Hydraulic Pitch Control Delay Estimation and Compensation Method for Large Wind Turbine

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Abstract. At present, using hydraulic pitch control for large wind turbines is becoming a trend. However, there will be a delay in the process of hydraulic pitch control, which will affect the stability of the system. In view of the influence caused by the delay in the wind turbine system, this paper designs a delay estimator and compensator using the Assumed Mode method, which linearizes the perturbation generated in the process of hydraulic pitch control and calculates the parameters with the method of function fitting, so as to overcome the adverse effect caused by the delay of hydraulic pitch control. At the same time, a pitch control system based on fuzzy control is designed to form a closed-loop control system. The parameters of 3MW wind turbine are taken as an example for simulation, the results show that this method can accurately estimate the delay generated in the process of pitch control, and can still well compensate the delay caused by the system under the condition of regulating pitch angle.

1. Introduction
As the capacity of wind turbine is gradually towards to large-scale development [1], the traditional electric pitch control, due to its disadvantages such as backlashes generated, is being replaced by the hydraulic pitch control system. As a key part of the whole technology of wind turbine, pitch control has an important research value. The wind turbine controlled by pitch control has better control performance, which can capture wind energy more efficiently and extend the life time of the wind turbine.

The existing pitch control technology is constantly improved. Ref. [2] proposed an independent pitch control method based on perturbation adaptive control technology. This control method could effectively reduce the partial load of the wind turbine under the wind shear condition. In Ref. [3], a robust adaptive control method was adopted to design an independent pitch tracking controller. A blade dynamic mathematical model with time-varying and unknown perturbations was established to describe the nonlinear dynamic behavior of the blade system. Ref. [4] gave an independent pitch control method based on feedforward compensation. A kind of acceleration weight coefficient distributor was designed to control the blades of the wind turbine individually, and the whole control system was compensated based on the theory of feedforward compensation. Ref. [5] used graphic method to analyze and design the proportional integral pitch controller for a large wind turbine. In Ref. [6], a new back-push control algorithm of finite time command filtering was proposed to eliminate the interference of noise and friction in the system. And the tracking accuracy of this algorithm was guaranteed by using the finite time error compensation mechanism. The robust multivariable IPC
method in Ref. [7] based on $H_\infty$ loop shaping had the excellent performance to suppress the perturbation load within a certain frequency range. With the improvement of pitch control, the delay caused by hydraulic pitch control has become the problem that cannot be ignored. It will bring perturbation to the control of the wind turbine, and will lead to the loss of stability of the wind turbine system and the irregular vibration of the tower, which would result in the damage of the wind turbine or even the occurrence of major accidents.

Based on the traditional theory of pitch control, the paper analyses the reason of delay in the process of pitch control, and estimates the delay. According to the estimated delay, a delay compensator is designed. With this method, the delay caused by the pitch control process is effectively estimated and compensated with the estimated value. So it can improve the efficiency of the wind turbine and reduce the load. A collective pitch controller based on fuzzy control is designed to make the method more general.

Finally, on the basis of the theoretical research, the parameters of a certain type of 3MW wind turbine are taken as an example and verified by MATLAB/Simulink.

2. Blade-tower linearization model
For large wind turbine units, this paper linearizes the blade flap vibration and the tower fore-aft vibration based on the Assumed Mode method, and couples them into a two-degree of freedom system. The linearization model is established as follows [8]:

$$\ddot{M}y + D\dot{y} + S\dot{y} = F \Delta \beta$$

(1)

Here $y = [y_t, y_b]^T$, $y_t$ and $y_b$ are the fore-aft vibration displacement of the tower and the flap vibration displacement of the blade, respectively; $\Delta \beta$ is the change value of pitch Angle; mass matrix $M = \begin{bmatrix} m_t & m_b \\ m_b & m_t \end{bmatrix}$; stiffness matrix $S = \begin{bmatrix} s_t & 0 \\ 0 & s_b \end{bmatrix}$; damping matrix $D = \begin{bmatrix} d_t & d_b \\ d_b & d_t \end{bmatrix}$; and external force matrix $F = \begin{bmatrix} f_t \\ f_b \end{bmatrix}$.

The linear model of the change of pitch angle to the mode deflection of the tower fore-aft vibration is transformed into the transfer function through the Laplace transform:

$$G(s) = \frac{a_2s^2 + a_1s + a_0}{b_5s^4 + b_4s^3 + b_3s^2 + b_2s + b_1}$$

(2)

Here, $a_0 = s_b f_t$; $a_1 = f_s d_b - d_b f_t$; $a_2 = f_s m_b - m_b f_s$; $b_0 = s_b s_t$; $b_1 = d_b s_s + s_b d_t$; $b_2 = s_b m_b - d_c^2 + d_b d_s + m_b s_b$; $b_3 = m_b d_t - 2m_t d_s + c_0 m_s$; $b_4 = m_b m_b - m_b^2$.

The mass and stiffness of the tower and the blades will vary with the height and radius. Taking the discrete parameters of the 3MW wind turbine as an example, the mass and stiffness of the tower and the blades as well as the coupling mass of them are calculated. The spatial model $u_r, u_b$ of the tower and blade are imported, and the modal mass and modal stiffness are calculated as follows:

$$m_i = \int_0^R u_i^2(r) m_i(r) dr; \quad m_t = \int_0^R u_t^2(r) m_t(r) dr; \quad m_b = \int_0^R s_b^2(r) m_b(r) dr; \quad s_i = \int_0^R [\dot{u}_i]^2(z) s_i(z) dz.$$

Here, $R$ is the radius of the wind wheel; $H$ is the height of the tower; $r$ is the vertical distance between the reference point on the blade and the center of the wind wheel; $z$ is the vertical distance between the reference point on the tower and the horizontal plane; $m_{si}$ and $s_{si}$ are the mass and stiffness of the blade per unit length; $m_i$ and $s_i$ are the mass and stiffness of the tower per unit length.
The mass and stiffness of blade and tower mentioned in above are all discrete point values. In order to simulate the actual state of wind turbine better, the paper makes the discrete points continuous with the statistical principle. The paper uses MATLAB/Simulink to synthesize a continuous curve, and then gives the fitting equations shown as (2.3)-(2.6). The fitting curve is shown in figure 1.

\[
s_{bl}(r) = 27.49r^2 - 2503r + 5.665 \times 10^4
\]

\[
s_{tl}(z) = 0.9425z^3 - 84.22z^2 - 3865z + 4.264 \times 10^5
\]

\[
m_{bl}(r) = -0.0258r^3 + 2.393r^2 - 73.3464r + 856.2078
\]

\[
m_{tl}(z) = -0.9z^2 - 14z + 3583
\]

Figure 1. Fitting curves of blade and tower stiffness and mass

The damping of the blade and tower in the wind turbine is composed of the structural damping \( d_{struct} \) and the aerodynamic damping \( d_{aero} \). The structural damping is the damping of the blades and the tower itself, while aerodynamic damping is the damping caused by the coupling system between the blades and the tower. Let the structural damping ratio of the blade and the structural damping ratio of the tower be \( \xi_b \) and \( \xi_t \) respectively, and the structural damping ratio of the blade and the tower can be obtained as follows:

\[
(d_b)_{struct} = 2\xi_b \sqrt{s_{bl} m_b}
\]

\[
(d_t)_{struct} = 2\xi_t \sqrt{s_{tl} m_t}
\]

The aerodynamic damping is nonlinear and can be obtained according to the leaf element theory [9]. Thus, the element of the damping matrix is:

\[
d_b = (d_b)_{aero} + (d_b)_{struct}
\]

\[
d_t = (d_t)_{aero} + (d_t)_{struct}
\]

By observing the process of building the tower model, it can be noted that the external force acting on the tower is the thrust, but when the tower is coupled with the blade, the external force is complex and non-linear. Therefore, according to the leaf element theory, the complex nonlinear model of tower and blade is linearized, and the external force model of tower and blade is established on the premise of the ideal tip speed ratio:
Here, \( p(r) = -\frac{1}{2} \rho c^2(r) r \omega \alpha \); \( \omega \) is the angular velocity of wind wheel; \( v \) is the wind speed; \( \rho \) is the air density; \( c(r) \) is the flow speed, \( c(r) = v \left(1 + \frac{\omega^2 r^2}{v^2}\right)^{\frac{1}{2}} \); \( C_L \) is the lift coefficient.

As stated above, we can calculate the coefficients in the transfer function from the change of pitch angle to the tower deflection, as shown in Table 1.

| a_2 | a_1 | a_0 | b_4 | b_3 | b_2 | b_1 | b_0 |
|-----|-----|-----|-----|-----|-----|-----|-----|
| 4.189 | -7.456 | -150.948 | 1 | 5.833 | 201.561 | 312.787 | 6014 |

3. Delay estimation and compensation

The delay caused by the hydraulic-driven pitch control technology used in wind turbines can degrade the performance of the entire wind energy conversion system, and this delay is ignored in most model building processes. Therefore, in order to simulate the operation conditions of wind turbine furthermore, the paper designs a delay estimator. And the estimated delay is used to compensate the system, so as to overcome the adverse impact of unknown delay caused by hydraulic drive unit on the whole system.

Considering the delay of the system, the linear model of the system is established based on the above transfer function:

\[
G_{\Delta \beta \rightarrow y_t} = G(s) e^{-\tau s}
\]

Here, \( y_t \) is tower fore-aft vibration modal deflection; \( \Delta \beta \) is the change in pitch Angle; \( \tau \) is hydraulic drive unit caused by unknown delay. Assuming that time-varying delay, the mathematical model of system delay to be established is as follows:

\[
\tau(t) = 2.5 + 0.5 \sin(3t)
\]

In order to describe and estimate the delay generated by the system, based on the aforementioned transfer function, the system delay is described by the equation of state as follows:

\[
\begin{cases}
\dot{x}(t) = A x(t) + B \Delta \beta(t) \\
y_t(t) = C x(t - \tau(t))
\end{cases}
\]

Here, \( C_i (sI - A_i)^{-1} B_i = G(s) \).

Let \( d(t) = C x(t - \tau(t)) - C x(t) \), then \( y_t(t) = C x(t) + d(t) \), here, \( d(t) \) is the perturbation caused by the unknown delay.

Let \( x_p(t) = \begin{bmatrix} x(t) \\ d(t) \end{bmatrix} \), \( N_p = \begin{bmatrix} I_4 & O_{4 \times 1} \\ O_{4 \times 4} & O_{4 \times 1} \end{bmatrix} \), \( A_p = \begin{bmatrix} A_i & O_{4 \times 1} \\ O_{4 \times 4} & O_{4 \times 1} \end{bmatrix} \), \( B_p = \begin{bmatrix} B_i \\ O_{4 \times 1} \end{bmatrix} \), \( C_p = \begin{bmatrix} C_i & I_1 \end{bmatrix} \). Scalable system [10]:

\[
\begin{align*}
\int_0^r p(r) u_b(r) \, dr \\
3 \int_0^r p(r) \, dr
\end{align*}
\]
A delay estimator is designed for the system:

\[ (N_p + L_p C_p) \dot{x}_p (t) = (A_p - K_p C_p) \dot{x}_p (t) + B_p \Delta \beta (t) + L_p \dot{y}_i (t) + K_p y_i (t) \]  

(16)

Here, \( L_p \) is derivative gain, \( L_p = \begin{bmatrix} O_{o d} \\ I_i \end{bmatrix} \); \( K_p \) is proportional gain; \( \dot{x}_p (t) \) is extend the estimate of system \( x_p (t) \).

Introduced state quantity \( \sigma (t) \), let \( (N_p + L_p C_p) \dot{x}_p (t) = (N_p + L_p C_p) \sigma (t) + L_p \dot{y}_i (t) \), so \( \dot{x}_p (t) = \sigma (t) + (N_p + L_p C_p)^{-1} L_p \dot{y}_i (t) \), and the estimator can be rewritten as:

\[ (N_p + L_p C_p) \dot{\sigma} (t) = (A_p - K_p C_p) \sigma (t) + B_p \Delta \beta (t) \]  

(17)

Therefore, the estimator of the delay perturbation can be obtained:

\[ \dot{\hat{d}} (t) = [O_{o d} \quad I_i] \dot{x}_p (t) \]  

(18)

The output after compensation is:

\[ y_w (t) = y_i (t) - \dot{\hat{d}} (t) \]  

(19)

From the above derivation, it can be concluded that the delay estimator can effectively estimate the delay in the process of hydraulic pitch control, so that the compensated output is not affected by the delay.

4. Design of collective pitch controller

The whole system of wind turbine is highly nonlinear, and the relationship between pitch angle and tower deflection is very complicated. With the wind turbine up sizing, the traditional PID control system has been difficult to meet the controller's demand for response accuracy. Therefore, the paper adopts the traditional Mamdani fuzzy reasoning method to establish fuzzy rules [11] and defuzzify the output variables, so as to obtain the desired specific results. The system block diagram of fuzzy control is shown in figure 2.

![Figure 2. Structure diagram of fuzzy control system](image)

As shown in figure 2, a second-order fuzzy controller is designed. When inputs are the deviation \( E \) of tower deflection and the variation value \( EC \) of tower deflection deviation, the output is the variation value \( \Delta \beta \) of pitch angle, and the actual variation range is \([-6,6]\). \( E, EC, \Delta \beta \in [-6, -5, -4, -3, -2, -1, 1, 2, 3, 4, 5, 6] \). The input and output are quantified respectively, and the parameters of the fuzzy controller are shown in table 2.
Table 2. The parameters of fuzzy controller

| E       | EC       | Δβ       | K₁      | K₂      | K₃      |
|---------|----------|----------|---------|---------|---------|
| [-0.6207m,0.6207m] | [-2×10⁻⁴m/s,2×10⁻⁴m/s] | [-15°,15°] | 9.6665  | 3×10⁻⁴  | 2.5     |

According to the actual operation of wind turbine, the table of fuzzy control rules is shown in table 3.

Table 3. The fuzzy control rule table

| E       | EC       | NB | NM | NS | ZE | PS | PM | PB |
|---------|----------|----|----|----|----|----|----|----|
| NB      | PB       | PB | PB | PB | PB | ZE | ZE |    |
| NM      | PB       | PB | PB | PM | PM | ZE | ZE |    |
| NS      | PB       | PM | PS | PS | PS | NS | NM | NB |
| ZE      | PM       | PM | ZE | NS | NM | NB | NB |    |
| PS      | PM       | NS | NS | NS | NS | NB | NB |    |
| PM      | PM       | NS | NM | NM | NM | NB | NB |    |
| PB      | PS       | NS | NM | NB | NB | NB | NB |    |

According to the inference and properties of the fuzzy inference method, the fuzzy set of output can be obtained. The off-line fuzzy calculation program is designed and the fuzzy control rule table is obtained, then the fuzzy pitch control module can be added to the original control system.

5. Simulation analysis

In the delay estimation and compensation, this paper takes the parameters of the 3MW wind turbine as an example for simulation. The rated wind speed is 10.5m/s, the rotor rated speed is 1.52rad/s, and the initial pitch angle is 0°.

First, the paper calculates the given value of tower deflection, which is related to the change rule of the inside and outside diameter of the tower with the height. And then the paper designs an off-line program to calculate the given value of tower deflection \( y'_{\text{t}} = 0.0168 \).

Under the premise of pitch angle variation, delay estimation and compensation are shown in figure 3 and figure 4 respectively.

![Figure 3. Estimation effect of the delayed under collective pitch control](image-url)
Figure 4. Compensation effect of the delayed under collective pitch control

It can be seen that, in the premise of pitch controller system conditions, the delay estimator can relatively accurate estimation and compensation system of delay. It makes the response time of the system earlier, and the tower deflection fluctuates stably in the interval [-1m, 1m] in a shorter time. Thus, the effect to the wind turbine system caused by the long-term irregular vibration of the tower is reduced.

Adjusting the system mathematical models for delay $\tau(t) = 3 + \sin(6t)$ and $\tau(t) = 8 + 0.5\sin(2t)$ respectively, the simulation results are shown in figure 5 and figure 6. It can be seen that when the delay mathematical model is changed, the system can still perform delay estimation and compensation well, and there is no obvious fluctuation in the deflection range of the tower.

6. Conclusion

The paper has studied the delay caused by hydraulic pitch control in wind turbine and has established the transfer function from pitch angle change value to tower deflection on the basis of the blade-tower dynamics model. The linear relationship between tower deflection and pitch angle change has been determined and the delay caused by the system has been estimated and compensated. The simulation results have shown that the delay estimator and compensator can accurately estimate and compensate the delay in the process of hydraulic pitch control. Thus, the response time of the system has been shortened and the system has been stabilized in a constant range in a short time. The affection
generated by irregular vibration of the tower in wind turbine can be reduced and the life time of the wind turbine can be extended.

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