Research Article

Aeroelastic Flutter and Sliding Mode Control of Wind Turbine Blade

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Received 21 April 2020; Revised 16 June 2020; Accepted 4 July 2020; Published 26 July 2020

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Flutter is an important form of wind turbine blade failure. Based on damping analysis, synthetically considering aeroelastic vibration instability of the blade and using the parameter fitting method, the aeroelastic flutter model of the pretwisted blade is built, with the simulation and emulation of flap and lead-lag directions flutter of the 2D dangerous cross section realized. Through the construction of two controllers, modular combinatorial sliding mode controller and sliding mode controller based on LMI for parameterized design suppress blade aeroelastic flutter. The results show that a better control effect can be achieved on the premise of the design of the precise parameters of the controller: the proposed sliding mode control algorithm based on LMI can effectively act on the aeroelastic system of the blade, significantly reduce the vibration frequency, and make the aeroelastic system converge to an acceptable static difference in a short time, which proves the effectiveness of sliding mode control in suppressing high-frequency vibration under high wind speed.

1. Introduction

Wind energy is a kind of clean energy with high commercial value, and wind turbine is an important part of capturing and converting wind energy into electric energy [1]. As the main part of wind turbine, the wind turbine blade has always been a significant research issue in the field because of its high-performance requirements, difficult size, and aerodynamic shape structure design. As a typical nonlinear aeroelastic unstable phenomenon, flutter is an important reason of fatigue damage for wind turbine [2]. How to effectively avoid flutter-induced aeroelastic instability has become an important research. The blade will be coupled by aerodynamic force, elastic force, inertial force, and other forces. Once the coupling result is divergent, the blade will show the instability of vibration and flutter, which is characterized by the fact that the amplitude cannot be automatically attenuated and gradually divergent. Flutter will bring fatal damage to the blade structure [3]. So, how to protect the blade from flutter becomes the focus point of wind turbine research.

In order to meet the analysis requirements of different wind turbine blades, it is necessary to select the appropriate simulation structure model. The commonly used structure analysis models include elastic hinge model [4], finite element model [5], and typical section model [6, 7]. The typical section model is widely used because it can reflect the aeroelastic vibration of blade easily, quickly, and accurately. The aeroelastic stability is a typical problem of whether the fluid solid coupling converges. That is to say, the blade, as an elastic body, is affected by the fluid in the fluid domain (air) to change its flexible shape, which in turn affects the fluid phenomenon; consequently, the research process is relatively complex. In [8], the method of passive control is used to suppress flutter by an adaptive design. In [9], the aeroelastic vibration response of the blade is improved by nonequilibrium aeroelastic cutting. In [10], the relationship between damping and aeroelastic instability is studied by modal analysis. In [11], two input and output controllers are designed based on the influence of nonlinear constraints on the flutter system. In [12], the coupling equations of motion of the system and the construction of the transonic aerosol
elastici model in the reduced order wing and control surface state space are considered, and the suboptimal control method output feedback based on genetic algorithm is constructed to design the flutter suppression law. Cheng et al. and Yang et al. [13, 14] analyzed the influence of blade structure and environmental variables on the blade system.

In this paper, the aerelastic model expression and fitting aerelastic factors considering structural damping are developed. Through the typical section analysis method, the aerelastic vibration response of the blade in the case of high wind speed and high angle of attack is analyzed, and the active control process of sliding mode control of flutter is simulated. Sliding mode control is a simple and effective variable structure control method, which is flexible in physical realization, fast in response, and excellent in control effect. It has been applied in many industrial fields [15].

### 2. Modeling of Blade Vibration

#### 2.1. Aeroelastic Model and Motion Equation

In the analysis of blade vibration, the damping phenomenon should be fully considered, including structural damping and aerodynamic damping. Composite material is often used in the blade manufacturing, and the structure damping can be detected through actual measurement. Aerodynamic damping is the action of air on the vibration of flexible body blades in reverse to the wind force. Before the occurrence of flutter, the aerodynamic damping is positive to suppress the vibration of blades and reduce the amplitude; otherwise, the vibration of blades will not be self-attenuated due to the strengthening of vibration. The typical section of large aspect ratio airfoil is considered in blade modeling, and the distance from the section to the blade root is $r = 3.75m$; $y$ and $z$ represent the displacement of leg and flap direction, respectively. $\alpha$ is attack angle; $U$ is the wind speed value, which is 15m/s as to simulate the working conditions at high speed wind. $c$ is chord length (chord direction $t$ and normal direction $n$); $V_{\alpha}$ is the relative wind speed after considering the blade rotation. The blade length $L$ is 15m; blade rotation speed $\Omega = \lambda \cdot U/L$, where $\lambda$ is the tip speed ratio coefficient and the value is 2.

In order to compensate for the power loss of aerelastic deformation and increase the torsional rigidity, the blade pretorsional angle is as follows: $\theta = (r/L) \cdot \theta_0$, $\theta_0 = \pi/12$, $\omega_t$ and $\omega_n$ are chord and normal natural frequencies, respectively, which are chosen as 12 rad/m and 8 rad/m. $\xi_t$ and $\xi_n$ are chordal and normal damping ratios, respectively. In the aerelastic flutter, the blade absorbs energy from the fluid so that the amplitude of the blade does not self-attenuate and shows negative aerodynamic damping, with absolute values of 0.03 and 0.06, respectively. $\rho_a$ is the section density, which is given in the form of parameter fitting. Air density $\rho_a = 1.29kg \cdot m^{-3}$, and parameter distribution on the blade is shown in Figure 1.

The vibration equation model of two-dimensional typical dangerous section is selected, and the full damping behavior is fully considered [16, 17]. The relative reduction time is defined as $\tau = t \cdot V_{\alpha}/c$. The section vibration flap angle is defined as $\phi_2 = z \cdot c/r$, and $\phi_y = y \cdot c/r$ is section vibration leg angle. Then, the aerelastic equations of the chosen section can be expressed as follows:

$$\phi_i + \Omega^2 \phi_i = \frac{c\rho_a V_{\alpha}^2}{2\rho_a r} \left[ K_y \begin{bmatrix} K_{cs} \\ K_{sw} \end{bmatrix} \right] \phi_i,$$  \hspace{1cm} (1)

where $i = y, z$, and $K_y$ and $K_z$ are aerodynamic parameters of swing and swing directions, respectively. The set pretwist angle can provide complete damping for the blade, and the structural damping parameters are expressed as follows:

$$K_{cs} = C_{\phi} K_{so} C_{\phi}^T,$$  \hspace{1cm} (2)

where $K_{so}$ is the reduced damping parameter matrix and $C_{\phi}$ is the pretwist effect coefficient, which are expressed as follows:

$$K_{so} = \begin{bmatrix} 2\xi_t \omega_t \frac{\xi_t}{\omega_t} \frac{\xi_t}{\omega_t} \\ 0 \end{bmatrix},$$  \hspace{1cm} (3)

$$C_{\phi} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix},$$  \hspace{1cm} (4)

So, the damping parameter matrix of complete structure can be expressed as $\Omega K_{cs}$; similarly, the structural stiffness parameters can be calculated:

$$K_t = C_{\phi} K_{st} C_{\phi}^T,$$  \hspace{1cm} (5)

$$K_S = C_{\phi} K_{st} C_{\phi}^T.$$  \hspace{1cm} (6)

The stiffness parameter matrix of complete structure can be obtained:

$$K_{sw} = K_t + I_{2 \times 2}.$$  \hspace{1cm} (7)

Order $X = \begin{bmatrix} \phi_y & \phi_z \end{bmatrix}$, the aerelastic equation of flap, and leg angle with full damping can be developed; $M \dot{X} + C \dot{X} + KX = Q$ is considered; then, equation (8) can be derived:

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\phi}_y \\ \dot{\phi}_z \end{bmatrix} + \Omega K_{cs} + \Omega^2 K_{sw} \begin{bmatrix} \phi_y \\ \phi_z \end{bmatrix} = \frac{c\rho_a V_{\alpha}^2}{2\rho_a r} \begin{bmatrix} C_D \cos \Psi - C_L \sin \Psi \\ C_D \sin \Psi + C_L \cos \Psi \end{bmatrix}. $$  \hspace{1cm} (8)
\( C_L \) and \( C_D \) are the aerodynamic lift and drag parameters, and \( \rho_b \) is the cross-section density. In order to be more practical, the fitting method is adopted to obtain the above parameters.

### 3. Parameter Fitting and Analysis

The blade is not a simple extension of the same section; the structural parameters at different sections are different and change with the analysis radius. In this paper, the section density \( \rho_b \) and chord length \( c \) are considered. The airfoil section based on NA63215 is considered. The chord length \( c \) and section density \( \rho_b \) are fitted to a sixth order sine sum curve:

\[
F(n) = \sum_{i=1}^{6} p_i \sin(q_i n + w_i),
\]

where fitting variable \( n = r/L \). When the aeroelastic stability of blades is analyzed, the accurate calculation of aerodynamic lift coefficient \( C_L \) and aerodynamic drag coefficient \( C_D \) are of practical significance. The curve fitting is also carried out for the attack angle with \(-\pi/2 < \alpha < \pi/2\); then, the fitting variable \( n = \alpha \), and the results are shown in Table 1.

In order to carry out the subsequent analysis, the above expression is now converted into the state space form of the first-order equations: 
\[
Y = \begin{bmatrix} \phi_y & \phi_z & \phi_y & \phi_z \end{bmatrix}^T, \quad \text{so we can obtain} \quad Y(t) = \Lambda Y(t) + B, \quad Y_0(t) = CY(t),
\]

where
\[
\Lambda = \begin{bmatrix} F_1 & F_2 \\ -M^{-1} \cdot K & -M^{-1} \cdot C \end{bmatrix},
\]
\[
B = \begin{bmatrix} F_3 \\ -M^{-1} \cdot K \cdot Q \end{bmatrix}.
\]

There are many methods to evaluate the stability of the system. For example, the eigenvalue determination, Bode diagram, and Lyapunov criterion. According to the characteristics of the blade system, the stability of the blade in the two directions of the flap and leg is analyzed comprehensively. Even when the blade is stable, whether the amplitude and frequency are in line with the physical reality should be judged [15–17]. Therefore, time domain response analysis and limit cycle analysis are selected to observe the blade vibration response under aerodynamic force. Most of the dangerous sections appear at the blade root along the span of about 25% [17]. According to this standard, the section displacement is calculated by the fourth-order five level Runge–Kutta method, and the vibration of dangerous section is observed to represent the forced response of blade and the phase track distribution of blade in two directions, so as to comprehensively evaluate the aeroelastic vibration behavior of blade. The results are shown in Figure 2.

Based on the case of extreme wind speed, the uncontrolled vibration of the blade cross-section when the flutter occurs under the aerodynamic force is simulated with the medium-sized wind turbine parameters introduced into the aeroelastic model. From Figure 2, it can be found that the vibration divergence of the blade under the condition of high wind speed and high angle of attack, that is, the vibration in the two directions of flap and leg vibration does not decay with time, and the vibration frequency is high and the amplitude is increasing. It can be seen from the limit cycle distribution that the vibration range of the two directions is large and does not converge, and the vibration frequency is very high. It can be judged that, in this case, if the blade vibration is as shown in the simulation, the flutter failure will occur, so it must be suppressed.

### 4. Sliding Mode Flutter Control

#### 4.1. Direct Sliding Mode Control Based on Module Building

Sliding mode control, originated from relay control and bang–bang control, is a branch of variable structure control. As a nonlinear control strategy, the basic feature is the discontinuity of the control process. The control system can

**Table 1: Fitting parameters.**

| Type | \( c \) | \( \rho_b \) | \( C_L \) | \( C_D \) |
|------|--------|--------|--------|--------|
| p1   | 5.561  | 21.66  | 0.869  | 3.309  |
| q1   | 3.943  | 4.656  | 2.073  | 0.351  |
| w1   | -0.382 | 0.260  | 0.041  | 1.488  |
| p2   | 141.9  | 25.49  | 0.307  | 0.715  |
| q2   | 8.576  | 8.564  | 4.013  | 2.037  |
| w2   | -0.396 | -0.269 | -0.058 | -1.58  |
| p3   | 139.1  | 12.50  | 0.199  | 2.658  |
| q3   | 8.63   | 12.53  | 5.892  | 0.402  |
| w3   | 2.71   | 0.794  | 0.051  | -1.663 |
| p4   | 0.332  | 4.097  | 0.171  | -0.018 |
| q4   | 18.44  | 21.25  | 0.713  | 2.987  |
| w4   | -0.409 | -1.891 | 0.847  | -1.528 |
| p5   | 0.258  | 2.297  | 0.138  | 0.020  |
| q5   | 24.52  | 25.08  | 7.613  | 3.949  |
| w5   | -1.307 | -1.400 | -0.119 | 1.586  |
| p6   | 0.140  | 0.370  | 0.086  | 0.0003 |
| q6   | 30.59  | 36.38  | 9.298  | 4.816  |
| w6   | -1.185 | -5.521 | -0.193 | -1.575 |
change the control object purposefully and dynamically. The control structure can change the control structure and control law according to the degree of the system deviating from the preset "sliding mode" [18–20]. In this paper, the sliding mode-aeroelastic control system is constructed by two methods.

Simulink is an important part of MATLAB. It can be used in many kinds of simulation and experiments after being designed in the software environment. It can simulate the process of system control and data processing by building the modules of each part, constructing the relationship between modules, and assigning values within the modules. It is a simulation building form of the controller, which can be transformed into the design process of the actual controller. Firstly, a sliding mode control method based on Simulink is proposed. By adding an optimal control law, the control stability can be judged by observing the deviation index [19, 20].

Take the deviation signal of the swing direction equivalent to the zero point as the feedback \((s = e)\). Take the initial position before blade vibration as the standard point [21]. Select the proportional switching method, and set the sliding mode control function and control rate as follows:

\[
S = K_3|s| + K_4s,
\]  
(12)

\[
u = K_5s + K_5\text{sgn}(s).
\]  
(13)

Set the feedback gain to \(K_4 = 0.5\), \(K_i (i = 1–5)\) are set to 20, 20, 0.5, 2, and 0.5. Taking the relative reduction time as the abscissa to analyze the control performance, the control effect is as follows:

It is obvious that the amplitudes and frequencies of the flap and leg vibration can be greatly reduced under this sliding mode control. However, the disadvantages cannot be ignored; buffeting cannot be completely eliminated in this case. It can be clearly found in the controlled vibration change the control object purposefully and dynamically. The control structure can change the control structure and control law according to the degree of the system deviating from the preset "sliding mode" [18–20]. In this paper, the sliding mode-aeroelastic control system is constructed by two methods.

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It is obvious that the amplitudes and frequencies of the flap and leg vibration can be greatly reduced under this sliding mode control. However, the disadvantages cannot be ignored; buffeting cannot be completely eliminated in this case. It can be clearly found in the controlled vibration
performance and limit cycles in Figure 4 that the amplitudes after local amplification are very obvious. Although the amplitude is greatly reduced, maintaining this vibration for a long time may have adverse effects on the blades. From the controlled performance, the sliding mode control based on module building realizes flutter suppression and stable response, which can be realized through the data processing module in the controller. For the blades with large flexibility, it is a simple and easy control strategy with low control cost. In order to prove the generality of sliding mode control and explore more accurate control strategy, the second kind of module in the controller. For the blades with large flexibility, the sliding mode control based on LMI (Linear Matrix Inequality, LMI) are designed to control the aeroelastic system of the blade.

4.2. Design of Sliding Mode Controller Based on LMI. In the design of sliding mode controller, a lot of constraint calculation is needed, so it is very difficult to design the controller precisely, especially to find the linear inequality [22]. In this paper, the design of sliding mode parameters based on LMI greatly increases the accuracy and controllability of the design.

Based on model transformation, let $x = Y$. And the variable is brought into the state space expression of the aeroelastic system. The sliding mode function is defined as $s = B^T P x$, where $P$ is the fourth-order symmetric positive definite square matrix. The LMI method is used to design the value of $P$ matrix and then determine the sliding mode function. Set the control law as follows:

$$u(t) = -K x + v(t).$$

(14)

According to equation (13), we can obtain

$$v(t) = K x - (B^T P B)^{-1} B^T P A x (t) - (B^T P B)^{-1} B^T P B \delta_f + e_i \text{sgn}(s).$$

(15)

Considering uncertainty and interference, $\overline{A} = A - BK$ is brought into the above formula. Therefore, the expression of aeroelastic state space of the original blade is rewritten as follows:

$$x(t) = \overline{A} x(t) + B(v + f(x, t)).$$

(16)

Finding $K$, makes $\overline{A}$ Herwitz matrix, and the system has closed-loop stability. Take the Lyapunov function:

$$V = x^T P x,$$

then

$$V = 2x^T P \overline{A} x + 2x^T P B (v + f(x, t)).$$

(17)

According to the control law, there must be a time when the sliding mode function is zero, so it can be rewritten as follows:

$$V = 2x^T P \overline{A} x = x^T (P \overline{A} + \overline{A} P) x.$$

(18)

To satisfy that $V$ is always negative, it is necessary to $P \overline{A} + \overline{A} P < 0$; then, $H = P^{-1}$, $N = K H$, and satisfy the symmetric positive qualitative of $P$:

$$\Lambda H - B N + N^T B^T < 0.$$

(19)

The thickness of sliding mode is 0.05. Considering the small amplitude of blade, the uncertain interference is taken as a small amplitude cosine signal. Through LMI calculation, we can obtain

$$P = \begin{bmatrix} 2.6101 & 0.9239 & 0.1915 & 0.4736 \\ 0.9239 & 4.0559 & 0.5636 & 1.3993 \\ 0.1915 & 0.5636 & 0.1160 & 0.2105 \\ 0.4736 & 1.3993 & 0.2105 & 0.5419 \end{bmatrix},$$

(20)

$$K = \begin{bmatrix} -0.2662 & -1.5429 & 0.4950 & 1.2844 \end{bmatrix}.$$  

(21)

It can be proved that $\overline{A}$ is the Hurwitz matrix under this value, and the aeroelastic response in the two directions.

Figure 3: Module construction of the aeroelastic control system.
flap and leg after control can be observed by the model parameters mentioned above.

It can be observed from Figure 5 that when the aeroelastic system of the blade flutters, through the sliding mode control based on LMI, the flutter in both the flap and leg directions is well suppressed. Finally, the vibration in both directions converges to a stable value quickly, which means that, after the process of the proposed algorithm, the steady-state time of the system is short, reflecting the satisfactory steady-state control performance of the algorithm. Meanwhile, the vibration frequencies of the aeroelastic system are greatly reduced, which is able to avoid the hidden failure of the blade caused by high-frequency vibration. In the implementation of the algorithm, there is no need for complex iterative calculation; consequently, the processing speed is fast enough, which can effectively suppress the errors that may be introduced in the implementation process. Compared with the modular sliding control algorithm, the stabilization time is shorter and the static error is smaller after stabilization. In engineering implementation, the control actuator has many options depending on different blade types and working conditions [22, 23]; it can be realized by connecting the pitch system and setting actuators in the blade skin, such as SMA electric heating, piezoelectric materials, and current control by electromagnetic rheological fluid. Besides, the sliding mode control based on LMI is mainly based on matrix operation, which can be implemented in statements with MATLAB or other programming languages. Through OPC technology [24], it can be easily realized in PLC controller hardware and has positive engineering practical application value.
5. Conclusion

(1) In this paper, the aeroelastic response of the typical section of the blade under high wind speed and high angle of attack is modeled by fully considering the damping effect, which is used to analyze and simulate the vibration of the horizontal axis wind turbine blade under flutter.

(2) A flexible sliding mode controller is built by the way of module building of Simulink, which can achieve the purpose of flutter suppression. Although there is local chattering, it is still a simple and economic controller design method. A new type of sliding mode controller is designed and constructed by parameters’ LMI-based sliding mode controller. The results show that the final response converges, the amplitude and frequency are greatly reduced, the local chattering is weakened, the stability time is short, the static error is acceptable, and the control effect is satisfactory.

(3) The advantages of the sliding mode algorithm are the accuracy of the model is not so essential and the algorithm is insensitive to parameter changes and external interference, with strong robustness. Through the switching of the sliding surface function, the tracking error is gradually reduced, and finally a better control performance is achieved. Especially for the flexible body of wind turbine blade, even if the small buffeting exists, the small static error can be accepted under the premise of response convergence, which can be well combined with the sliding mode controller. Through the analysis of vibration and limit cycle of LMI-based sliding mode control, we can conclude that the proposed
algorithm can suppress the flutter vibration of blades and make the aeroelastic system finally converge with short stability time, which can suppress the high-frequency vibration at high wind speed. Therefore, the effectiveness of the proposed algorithm is comprehensively verified. Sliding mode control has made great progress in many engineering fields, but the research on flutter suppression technology based on risk section analysis is still less, which has the research value.

Data Availability

The results of the analysis and the model building process have been completely presented, and even the values of the results are visualized. So, the result data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant no. 51675315).

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