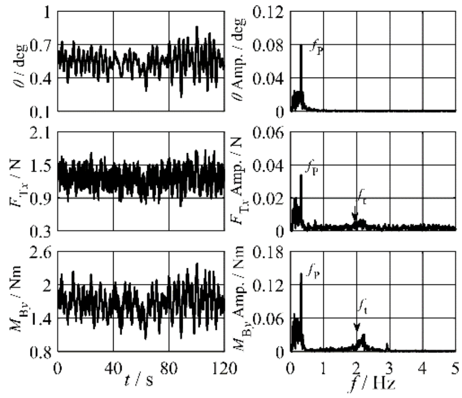

Figure 6. The responseof θ, F_{Tx} and M_{By} in parked test

3.2 Independent pitch control performance in still water

To evaluate the effect of independent variable pitch control on motion stability and structural load of floating wind turbine. The system response of floating wind turbine under uniform and independent pitch control under static water conditions is compared. During the test, the floating wind turbine was in static water and uniform wind environment, the wind speed was 1.425m/s, and the wind turbine rotor speed was 70rpm. Execute unified and independent pitch changing commands on wind turbine respectively. The corresponding parameters of CBP are *a*=8 and *b*=0, and the corresponding parameters of IBP are *a*=8 and *b*=8. See figure 4 for the curve of pitch angle changing with azimuth angle.

Measure the movement and load response of floating wind turbine in two conditions in real time, as shown in figure 7-9. Compared with the uniform variable pitch, average pitch angle, tower top thrust and tower bottom bending moment of floating wind turbine under periodic variable pitch are reduced by 17.3%, 10% and 17% respectively. When the blade rotates to the upper half plane, namely, the azimuth angle ψ=270°~90°, the pitch angle increases, and the local angle of attack decreases, and the aerodynamic thrust decreases. When the blade rotates to the bottom half plane, namely, the azimuth angle ψ=90°~270°, the pitch angle of blade decreases, and the aerodynamic thrust ofblade increases. Therefore, the distance between aerodynamic thrust point and the bottom of tower decreases, and the bending moment of bottom decreases, and the pitch performance of platform is improved to some extent. However, it should be noted that the periodic variation of blade pitch angle is caused by periodic variation of periodic impeller, and the aerodynamic load of wind turbine shows a periodic variation trend, which aggravates the fluctuations of pitch angle, tower top thrust and tower bottom bending moment, which may induce fatigue damage.

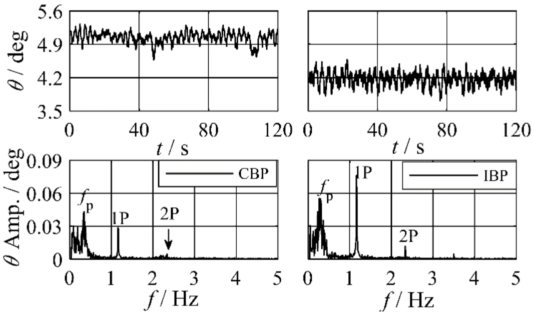

Figure 7. The response of θ under CBP and IBP

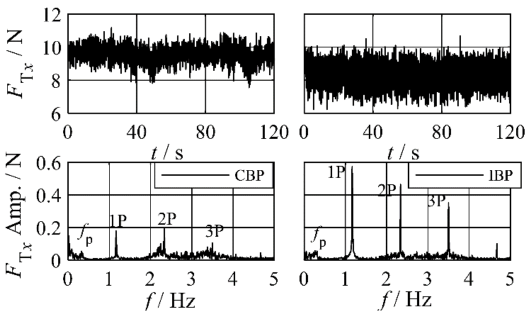

Figure 8. The response of F_{Tx} under CBP and IBP

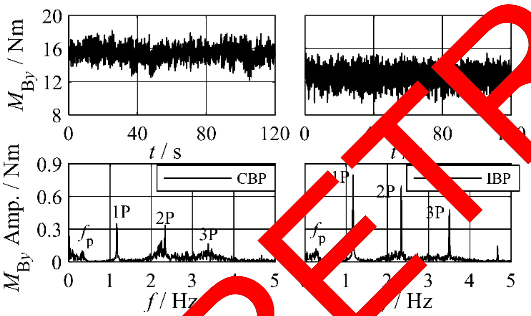

Figure 9. The response of M_{By} under CBP and IBP

3.3 Independent pitch control performance under regular wave

Floating wind turbines are often subjected to regular wave action in real sea environments. For this purpose, the motion and load response of a floating wind turbine under the control of independent pitch in regular waves are investigated experimentally in this section. During the test, the floating wind turbine was in regular wave and uniform wind environment with wave height of 6.25cm, period of 1.25s, wind speed of 1.425m/s and wind turbine rotor speed of 0-80rpm.

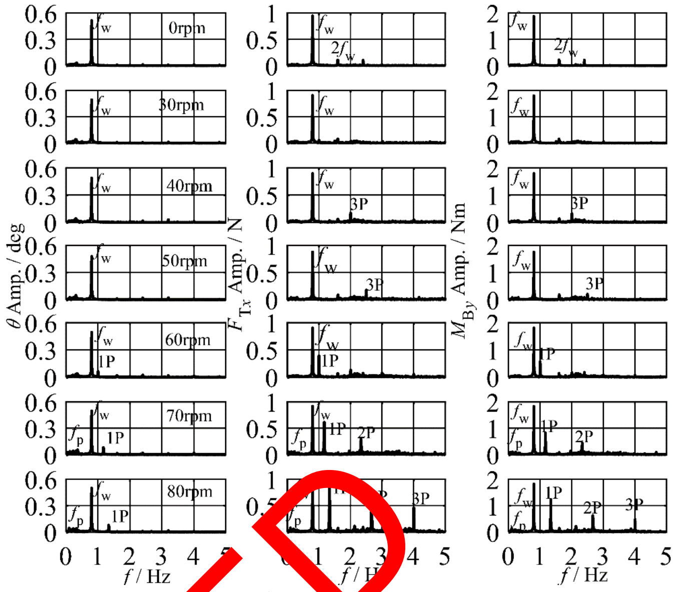

Figure 10. The FWT response in frequency domain under different rotor speeds in regular wave

As can be seen from the spectrum diagram shown in Figure 10, the wave-frequency response occupies a major part. Under uniform wind, the aerodynamic load of wind turbine rotoronly provides a relatively stable forward thrust to the wind turbine system, while the wave will make floating wind turbine produce periodic reciprocating motion at the equilibrium position, which changes the relative inflow velocity of blade section and inclination angle of wind turbine system at the upper part of platform, resulting in changes in the thrust at the top of tower and the bending moment at the bottom of tower. It can be seen that the wave plays an important role in the structure and load change of floating wind turbine. Therefore, in the design of floating wind turbine, the natural frequency of six freedom degrees system, the natural frequency of the tower and the frequency doubling of wind turbine rotor should avoid the real wave frequency as far as possible, so as to avoid the wind turbine in service due to resonance excitation of large motion and load.

4. Conclusion

In order to evaluate the control performance of independent variable pitch on floating wind turbine, a set of control mechanism model of independent variable pitch of floating wind turbine based on space linkage mechanism is designed and developed in this paper, and an integrated testing and research system for wind and wave flow of floating wind turbine is built to carry out experimental research on independent variable pitch control under different environmental conditions. Based on the above analysis and discussion, the following conclusions can be reached:

(1) The independent variable pitch control mechanism based on space connecting rod can realize independent control of any pitch angle of three blades of wind turbine by coordinating stroke of three electric push rods, with simple structure and reliable control accuracy.

(2) Compared with unified variable pitch, independent variable pitch can effectively reduce movement of floating wind turbine system and the mean load of structure. Under regular waves, the pitch angle of floating platform is reduced by 17.2%, the top thrust and the bottom bending moment are reduced by 13.2% and 18.9% respectively. Under irregular waves, the pitch angle of platform can be reduced by 16.6%, the top thrust and the top bending moment can be reduced by 12.7% and 17.8%.

(3) Due to the high frequency control of pitch angle by independent variable pitch, stronger wind turbine frequency rotation and frequency doubling response will be stimulated, thus intensifying the movement of floating wind turbine system and dynamic load of structure, which may cause structural fatigue damage. Therefore, it is necessary to strike a balance between suppressing load mean value and fluctuation to achieve collaborative optimization control of comprehensive performance.

It should be noted that this paper only carried out systematic experimental research on periodic pitch control, which is a simple independent pitch control. In the follow-up study, the independent pitch control method and test system based on state feedback will be further developed. In addition, this paper only studies the independent variable pitch control performance of floating wind turbine under uniform wind field. However, in the real environment, the wind field usually has the characteristics of turbulence, shear and other non-uniform time and space, so it is necessary to further study the action mechanism and influence law of independent variable pitch control on the motion and load of floating wind turbine under complex wind field, so as to provide efficient and reliable solutions for the advanced control of floating wind turbine.

RETRACTED

References

[1] BOSSANYI E A. Wind Turbine Control for Load Reduction [J]. Wind Energy, 2003, 6(3): 229-44.

[2] NIELSEN F G, HANSON T D, SKAARE B R. Integrated Dynamic Analysis of Floating Offshore Wind Turbines [C].Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering, New York, USA: ASME, 2006: 951-959 .

[3] LARSEN T J, HANSON T D. A Method to Avoid Negative Damped Low Frequent Tower Vibrations for a Floating, Pitch Controlled Wind Turbine [J]. Journal of Physics: Conference Series, 2007, 75: 012073.

[4] JONKMAN J. Influence of Control on the Pitch Damping of a Floating Wind Turbine [M]. 46th AIAA Aerospace Sciences Meeting and Exhibit. Reno, Nevada, 2008.

[5] NAMIK H, STOL K. Individual blade pitch control of floating offshore wind turbines [J]. Wind Energy, 2010, 13(1): 74-85.

[6] ZHANG Y, CHEN Z, CHENG M. Proportional resonant individual pitch control for mitigation of wind turbines loads [J]. IET Renewable Power Generation, 2013, 7(3): 191-200.

[7] HAN B, ZHOU L, YANG F, et al. Individual pitch controller based on fuzzy logic control for wind turbine load mitigation [J]. IET Renewable Power Generation, 2016, 10(5): 687-93.

[8] LU Xiaoping, LI Wei, LIN Yonggang. Research on the Individual Pitch Control of Floating Offshore Wind Turbines [J]. Acta Energiae Solaris Sinica, 2012, 33(04): 600-8.

[9] ZHOU Lawu, YANG Binyou, HAN Bing, et al. Individual Blade Pitch Control for the Floating Offshore Wind Turbines Bearing the Air-Hydrodynamic Coupling Loads [J]. Transactions of China Electrotechnical Society, 2019, 34(17): 3607-14.

[10] BOTTRELL G W. Passive Cyclic Pitch Control for Horizontal Axis Wind Turbines [J]. Wind Turbine Dynamics, 1981: 271-275.

[11] LARSEN T J, MADSEN H A, THOMSEN K, et al. Reduction of Teeter Angle Excursions for a Two-bladed Downwind Rotor Using Cyclic Pitch Control [C].Proceedings of the Conf Proc 2007 European Wind Energy Conference and Exhibition, Milan, 2007.

[12] BOTTASSO C L, CROCE A, RIBOLDI C E D, et al. Cyclic Pitch Control for the Reduction of Ultimate Loads on Wind Turbines [J]. Journal of Physics: Conference Series, 2014, 524(1): 012063.

[13] LI Q A, KAMADA Y, MAEDA T, et al. Fundamental Study on Aerodynamic Force of Floating Offshore Wind Turbine With Cyclic Pitch Mechanism [J]. Energy, 2016, 99: 20-31.

[14] ZHANG Qi, PENG Zhike, TIAN Xinliang, et al. Model Design of Floating Offshore Wind Turbine andApplication in Ocean Engineering Tests [J]. Research and Exploration in Laboratory, 2019, 38(06): 9-12+7.

[15] ZHANG Li, DING Qinwei, LI Chun, et al. Comparative Study on Effects of Wind Load on Motion Characteristics of Offshore Floating Wind Turbine Platforms [J]. Acta Energiae Solaris Sinica, 2021, 42(09): 302-11.