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Research Article

Wind and Wave Disturbances Compensation to Floating Offshore Wind Turbine Using Improved Individual Pitch Control Based on Fuzzy Control Strategy

Feng Yang,[1] Qing-wang Song,[1] Lei Wang,[2] Shan Zuo,[3] and Sheng-shan Li[1]

[1] *School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China*
[2] *School of Automation, Chongqing University, Chongqing 400044, China*
[3] *School of Energy Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China*

Correspondence should be addressed to Lei Wang; leiwang08@cqu.edu.cn

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Due to the rich and high quality of offshore wind resources, floating offshore wind turbine (FOWT) arouses the attentions of many researchers. But on a floating platform, the wave and wind induced loads can significantly affect power regulation and vibration of the structure. Therefore, reducing these loads becomes a challenging part of the design of the floating system. To better alleviate these fatigue loads, a control system making compensations to these disturbances is proposed. In this paper an individual pitch control (IPC) system integrated with disturbance accommodating control (DAC) and model prediction control (MPC) through fuzzy control is developed to alleviate the fatigue loads. DAC is mainly used to mitigate the effects of wind disturbance and MPC counteracts the effects of wave on the structure. The new individual pitch controller is tested on the NREL offshore 5 MW wind turbine mounted on a barge with a spread-mooring system, running in FAST, operating above-rated condition. Compared to the original baseline collective pitch control (CPC) (Jonkman et al., 2007), the IPC system shows a better performance in reducing fatigue loads and is robust to complex wind and wave disturbances as well.

1. Introduction

Wind has been proved to be the most promising renewable energy resource during the last few decades. Compared to onshore wind turbines, floating offshore wind turbines have more potential to become a large contributor to society due to the rich and high quality of offshore wind resource. However, offshore wind brings new problems to floating offshore wind turbines including additional wave loading, unstable platform, and ice problems. The above problems aggravate the unbalanced fatigue loads of the structure. Therefore, reducing these fatigue loads becomes an extremely important but challenging part of the design of the floating system.

Currently, variable speed variable pitch wind turbines [1] simply use collective pitch control with PID controller to limit the excess of wind power above rated wind speed, neglecting the uneven loads distributed in the structure. However, aerodynamic forces and wave influence on the structure are different. Hence, the wind turbine and platform endure unbalanced loads all the way [2]. IPC which has excellent performance in wind turbine control can be used to alleviate the wind turbine fatigue loads caused mainly by wind and waves [3].

In the last few years some related works have been done to explore the way to reduce these fatigue loads. National Renewable Energy Laboratory (NREL) provides us with a variety of wind turbine models to test various kinds of important features using FAST. Jonkman has done a wide range of research work on the floating offshore wind turbines with a baseline controller. Bossanyi [4] introduced the IPC conception and reduced fatigue loads around one time the rotational frequency (1p). The IPC used in [5, 6] are based on two separate single input single output (SISO) systems. Using Coleman transformation, the 1p variables of the blade loads can be transformed into stationary variables like rotor tilt and yaw moments. The SISO systems use PI controllers to reduce the tilt and yaw moments. However, FOWT is a strongly coupled nonlinear time-varying system with complex disturbances, and obviously SISO cannot account for these disturbances. This can be improved by H_∞ control in [7–10], sliding mode in [11, 12], optimal control in [13, 14], or linear quadratic Gaussian control (LQG) [15, 16]. The LQG controller consists of a linear model of the wind turbine and a state estimator used to estimate the states of the model from known turbine variables by Kalman filter. A control law which can minimize the quadratic cost function of the wind turbine sates was used to make the control. This method successfully brings about a significant loads reduction but has no effect on the fatigue loads of the stationary parts.

Another way to deal with the strong disturbance is disturbance-accommodating controllers implemented by Namik and Stol [17] on Spar-Buoy floating wind turbine. DAC controller consisted of a state regulation term with full state feedback controllers and a disturbance estimator is used to lower the influence of persistent disturbances like turbulence wind on the wind turbine. Compared to the original baseline controller designed by Jonkman, the DAC reduces tower fore-aft and side-side bending fatigue loads greatly. But the disturbance estimator in DAC did not consider much influence of the wave. To study the impact of wave on wind turbine, Bae and Kim [18] investigated the wave-load effect on 5 MW monocolumn TLP-type FOWT. The sum-frequency wave loading is applied in both coupled and uncoupled condition, the results show that there exist complicated coupling effects among wind turbine variables, and wave condition should be fully considered when designing the FOWT.

It is notable that the above method cannot bring all the disturbances into consideration. Wind as well as wave should be fully considered. In this paper a new individual pitch control based on combined DAC and MPC using fuzzy control is proposed. DAC can deal with persistent disturbances like wind but ignore the wave who is a type of periodic disturbance. MPC can reduce the structural oscillation and decrease the fatigue loads caused by incident waves through tracking the state trajectory of the undisturbed reference model. So the new individual pitch control strategy that combines the two methods through fuzzy control can better deal with wind and wave disturbances.

Section 2 introduces the configuration of the floating offshore wind turbine. Section 3 gives a brief introduction to the disturbances such as wind and wave. Section 4 focuses on the design of the new controller. First give a detailed introduction to the DAC and MPC, and then a new individual pitch controller combined with DAC and MPC comes into being through fuzzy control. In Section 5 the new individual pitch controller is tested and proved to be effective for the fatigue loads reduction.

2. Wind Turbine Configurations

The wind turbine used in this paper is a model called "NREL offshore 5-MW baseline wind turbine" from NREL. This is a realistic model of a three-bladed upwind 5-MW wind turbine mounted on a barge with a spread-mooring system developed at MIT through a contract with NREL [19]. The gross properties of the wind turbine are given in Table 1, and the platform properties are given in Table 2.

3. Disturbance Loads Modeling

Wind turbine is not a static structure. Due to rotating rotor, turbulent wind, complex wave conditions, huge slender components, and complex design, the structural vibrations, which can significantly contribute to dynamic fatigue loading of the structure, are introduced to the system. Among all the factors cause fatigue loads of wind turbine wave and wind should be first taken into consideration.

3.1. Wind Loads. Wind turbine components exposed in wind condition will cause movement because of aerodynamics between wind flow and wind turbine structure. That is the reason wind turbine can be used to generate electricity. Wind shear and tower shadow will introduce additional disturbance to the wind turbine system. Wind model is important to loads definition as well as design of the wind turbine and platform system. The accuracy of wind parameters affects the design of wind turbine system significantly. The wind load can be modeled by formulas based on lift theory [20]:

$$\begin{gathered} F_{\text{wind}} = \frac{1}{2}\rho_{\text{air}}\nu_{\text{wind}}SC_z, \\ \nu_{\text{wind}} = \nu_{\text{mean}} + \nu_{\text{ws}} + \nu_{\text{ts}} + \nu_{\text{wk}}, \end{gathered} \tag{1}$$

where F_{wind} is the wind forces on blade, ρ_{air} is air density, S is the blade surface area, and ν_{wind} is the wind speed which consists of mean wind speed ν_{mean}, the wind shear component ν_{ws}, the tower shadow component ν_{ts}, and far wake component of one preceding wind turbine ν_{wk}. Wind shear and the tower shadow which lead to significant vibration of the structure were specified in [21].

3.2. Wave Loads. In addition to wind condition wave force is also a main contributor to loads on the structure. The wave force can be calculated based on Airy's linear theory where the horizontal and vertical wave velocity are introduced in [22]

$$\begin{gathered} F_{\text{wave}} = \frac{1}{2}\rho_{\text{water}}C_D D\,|u|\,u + \rho_{\text{water}}C_I\frac{\pi D^2}{4}a_x, \\ u = \frac{\omega h}{2}\frac{\cos ky}{\sin kd}\cos(kx - \omega t), \end{gathered} \tag{2}$$

where F_{wave} is the wave force on platform, ρ_{water} is water density, C_D and C_I are the drag and inertia coefficients, respectively, D is the diameter of the structural member u which is the horizontal velocity of water, and a_x is the water-particle acceleration which can be obtained by means of $a_x \approx \partial u/\partial t$. The first part of this formula can be described as the drag term who is proportional to the square of the water velocity. Another part is referred to the inertial term. It is proportional to the water acceleration.

Table 1: NREL 5 MW wind turbine model properties.

Properties	Value
Rating	5 MW
Rotor orientation, configuration	Upwind, 3 blades
Control	Variable speed, collective pitch
Drivetrain	Multiple-stage gearbox
Rotor, hub diameter	126 m, 3 m
Hub height	90 m
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, rated rotor speed	6.9 rpm, 12.1 rpm
Rated tip speed	80 m/s
Overhang, shaft tilt, precone	5 m, 5°, 2.5°
Rotor mass	110,000 kg
Nacelle mass	240,000 kg
Tower mass	347,460 kg
Coordinate location of overall CM	(−0.2 m, 0.0 m, 64.0 m)

Using the data from NREL.

Table 2: NREL 5 MW platform properties.

Properties	Value
Diameter, height	36 m, 9.5 m
Draft, freeboard	5 m, 4.5 m
Water displacement	5,089 m^3
Mass, including ballast	4,519,150 kg
CM location below SWL	3.88238 m
Roll inertia about CM	390,147,000 kg·m^2
Pitch inertia about CM	390,147,000 kg·m^2
Yaw inertia about CM	750,866,000 kg·m^2
Anchor (water) depth	200 m
Line diameter	0.127 m
Line mass density	116.0 kg/m
Line extensional stiffness	1,500,000,000 N

Using the data from NREL.

4. Controller Design

This section describes the new individual pitch control based on disturbance accommodating control with wave disturbance compensation component using model predictive control method. Furthermore, a cooperation strategy using fuzzy control was introduced to actively alleviate the fatigue loads caused by wave and wind disturbances.

4.1. IPC with DAC. Disturbance accommodating control [23] which is a kind of feedforward control is an effective method to reduce the influence caused by persistent disturbances like wind. In this section the use of DAC on floating offshore wind turbine is introduced where the wind condition was considered into the DAC system. Since variables related to disturbances are assumed to be unavailable straightway, a disturbance estimator designed through variables which can directly be measured was employed. To design the IPC controller first, a generic linearized state-space mode should be described as

$$\dot{x} = Ax + Bu + B_d u_d, \tag{3}$$

$$y = Cx + Du + D_d u_d, \tag{4}$$

where A is the state matrix, B is the actuator gain matrix, B_d is the disturbance gain matrix, C is the measurements to the states, D is the measurements to the control inputs, D_d is the measurements to the disturbance inputs, x relates to the state variable vector, y relates to the system output vector, u relates to the actuators vector, and u_d relates to disturbance inputs vector. In order to minimize the effects caused by disturbances such as wind and platform, persistent disturbances should be first modeled by (5) and (6) where z is the disturbance states vector and G and Q are assumed to be known but with unknown initial conditions [24]. The natures of the assumed model can be determined by the matrices G and Q

$$u_d = Gz, \tag{5}$$

$$\dot{z} = Qz. \tag{6}$$

The feedback control law that can deal with the effects of disturbances on wind turbine is given by (7), where K is the state feedback controller gain matrix and G_d is the disturbance reduction gain matrix:

$$u = -Kx + G_d z. \tag{7}$$

Equation (8) can be derived from (3), (5), and (7), which clearly shows that in order to cancel the effects of persistent disturbances, (9) must hold true:

$$\dot{x} = (A - BK)x + (BG_d + B_d G)z, \tag{8}$$

$$BG_d + B_d G = 0. \tag{9}$$

A disturbance state estimator can be designed by a new state vector ω which consists of turbine states and disturbance states. Through (3) to (6), a new a state-space model is created and given by

$$\begin{aligned} \dot{\omega} &= \overline{A}\omega + \overline{B}u, \\ y &= \overline{C}\omega + Du, \end{aligned} \tag{10}$$

where $\overline{A} = \left[\begin{smallmatrix} A & B_d G \\ 0 & Q \end{smallmatrix}\right]$, $\overline{B} = \left[\begin{smallmatrix} B \\ 0 \end{smallmatrix}\right]$, and $\overline{C} = \left[C \ \ D_d G\right]$. The state estimator dynamics are given by (11) and (12) where K_e is the state estimator gain matrix. The $\widehat{}$ symbol indicates an estimate as follows:

$$\dot{\widehat{\omega}} = \overline{A}\widehat{\omega} + \overline{B}u + K_e\left(y - \widehat{y}\right), \tag{11}$$

$$\widehat{y} = \overline{C}\widehat{\omega} + Du, \tag{12}$$

$$\dot{e} = \omega - \widehat{\omega} = \overline{A}(\omega - \widehat{\omega}) - K_e\overline{C}(\omega - \widehat{\omega}) = \left(\overline{A} - K_e C\right)e. \tag{13}$$

Therefore, if the pair $(\overline{A}, \overline{C})$ is observable, then the augmented vector ω can be fully estimated [25].

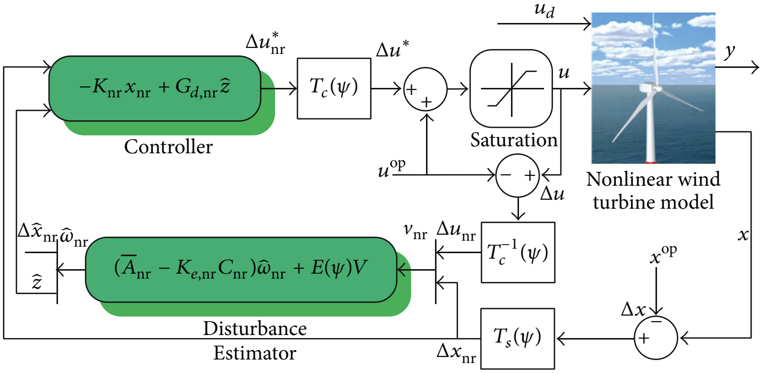

FIGURE 1: DAC implemented for OFWT.

Finally, multiblade coordinate transformation (MBC) is used to deal with the periodic nature of the wind turbine. The DAC law in the nonrotating frame and the time-invariant DAC gain matrix are given by (14) and (15), respectively. MBC transformation matrices $T_c(\psi)$, $T_s(\psi)$, and $T_0(\psi)$ transform the corresponding input vectors to the nonrotating frame of reference. The nr symbol indicates nonrotating frame variables:

$$u_{\text{nr}} = -K_{\text{nr}}x_{\text{nr}} + G_{d,\text{nr}}\hat{z}, \tag{14}$$

$$G_{d,\text{nr}} = -B^{+}_{\text{nr}}B_{d,\text{nr}}G. \tag{15}$$

The DAC law transformed into the mixed frame of reference is described as

$$u = -T_c(\psi) K_{\text{nr}} T_s^{-1}(\psi)\hat{x} + T_c(\psi) G_{d,\text{nr}}\hat{z}. \tag{16}$$

The disturbance estimator for the MBC transformed system can be expressed in

$$\begin{aligned}\widehat{\omega}_{\text{nr}} &= \left(\overline{A}_{\text{nr}} - K_{e,\text{nr}}C_{\text{nr}}\right)\widehat{\omega}_{\text{nr}} + \overline{B}_{\text{nr}}T_c^{-1}(\psi)\,u \\ &\quad + K_{e,\text{nr}}T_0^{-1}(\psi)\,y \\ &= \left(\overline{A}_{\text{nr}} - K_{e,\text{nr}}C_{\text{nr}}\right)\widehat{\omega}_{\text{nr}} \\ &\quad + \left[\overline{B}_{\text{nr}}T_c^{-1}(\psi)\ \ K_{e,\text{nr}}T_0^{-1}(\psi)\right]\begin{bmatrix}u\\ y\end{bmatrix} \\ &= \left(\overline{A}_{\text{nr}} - K_{e,\text{nr}}C_{\text{nr}}\right)\widehat{\omega}_{\text{nr}} + E(\psi)V.\end{aligned} \tag{17}$$

The block diagram of DAC controller for FOWT is shown in Figure 1.

4.2. Wave Disturbance Compensation to the DAC. The IPC controller based on DAC takes the persistent disturbance like wind into consideration but ignoring the wave who is a type of periodic disturbance. In order to overcome the impact brought about by the wave, a compensation module is introduced and added to the DAC system. This periodic disturbance compensation module based on MPC method is added to the DAC system through fuzzy control.

4.2.1. Wave Disturbance Compensation Using MPC

(A) Model Predictive Controller. In this paper, to reduce the structural vibration caused by incident wave, MPC was utilized. Model predictive control is a closed-loop optimization model-based control strategy. The core of the algorithm is as follows: a dynamic model can predict the future, online repeated optimization, and the model error feedback correction. The main idea of this method is that the blades' pitch is controlled by a model predictive controller based on a reference model without periodic disturbance from incident waves. Then the state trajectory of the undisturbed system which can be used as a reference to the real system is produced by the reference model. The model predictive control will reduce the structural oscillation and decrease the fatigue loads caused by incident waves through tracking the state trajectory of the undisturbed reference model.

Assume that the model of the wave disturbance included OFWT open-loop system is given in

$$\begin{aligned}x(k+1) &= A_\omega x(k) + B_\omega u(k), \\ y(k) &= C_\omega x(k),\end{aligned} \tag{18}$$

where A_ω, B_ω, and C_ω are state matrix, actuator gain matrix, and measurements to the states of the disturbance included system, respectively.

When wave disturbance is removed in the state vector, the open-loop model of the undisturbed plant is given by

$$\begin{aligned}x_r(k+1) &= A_r x_r(k) + B_r u_c(k), \\ y_r(k) &= C_r x_r(k),\end{aligned} \tag{19}$$

where A_r, B_r, and C_r are state matrix, actuator gain matrix, and measurements to the states of the undisturbed system, respectively. And the controller for the undisturbed plant is described by

$$\begin{aligned}x_c(k+1) &= A_c x_c(k) + B_c y_r(k) + E_c r(k), \\ u_c(k) &= C_c x_c(k) + D_c y_r(k) + F_c r(k),\end{aligned} \tag{20}$$

where r is the reference signal. Variables with subscript c are control parameters. Assume that X and U are states and input variables. Then design of the model predictive controller becomes the following optimization problem at each step:

$$\min_{\{u(k),\dots,u(k+T-1)\}} \sum_{k=k_0}^{T} \left\|x(k)-x_r(k)\right\|_Q^2+\left\|u(k)\right\|_R^2$$

$$\text{s.t.} \quad \begin{cases} x(k_0)=x_0 \\ x_r(k_0)=x_{r0} \\ x(k+1)=A_\omega x(k)+B_\omega u(k) \\ y(k)=C_\omega x(k) \\ x_r(k+1)=A_r x_r(k)+B_r u_c(k) \\ y_r(k)=C_r x_r(k) \\ x_c(k+1)=A_c x_c(k)+B_c y_r(k)+E_c r(k) \\ u_c(k)=C_c x_c(k)+D_c y_r(k)+F_c r(k) \\ x(k)\in X \\ u(k)\in U \\ k=k_0,\dots,k_0+T. \end{cases} \tag{21}$$

At each iteration step the first value of input sequence $u(k)$ is applied to the control system. This process will repeat until an optimal solution is found. The initial states of the reference model can be seen as the initial states of the optimization problem. The states of the reference model are updated at each iteration step through a state estimator designed by extended Kalman filter. The nonlinear system is linearized at each sample time around the current state, so the matrices of the model at current state can be updated as well.

(B) State Estimator. Since not all the variables used in the model are directly available especially for the states related to disturbances like wind and wave, a state estimator need to be designed by available measurements. Here an extended Kalman filter is employed to estimate the unmeasured states as described in above system. Kalman filter is a recursive filter of high efficiency, which can estimate the state of the dynamic system from a series of measurement with incomplete noise. Based on the wind turbine system model and disturbance model described in (1) and (2), an extended Kalman filter is implemented to estimate the unavailable states caused by disturbances especially periodic disturbance like wave. For more detailed description of the estimator please refer to [26, 27].

(C) Reference Model. The Baseline control model implemented by Jonkman on the OFWT (5 MW), used to study the performance of the barge floating platform over rated speed condition [28] is selected to be the reference model to resemble the dynamics of the closed-loop system of a floating wind turbine. The control law of baseline control is given in (22) where θ_{angle} relates to the commanded pitch angle, k_p and k_i are the proportional and integral gain, respectively. The detailed parameters of baseline model controller are shown in Table 3:

$$\theta_{\text{angle}}(t)=k_p e(t)+k_i\int_0^t e(\tau)\,d\tau. \tag{22}$$

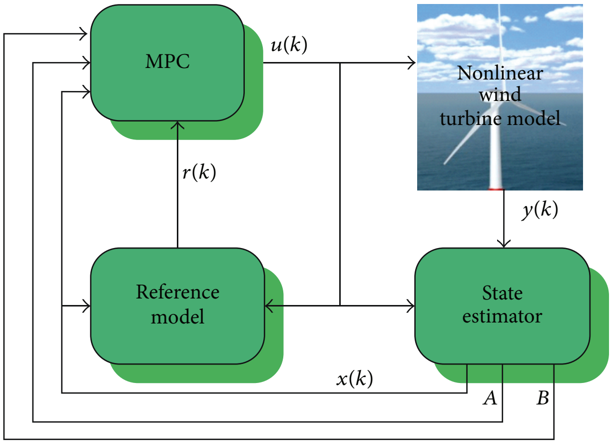

FIGURE 2: Wave disturbance using MPC.

TABLE 3: Baseline pitch controller properties.

Properties	Value
Rated power	5.296610 MW
Rated torque	43,093.55 N·m
Proportional gain	0.01882681
Integral gain	0.008068634
Minimum blade pitch	0°
Maximum blade pitch	90°
Maximum absolute blade pitch rate	8°/s

Using the data from NREL.

The control strategy is shown in Figure 2 which consists of three modules: a model predictive controller which can reduce the disturbance introduced by wave, a state estimator who can estimate the states that cannot be measured directly, and a reference model which can provide a reference without disturbance to the real disturbed system.

4.2.2. Cooperation Strategy Using Fuzzy Control. In this paper, Section 4.1 introduced the IPC based on DAC who takes the persistent disturbance like wind into consideration but ignoring the wave who is a type of periodic disturbance. This means that DAC controller can effectively deal with the wind disturbance but wave disturbance. And Section 4.2.1 describes a method to overcome influence caused by the wave disturbance on FOWT using model predictive control. In order to reduce or cancel the effect of both wind and wave disturbances on FOWT, the model predictive control component is added to the DAC system by fuzzy logic method based on the wind and wave loads on the FOWT system. The overall control strategy of FOWT is shown in Figure 3.

Fuzzy control which is widely used in complex systems like [10, 29] is a type of intelligent control based on fuzzy set theory, fuzzy linguistic variables, and fuzzy logic inference. The design process of a fuzzy controller generally consists of input and output variables definitions, fuzzification stage, rule base design, and defuzzification stage. Here the inputs

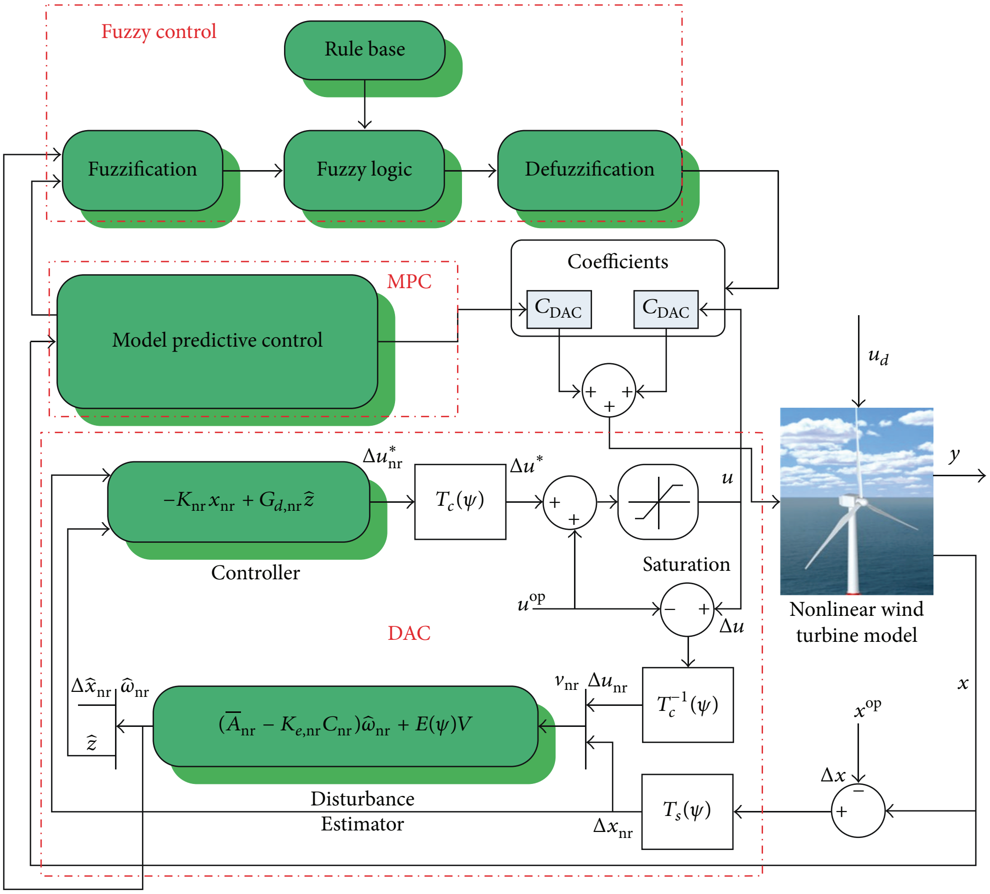

Figure 3: Block diagram of the overall control scheme.

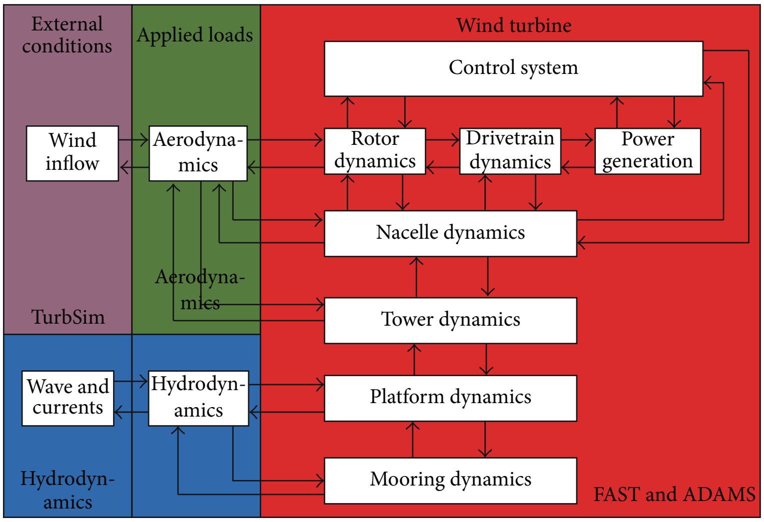

Figure 4: Offshore FAST structure (from NREL).

are wave force F_{wave} and wind force F_{wind}, and the outputs are C_{DAC} (DAC coefficient) and C_{MPC} (MPC coefficient). In the fuzzification stage inputs $F_{\text{wave}}, F_{\text{wind}}$ and outputs $C_{\text{DAC}}, C_{\text{MPC}}$ are represented by the fuzzy set membership I_1, I_2, C_1, and C_2, respectively:

$$I_1 = \{\text{NL}_{i1}, \text{NS}_{i1}, \text{ZE}_{i1} \cdot \text{PS}_{i1}, \text{PL}_{i1}\},$$

$$I_2 = \{\text{NL}_{i2}, \text{NS}_{i2}, \text{ZE}_{i2} \cdot \text{PS}_{i2}, \text{PL}_{i2}\},$$

$$C_1 = \{\text{PSS}_{o1}, \text{PS}_{o1}, \text{PM}_{o1} \cdot \text{PL}_{o1}, \text{PLL}_{o1}\},$$

$$C_2 = \{\text{PSS}_{o2}, \text{PS}_{o2}, \text{PM}_{o2} \cdot \text{PL}_{o2}, \text{PLL}_{o2}\}, \quad (23)$$

Table 4: Rule table of C_1.

C_1	NL_{i2}	NS_{i2}	ZE_{i2}	PS_{i2}	PL_{i2}
NL_{i1}	PM_{o1}	PS_{o1}	PS_{o1}	PSS_{o1}	PSS_{o1}
NS_{i1}	PL_{o1}	PM_{o1}	PS_{o1}	PSS_{o1}	PSS_{o1}
ZE_{i1}	PL_{o1}	PL_{o1}	PM_{o1}	PS_{o1}	PSS_{o1}
PS_{i1}	PLL_{o1}	PLL_{o1}	PLL_{o1}	PM_{o1}	PS_{o1}
PL_{i1}	PLL_{o1}	PLL_{o1}	PLL_{o1}	PL_{o1}	PM_{o1}

Table 5: Rule table of C_2.

C_2	NL_{i2}	NS_{i2}	ZE_{i2}	PS_{i2}	PL_{i2}
NL_{i1}	PM_{o2}	PL_{o2}	PL_{o2}	PLL_{o2}	PLL_{o2}
NS_{i1}	PS_{o2}	PM_{o2}	PL_{o2}	PLL_{o2}	PLL_{o2}
ZE_{i1}	PS_{o2}	PS_{o2}	PM_{o2}	PL_{o2}	PLL_{o2}
PS_{i1}	PSS_{o2}	PSS_{o2}	PS_{o2}	PM_{o2}	PL_{o2}
PL_{i1}	PSS_{o2}	PSS_{o2}	PSS_{o2}	PS_{o2}	PM_{o2}

where "NS," "NL," "ZE," "PS," and "PL" are entitled negative small, negative large, zero, positive small, and positive large, respectively. "PSS," "PSS," "PM," "PL," and "PLL" are entitled positive very small, positive small, positive small medium, positive large and positive very large, respectively.

The most important part of designing the fuzzy controller is to design the rule base. It stores the expert knowledge which governs the behavior of the fuzzy controller. The control rule described by the input variables F_{wave} (wave force), F_{wind} (wind force), and output variables C_{DAC} and C_{MPC} is given. If F_{wave} is I_1 and F_{wind} is I_2, then C_{DAC} is C_1 and C_2 is C_{DAC}. Since the wind disturbance has larger influence on the FOWT, the value of C_1 will increase or C_1 will decrease. Similarly, when wave disturbance increases, the value of C_2 will follow the same law. The detailed rule tables are shown in Tables 4 and 5.

5. Simulation and Results

To test the performance of the method proposed in this paper, the new individual pitch control based on combined DAC and MPC using fuzzy control is implemented in FAST where the controller of the wind turbine is implemented in a Dynamic Link Library (DLL) file called "DISCON.DLL." The FAST (Fatigue, Aerodynamics, Structures, and Turbulence) code is a comprehensive aeroelastic simulator capable of predicting both the extreme and fatigue loads of two- and three-bladed horizontal-axis wind turbines (HAWTs). The offshore FAST structure is shown in Figure 4.

As a comparison, "NREL offshore 5-MW baseline wind turbine" model whose detailed control parameter is described in Table 3 is also run in FAST. Both models operate above rated wind speed (11.4 m/s) with complex wave conditions. Figure 5 shows the wind condition with average 15 m/s turbulence wind speed and wave condition.

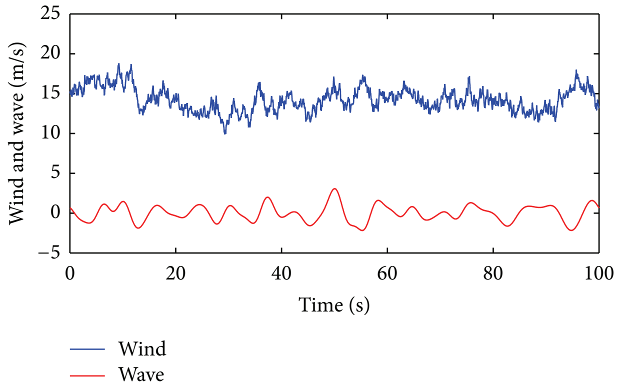

Figure 5: Wave and wind conditions.

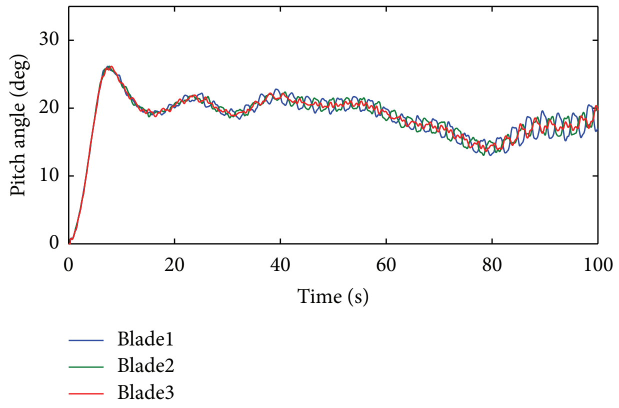

Figure 6: Pitch angles of three blades.

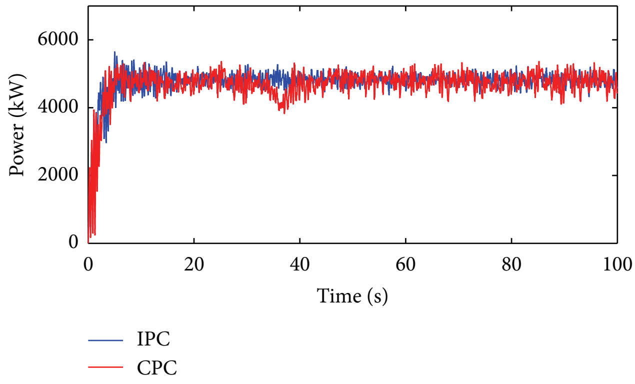

Figure 7: Power output.

The three blades can be controlled separately based on different loads distributed on each blade due to the new individual pitch controller. Figure 6 show that the three blades pitch angle changing individually with different wind and wave conditions. In order to analyze the performance of this new controller, several parameters can reflect that the wind turbine fatigue loads are selected. Tower fore-aft moment can refers to fatigue loads distributed on the tower, and out-of-plane bending moment, in-plane bending moment, flapwise moment, and edgewise moment represent the blade root loads. Figures 8, 9, 10, 11, and 12 show a significant loads reduction in both tower and blades compared to the baseline control due to the well design of wind and wave disturbance controller. To further illustrate the effect of new

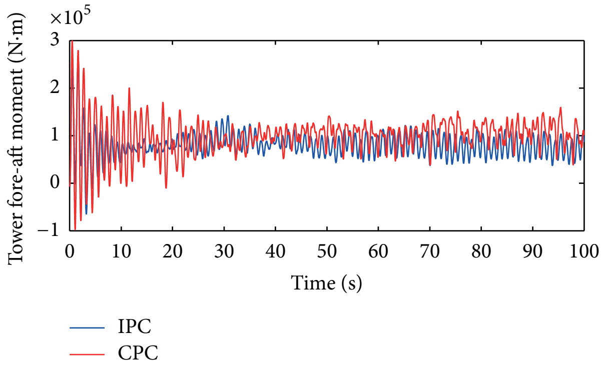

Figure 8: Tower fore-aft bending moment.

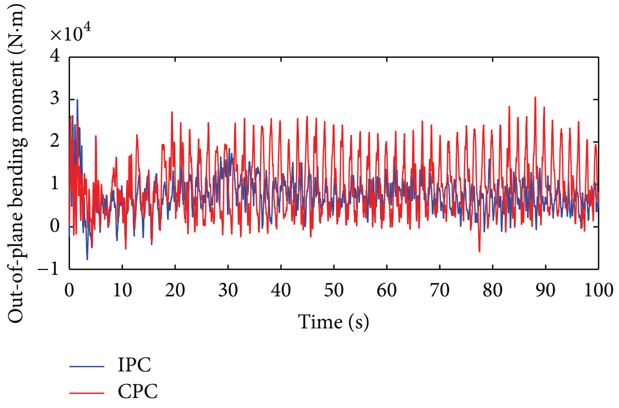

Figure 9: Out-of-plane bending moment.

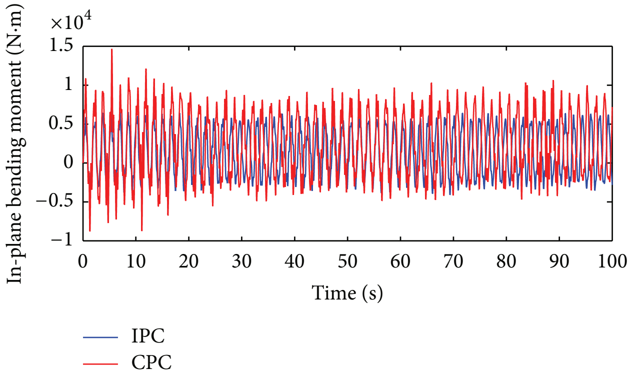

Figure 10: In-plane bending moment.

individual controller on fatigue loads reduction a summary of simulation, data is shown in Figure 13 where fatigue loads decrease by about 20% to 40%. Figures 8, 9, and 11 show that the magnitude becomes smaller with average declines also. In addition to reducing the fatigue load, the controller can ensure stable power output (Figure 7) as well as showing excellent robustness of the new pitch controller. Simulation results show that the new individual pitch controller is well designed and is highly effective to fatigue loads reduction.

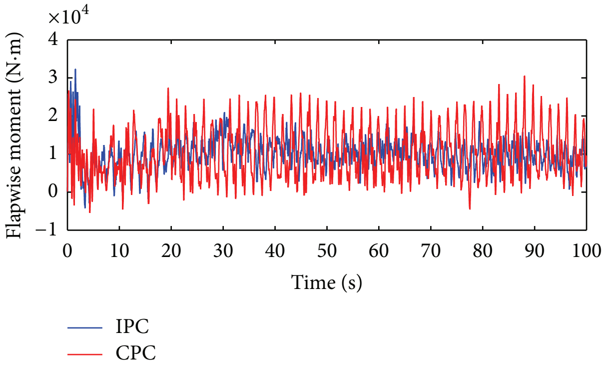

Figure 11: Flapwise moment.

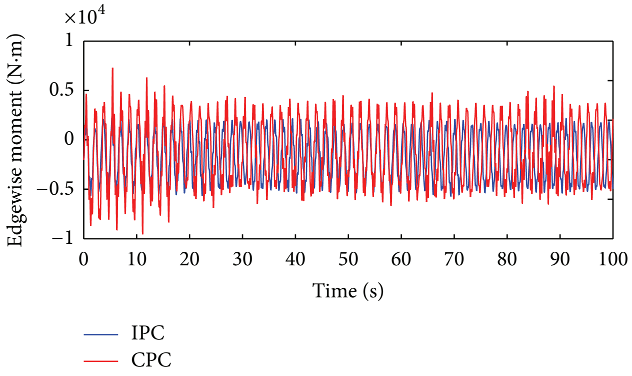

Figure 12: Edgewise moment.

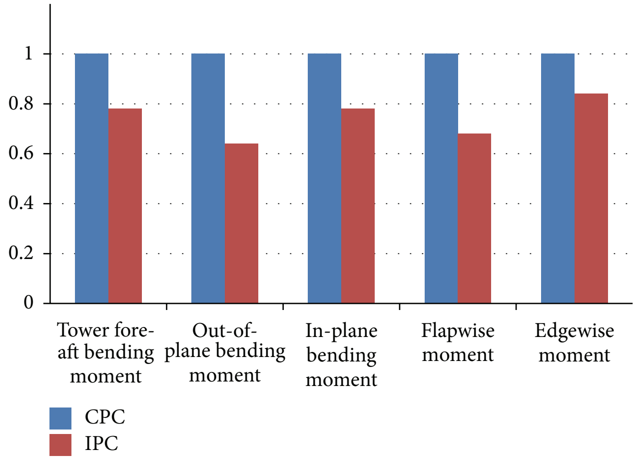

Figure 13: Fatigue loads comparison between CPC and IPC.

6. Conclusions

In this paper a new individual pitch control is proposed to reduce the fatigue loads caused by wind and wave disturbances. The new controller consists of three modules: DAC is a component aimed to eliminate the wind disturbances, MPC is a part who can remove the influence of wave disturbance on the wind turbine, and fuzzy control is used to combine the two algorithms to make cooperation work. Simulation results show that the new individual pitch controller shows excellent robustness to turbulence wind and complex wave conditions. In summary, compared to the baseline pitch controller, the new individual controller has a better performance in reducing fatigue loads caused by wind and wave disturbances and therefore is more suitable for FOWT.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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