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Vibration reduction strategy of offshore wind turbine under wind and wave loads

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Abstract. For purpose of studying the influence of wave on the wind turbines, the causes of aerodynamic load fluctuation and the aerodynamic torque ripple of hydrodynamic frequency is analysed in the mechanism by using the wave model. According to the formation mechanism, the existence of the ripples is verified on GH Bladed platform. To reduce the ripples caused by wind shear, tower shadow and waves of offshore wind turbine, a pitch control strategy is presented in this paper. Firstly, the integral gain of the top tower vibration acceleration signal is combined with the reference pitch angle value to reduce the uniform pitch. Then designing a low-pass filter to filter out the 3P output power ripple of the wind turbine, and converted into adjustment of individual pitch angles of three blades according to rotor azimuth, and superimposed with the changed uniform pitch angle at last. Simulation results indicate that the designed pitch control strategy can not only alleviate the 1P aerodynamic load ripple, but also suppress the aerodynamic torque and output power ripples at 3P and hydrodynamic frequency. The proposed pitch control strategy can reduce wind turbine fatigue loads and improve the output power quality.

1. Introduction

At present, offshore wind power has inevitably become an important energy source for sustainable development of coastal areas in China. However, the continuous wind and wave force acting on the wind turbine is very easy to produce vibration problems, and then affects the stability of offshore wind turbine performance, and has serious impact on output power quality. Therefore, in the analysis of the vibration characteristics of offshore wind turbine, we should fully consider the role of wind and wave force on the wind turbine.

The researches on the vibration characteristics of three-bladed wind turbine under wind loads show that: Wind shear and tower shadow may result in the pulsations of aerodynamic loads at 1P (P is the rotation frequency of wind wheel) [1] and aerodynamic torque at 3P [2] and this situation is aggravated with the increase of the capacity of wind turbine. Some research studies have been conducted to smooth two ripples. Simulation results in [3] showed that the proper individual pitch control can effectively reduce the 1P blade root load ripples of wind turbines. In [4,5], different individual pitch control strategies are designed to achieve wind turbine torque smoothing.

However, most existing papers on offshore wind turbines study the fatigue load, extreme load and dynamic response of the tower under the action of wave by using engineering wave mechanics [6-8]. The above research object is mainly the tower of wind turbine, and a few number of research focuses on the influence of the wave on the blade, even the aerodynamic characteristics and the output power.

Therefore, this paper focuses on the influence of wave on the vibration characteristics of the wind turbine. Firstly, the wave model is established to study the influence of regular wave on the tower fore-aft load and blade root flap-wise load, and the causes of the aerodynamic torque ripple of the hydrodynamic frequency are analysed in the mechanism. Secondly, the pitch control strategy is studied, because the pitch angle directly determines the input energy of the wind system, which can play an active restraining effect on the pulsation of aerodynamic load and the aerodynamic torque. Adjusting the pitch angle based on the vibration acceleration of the tower, the goal to reduce the fluctuating component of hydrodynamic frequency of the aerodynamic torque is realized. On this basis, regulating the pitch angle of each blade by output power and azimuth angle feedback to reduce 1P aerodynamic load and 3P aerodynamic torque ripple. Finally, the existence of the ripples of hydrodynamic frequency and the validity of the designed pitch control strategy are verified on GH Bladed platform.

2. Wave model and wave force calculation

2.1. Regular wave model

There are two research directions in the theory of wave description. One direction is to study the motion state of each particle in liquid from the angle of hydrodynamics, which is divided into linear wave theory (mainly linear airy) and nonlinear wave theory. The other direction is to consider the fluctuation of sea surface as a stochastic process, and to reveal the distribution of wave energy by studying its randomness. Of course, the study of the latter direction also requires fluid mechanics to describe the motion of each particle in liquid within an ideal fluctuation state. In shallow water, the linear wave theory is inapplicability, and the nonlinearity of the wave must be considered. The wave theory based on stream function has many advantages, such as use range is wide, can be extended to any order, the fitting conditions are good, can take account of ocean currents, and is mainly used for numerical simulation of nonlinear wave in shallow water near crushing.

A cylindrical body with a diameter of D is upright on the seafloor with a depth of h, and the regular incident wave spreads along the coast. Establish the coordinate system as shown in figure 1, the coordinate Origin 0 is in the cylinder axis and the seafloor intersection, the x axis propagates along the wave direction, the z axis is vertical upward.

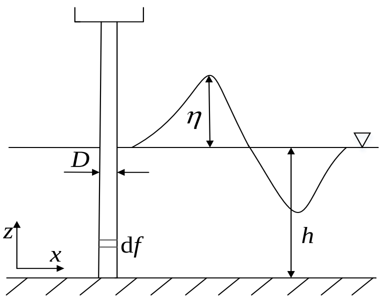

Figure 1. Regular wave diagram.

According to Dean Theory, the N-order stream function equation considering higher-order perturbation term is [9]:

$$\psi(x,z) = \frac{L}{T}z + \sum_{n=1}^{N} X(n)\sinh[nk(h+z)]\cos(nkx) \tag{1}$$

where, $X(n)$ is coefficient of higher order perturbation term, L is wave length, T is wave period.

The wave has periodic characteristics in time and space, so the stream function should also meet the following boundary conditions: $\psi(x,z,t) = \psi(x+L,z,t)$, $\psi(x,z,t) = \psi(x,z,t+T)$.

2.2. Irregular wave model

The waves in reality are random, the direction, size and period of the waves are irregular. The power spectrum of waves is an important means to describe random waves, which reflects the magnitude of the energy of random waves at different frequencies. Because of the randomness and complexity of waves, it is very difficult to derive power spectral expressions directly in theory, so the power spectral characteristics of random waves are described by using half theory and half empirical formula. The commonly used wave spectra included Pierson-Moskowitz (P-M) spectra, Jonswap spectra and Battle spectra. This paper uses P-M spectrum:

$$S(f) = 0.3123H^2T_p(f*T_p)^{-5}\exp[-1.25(f*T_p)^{-4}] \tag{2}$$

where, f is the wave frequency, H is the significant wave height, T_p is the peak spectral period.

In the study of wave-related studies, the period is usually defined according to the interval of two adjacent over-crossing zero points on wave surface. Based on the P-M spectrum, the spectral relationship between spectral peak period and zero-crossing period is satisfied the equation: $T_p \approx 1.41T_z$ [10], T_z represents zero-crossing period.

2.3. Calculation of wave force

Because the tower diameter of wind turbine is relatively small comparing to wave length, according to Morison theory, the horizontal wave force acting on the whole pile can be expressed as [9]:

$$F_x = \int_0^{h+\eta} \frac{1}{2} C_D \rho D v_x |v_x| dz + \int_0^{h+\eta} C_M \rho \frac{\pi D^2}{4} \frac{\partial v_x}{\partial t} dz \tag{3}$$

where v_x and $\partial v_x / \partial t$ are water particle velocity and acceleration in x direction respectively, ρ is seawater density, C_D is hydrodynamic drag coefficient, usually taken from 0.7~1.2, C_M is hydrodynamic inertia coefficient, usually taken from 0.7~2.0, η is wave height.

Equation (3) shows that the horizontal wave moment is mainly related to the variables v_x and η, and the other parameters are quantifies. Therefore, nonlinear wave period and height directly determine the dynamic response of the nonlinear wave on the offshore wind turbine.

3. Influence of regular wave on offshore wind turbine

3.1. Influence of regular wave on bottom tower load

The vibration caused by external force is forced vibration, and the equation of forced vibration of a single-degree-freedom system is as follows:

$$m\ddot{u} + c\dot{u} + ku = p(t) \tag{4}$$

where m is mass, k is stiffness, c is damping coefficient, u is displacement, $\dot{u}$ is velocity, $\ddot{u}$ is acceleration, $p(t)$ is load varying with time.

If the load $p(t)$ is any periodic load, it can be expanded into Fourier series:

$$p(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos\tilde{\omega}_n t + \sum_{n=1}^{\infty} b_n \sin\tilde{\omega}_n t \tag{5}$$

where a_0, a_n, b_n are coefficients, $\tilde{\omega}_n$ is the nth external load frequency.

The steady-state response of the system can be obtained by superposition principle, as shown in equation (6) [11]:

$$u(t)=\frac{1}{k}(a_0+\sum_{n=1}^{\infty}\frac{1}{(1-\beta_n{}^2)^2+(2\xi\beta_n)^2}(\{[a_n+2\xi\beta_n+b_n(1-\beta_n{}^2)]\sin\tilde{\omega}_n t\}$$
$$+[a_n(1-\beta_n{}^2)-b_n 2\xi\beta_n]\cos\tilde{\omega}_n t)) \quad (6)$$

where damping ratio $\beta_n=\tilde{\omega}_n/\omega$, ω is the natural frequency of the system, ξ is the ratio of system damping to critical damping.

Equation (6) shows that: the vibration frequency of the system is the same as that of the external load, only some phase difference exists. Therefore, under the periodic action of the wave, the bottom load of the tower will produce the fluctuating component of the hydrodynamic frequency.

3.2. Influence of regular wave on top tower load

The tower above the wave height is not directly affected by the wave, but because of the small damping matrix of the steel tube tower, the low-frequency vibration caused by the wave will run through the whole tower system. The relationship between bending moment of the bottom tower $M(t)$ and the horizontal displacement of the top tower $u_{top}(t)$ is satisfied [12]:

$$M(t)=Ku_{top}(t)H \quad (7)$$

where K is flexural rigidity of the tower, H is tower height.

Therefore, the top tower displacement and the bottom tower bending moment have the same waveform. The vibration caused by the wave will be transmitted from the bottom of the tower to the top, because of the damping effect, vibration energy weakened, but the vibration frequency unchanged.

3.3. Influence of regular wave on blade load and aerodynamic torque

The anteroposterior movement of the top tower affects the relative wind flow velocity on the blade. When the top tower moves backwards, the wind speed on the blade decreases, whereas the flow velocity increases. The wind speed under the influence of tower movement is:

$$V=V_0-\dot{u}_{top} \quad (8)$$

where V_0 is the original wind speed.

When the wind speed on the blade is changed, the aerodynamic load is changed and the movement of the tower affects the flow velocity when the load of the tower is changed, so the dynamic coupling effect exists between the rotor and the tower during the vibration of the wind turbine.

When the blade-tower coupling effect is not considered, the root shearing force of the rotating blade can be equivalent to the sum of the total inertia force of the blade, as shown in equation (9) [13]:

$$\{Q_B(t)\}=\sum_{i=1}^{n}m_{Bi}\ddot{w}_{Bi}(t) \quad (9)$$

where m_{Bi} is blade element quality, $\ddot{w}_{Bi}(t)$ is blade element acceleration.

Considering the coupling effect of blade-tower, the effective shearing force of single blade can be expressed as [14]:

$$\{\bar{Q}_B(t)\}=[\ddot{w}_{B1}+\ddot{u}_{top}(t)]m_{B1}+......[\ddot{w}_{Bn}+\ddot{u}_{top}(t)]m_{Bn} \quad (10)$$

Get equation (9) into equation (10):

$$\{\bar{Q}_B(t)\}=\sum_{i=1}^{n}m_{Bi}\ddot{w}_{Bi}(t)+\ddot{u}_{top}\sum_{i=1}^{n}m_{Bi}=Q_B(t)+\ddot{u}_{top}M_B \quad (11)$$

where M_B is mass matrix of blade.

Equation (11) considering the inertia action of the top tower to the blade, the coupling equation can be decoupled and analysed by the method of adding mass. Therefore, the shearing force of single blade is not only affected by its mass distribution and acceleration, but also by the vibration acceleration of the top tower, that is, in consideration of the coupling action of the blade-tower, the tower vibration caused by the wave will attach a shearing force of the same frequency to the root blade.

Blade root flap-wise shearing force $\bar{Q}_{Bx}$ and blade root flap-wise load M_{Bx} satisfy the relationship [15]:

$$M_{Bx} = \int_{r_0}^{R} \bar{Q}_{Bx} r dr = \int_{r_0}^{R} (Q_{Bx} + \ddot{u}_{top} M_B) r dr \tag{12}$$

where r_0 is hub radius, *R* is rotor radius, *r* is the blade element radius.

The change of the wind speed on the blade causes obvious change of the aerodynamic torque:

$$T_{aero} = \frac{1}{2}\rho\pi R^3 C_T(V,\Omega,\beta)V^2 = \frac{1}{2}\rho\pi R^3 C_T(V,\Omega,\beta)(V_0 - \dot{u}_{top})^2 \tag{13}$$

where ρ is air density, C_T is torque coefficient, Ω is rotor speed.

The equation (13) is linearized at any operating point:

$$\hat{T}_{areo} = (\hat{T}_{areo})'_{V_0}\hat{V}_0 - (\hat{T}_{areo})'_{V_0}\hat{\dot{u}}_{top} + (\hat{T}_{areo})'_{\Omega}\hat{\Omega} + (\hat{T}_{areo})'_{\beta}\hat{\beta} \tag{14}$$

From equations (12)-(14), it can be seen that the wave will make both the blade root load and the aerodynamic torque contain the fluctuating components of the hydrodynamic frequency, in which the impact of the wave on the aerodynamic torque is particularly obvious.

4. Pitch control strategy

The blade of the wind turbine is affected by the wave lapping on the tower, which produces the low-frequency vibration associated with the hydrodynamic frequency. In reality, 1P aerodynamic load pulsation and 3P aerodynamic torque ripple are produced by wind shear and tower shadow, which cannot be ignored. These not only cause additional load to the blades, but also produce the output torque pulsation, and affect the output power quality. Improving the aerodynamic characteristics of blades by adjusting the blade pitch angle, not only can reduce the 1P blade load from the source (the blade load hydrodynamic frequency component is smaller, not to be the main improvement object), but also can alleviate the hydrodynamic frequency component and the 3P pulsating component of aerodynamic torque and output power. The proposed pitch control strategy can reduce the wind turbine fatigue load and improve the output power quality of the offshore wind turbine.

Firstly, for purpose of reducing the pulsating component of the hydrodynamic frequency of the aerodynamic torque, according to equation (14), the input signal which is the front and back velocity of the top tower is feedback to adjust the pitch angle. The additional torque of the wind turbine caused by the wave is reduced:

$$\Delta T_{areo} = (T_{areo})'_{\beta}\beta_{ad} = (T_{areo})'_{\beta} G\dot{u}_{top} \tag{15}$$

Because measuring the acceleration of the tower is relatively easy, the tower speed is obtained directly by integrating the vibration acceleration of the tower:

$$\beta'_{\mathrm{ref}} = \beta_{\mathrm{ref}} - G\int \ddot{u}_{top} \tag{16}$$

Then, regulating the pitch angle of each blade by output power and azimuth angle feedback. A low-pass filter is used to obtain the 3P output power *P* ripple of wind turbine, and adjusting the pitch angle $\Delta\beta_i$ (i=1,2,3) of each blade according to azimuth angle θ_i. At last, add $\Delta\beta_i$ and β'_{ref} to get final individual pitch angle signal β_i, On the basis of weakening the aerodynamic torque component of hydrodynamic frequency, the aim to reduce the 1P aerodynamic load and 3P aerodynamic torque ripple is achieved. The detailed pitch control strategy is presented in figure 2.

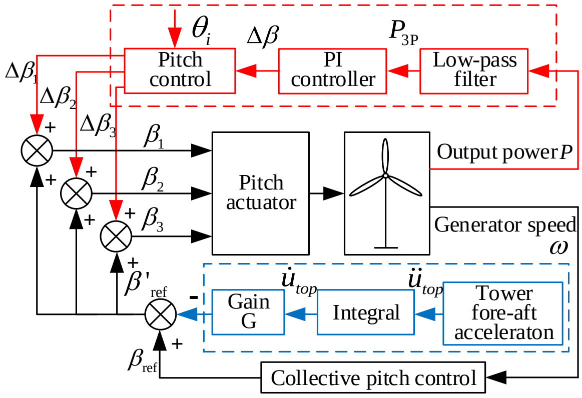

Figure 2. Block diagram of pitch control strategy.

The 2nd order transfer function of low-pass filter can be expressed as

$$G(s)=\frac{a_0 s^2+a_1 s+a_2}{b_0 s^2+b_1 s+b_2} \tag{17}$$

In this paper, the 0~1Hz low-pass filter is selected, and the coefficients of transfer function are a_0=0.067, a_1=0.134, a_2=0.067, b_0=1, b_1=-1.143, b_2=0.413.

After using the low-pass filter to get the 3P output power ripple, the pitch angle regulatory signal under PI Control can be indicated as equation (18):

$$\Delta\beta = K_p P_{3P}(t) + K_i \int_0^t P_{3P}(\tau) d\tau \tag{18}$$

where K_p, K_i are proportionality coefficient and integral coefficient in PI controller.

The distribution of wind velocity in the rotating plane is inhomogeneous, it increases with height and is closely related to the azimuth signal of the blade. If the pitch angle varies periodically with azimuth, the blade load fluctuations caused by non-uniformity distribution of wind velocity will be relieved. The pitch angle of blade *i* can be regulated as:

$$\Delta\beta_i = \cos\theta_i \Delta\beta \tag{19}$$

$$\beta_i = \beta'_{ref} + \Delta\beta_i \tag{20}$$

5. Case studies

Based on GH Bladed platform, a 5 MW three-bladed upwind double-fed wind turbine with monopole foundation is modelled. The constant wind speed at hub centre is 14 m/s, the height of regular wave is 2.8 m and wave period is 10 s, the direction of wave propagation is the direction of wind. The control parameters are obtained by experiments and set as follows: the initial pitch angle value is β_0=5.7°; the limits of pitch position and pitch rate are [0°, 90°] and [-9°, 9°]/s; and the control parameters in figure 2 are respectively K_p=0.05, K_i=0.001; G=0.02.

5.1. Verification of the influence of regular wave on wind turbine

For purpose of verifying the existence of the hydrodynamic frequency component of tower load, blade load and aerodynamic torque, the variation curves of each main data are observed without considering the wind shear and tower shadow effects, and the simulation results are shown in figures 3-5. "Without wave" indicates that there is no wave in operating environment of the wind turbine, and "with regular

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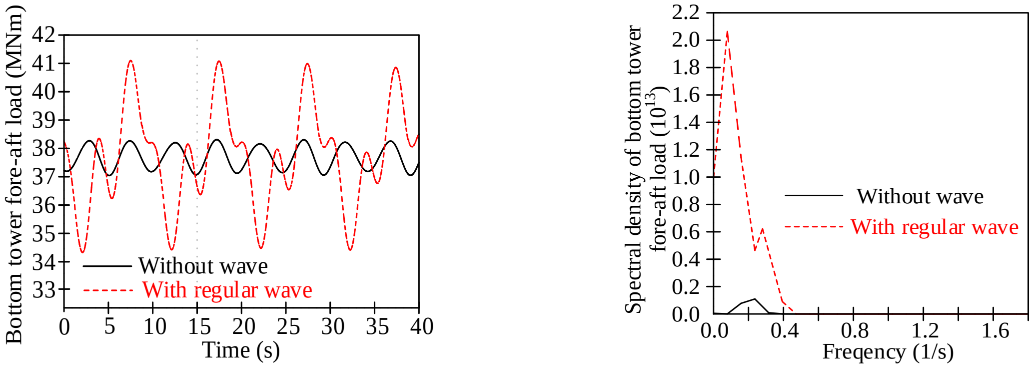
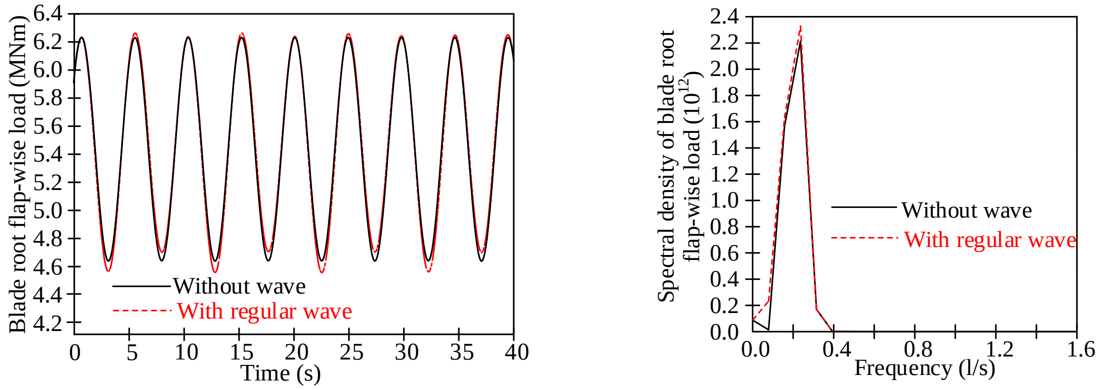
wave" indicates that there is regular wave in the environment.



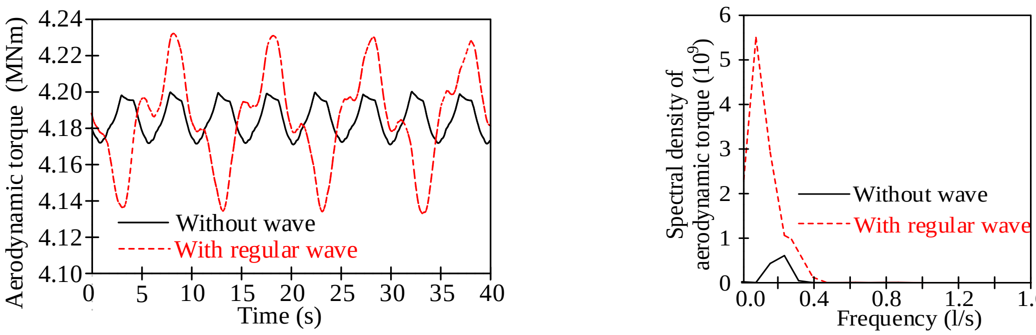
(a) (b)

Figure 3. Simulation results of bottom tower fore-aft load under or without under the action of regular wave.



(a) (b)

Figure 4. Simulation results of blade root flap-wise load under or without under the action of regular wave.



(a) (b)

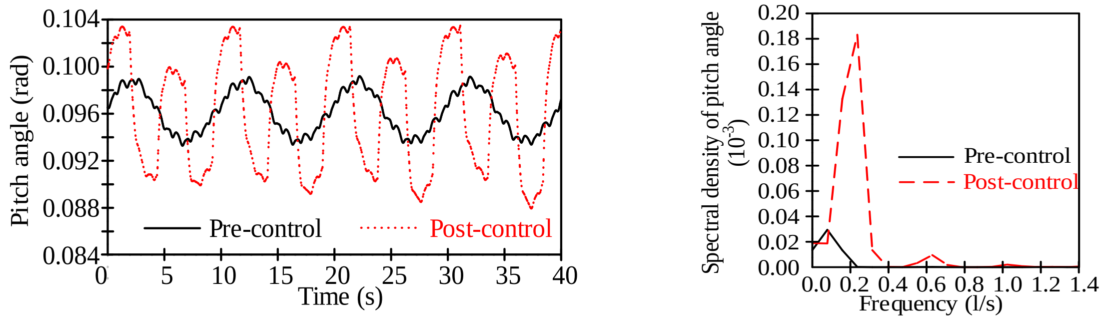
Figure 5. Simulation results of aerodynamic torque under or without under the action of regular wave.

The results of simulation can be concluded as follows:

- It can be seen from figure 3, the wave fluctuation frequency of 0.1 Hz triggers the tower low-frequency oscillation of 0.1 Hz. According to statistics, the peak spectral period of China's offshore sea area is roughly within the range of 3~10 s, that is, within the 0.1~0.33 Hz range [16], so it is very easy to trigger the tower low frequency vibration in the wave flow direction. If the wave fluctuation frequency and tower natural vibration frequency is similar, it will cause resonance.

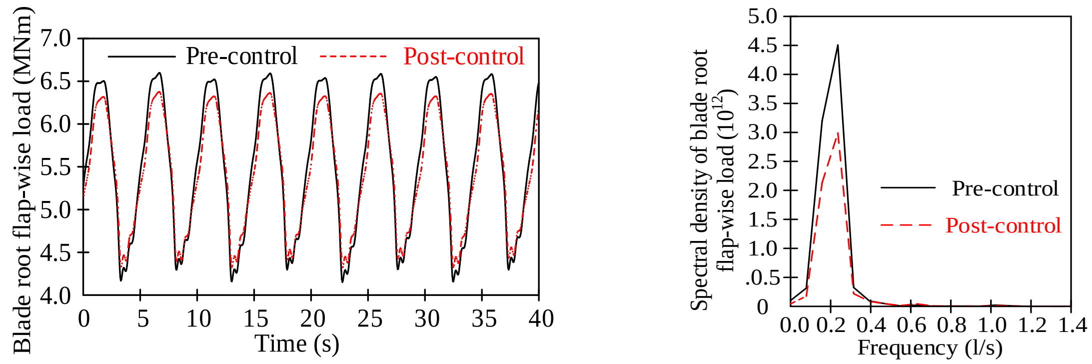
- From figures 4 and 5, in consideration of the coupling action of blade-tower, the regular wave will cause the blade root flap-wise load and aerodynamic torque to ripple at hydrodynamic frequency, but the former affected numerical value is much smaller than the latter.

5.2. Verification of the pitch control strategy



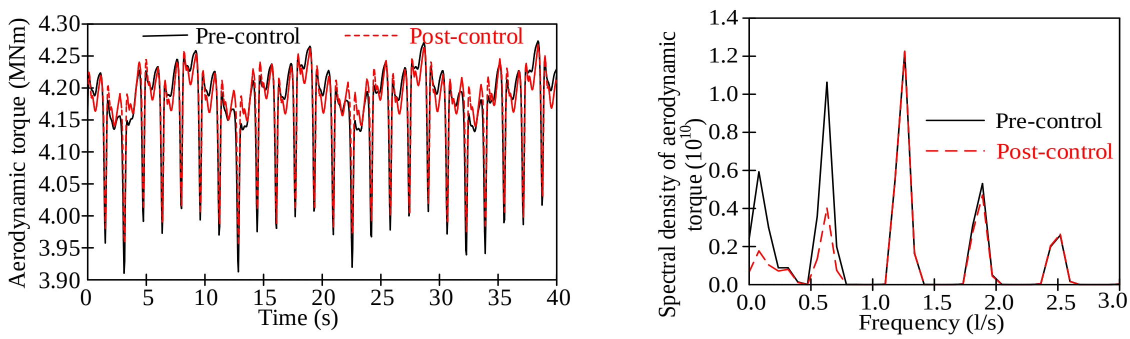
(a) (b)

Figure 6. Simulation results of pitch angle under or without under additional control.



(a) (b)

Figure 7. Simulation results of blade root flap-wise load under or without under additional control.



(a) (b)

Figure 8. Simulation results of aerodynamic torque under or without under additional control.

The simulation results of the proposed pitch control strategy are shown in figures 6-8 in consideration of the effects of wind shear and tower shadow, where "pre-control" indicates that there is no control strategy and "post-control" indicates that the additional pitch control strategy is active.

The results of simulation can be concluded as that:

- Figure 6(a), figure 7(a) and figure 8(a) show that: The control strategy adjusts the pitch angle of each blade periodically, which makes the amplitude of the blade root flap-wise load obvious smaller, while the aerodynamic torque is not obviously changed. Considering the direct correlation between the aerodynamic torque and the output power, the simulation results verify that the control strategy stabilizes the output power while reducing the aerodynamic load.
- Figure 6(b), figure 7(b) and figure 8(b) show that: the pitch control strategy can significantly decrease the amplitude of 1P blade flap-wise load (0.2268 Hz) and the aerodynamic torque ripples at 3P (0.6804 Hz) and hydrodynamic frequency (0.1 Hz) by adjusting the pitch angle in the frequency of water movement, 1P and 3P. The amplitude of 1P blade flap-wise load is reduced nearly 33%; the amplitude of aerodynamic torque fluctuation at hydrodynamic frequency is reduced nearly 64%, and the amplitude of aerodynamic torque ripple at 3P is reduced nearly 60%.

In addition, replace regular wave with irregular wave, which significant wave height is 2.8 m and peak spectral period is 10 s (Zero-crossing period is 7.09 s). The simulation results are shown in figure 9.

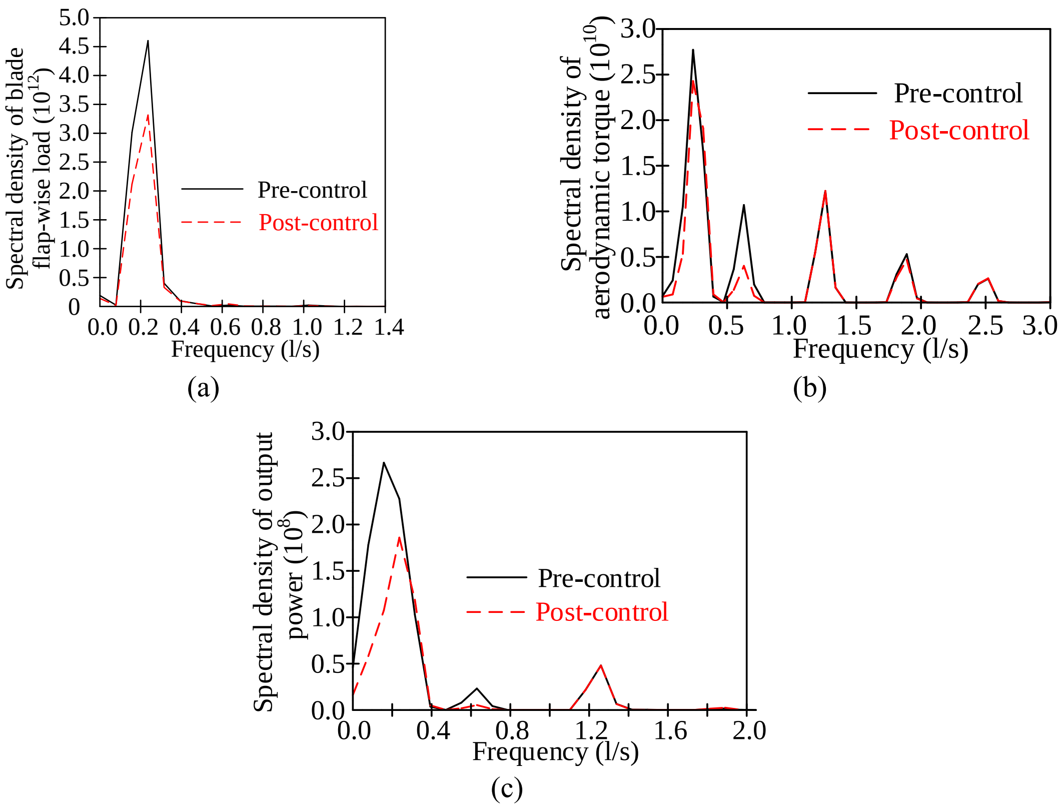


Figure 9. The simulation results of replacing regular wave with irregular wave.

Simulation results indicate that the designed pitch control strategy can alleviate the 1P aerodynamic load ripple, as well as the aerodynamic torque and output power ripples at 3P and hydrodynamic frequency even in a random wave environment.

6. Conclusions

With the large-scale development of offshore wind turbines, the low-frequency vibration caused by ocean waves is not negligible, and the 1P aerodynamic load fluctuation and 3P aerodynamic torque ripple aroused by wind shear and tower shadow effects are more serious. The pitch control strategy proposed in this paper adjusts each blade's pitch angle at the hydrodynamic frequency and the rotor rotational frequency of 1P and 3P to effectively alleviate 1P aerodynamic load and aerodynamic torque and output power ripples at 3P and hydrodynamic frequency of the offshore wind turbine. The designed pitch control strategy can reduce wind turbine fatigue loads and improve the output power quality.

Acknowledgments

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