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The Effects of Structural Viscous Damping on the Aeroelasticity of Wind Turbine Blade

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Abstract: The aeroelasticity of the wind turbine blade has become more and more important because the blade is becoming larger and larger. The influence of structural viscous damping will be introduced into the time domain analysis of the wind turbine blade, in order to analyze the aeroelastic response and control the flutter region of the wind turbine blade airfoil. The equation of motion for the blade airfoil, with the controllable viscous damping was established, based on the simplified aerodynamic force and torque calculated by the modified blade element momentum theory. The time domain responses of aeroelasticity of the wind turbine blade are analyzed numerically. The simulation results demonstrate that the torsional motion always keeps stable, but the flap motion shows very complicatedly aeroelastic response. Compared with the aeroelastic responses without damping, there are also two critical tip speed ratios with damping considered. When the viscous damping is taken in account, the lower critical tip speed ratio will become larger and the higher critical tip speed ratio will become smaller, as a result, the flutter region will be shortened. And if the damping coefficients are increased, the flutter region will be reduced much more quickly and even there is no flutter region at all when the damping coefficients become much larger. Therefore, if the damping can be controlled and applied to suppress the flutter of the wind turbine blade, it will work very efficiently.

Key words: Wind turbine blade, viscous damping, aeroelasticity, flutter, runge-kutta method

INTRODUCTION

Wind energy has been becoming one of the most important representatives as the new energy and clean energy in the world in the recent years. And as one of the most critical parts of the wind turbine, the blade is moving for the direction of more upsizing and flexibilily (Manwell *et al*., 2009). Because the occurring of wind turbine flutter will give rise to the severe accident, the aeroelatic problem of the wind turbine has been one of the key subjects of relative fields (Zhang *et al*., 2011; Hansen *et al*., 2006). Many researchers have made the achievements of the wind turbine flutter, totally in two aspects, frequency domain analysis and the time domain analysis. So they could get the critical flutter speed using the frequency domain analysis (Hansen, 2004; Lobitz, 2004; Lobitz, 2005) and get the time domain responses of some wind turbine characteristics.

Chaviaropoulos (2001) and Chaviaropoulos *et al*. (2003) presented a numerical tool for the investigating the aeroelastic stability, that is, stall flutter, of a single wind turbine blade subjected to combined flap/lead-lag motion, based on the extended ONERA lift and drag models. Sarkar *et al*. (2008) investigated the nonlinear aeroelastic behavior of a two-dimensional rotor blade in the dynamic stall regime. Chen *et al*. (2011) analyzed the horizontal axis wind turbine blade in steady stall considering the aerodynamic damping and the key parameters of the aerodynamic damping were researched. Fredric (2012) presented the resonances and the aerodynamic damping of a vertical axis wind turbine. There are some researches about the aerodynamic damping and its influence on the aeroelasticity.

However, there are little achievements for the effects of the viscous damping of structure on the aeroelasticity and the flutter of the wind turbine blade airfoil.

The detailed research for the aeroelaticity and the flutter region with damping and the changing laws will be presented in the paper, based on the modified blade element momentum theory. And the outlines of the paper are: the structural model of wind turbine blade airfoil, the aerodynamic force and torque based on the modified blade element momentum theory, the algorithm of the aeroelasticity of the wind turbine blade airfoil, numerical simulation and results analysis and the conclusions in the end.

THE STRUCTURAL MODEL OF WIND TURBINE BLADE AIRFOIL

Figure 1 shows the two-dimension model of the airfoil of wind turbine blade. The aerodynamic force T and

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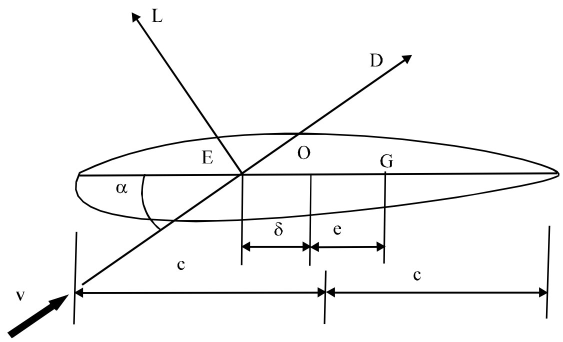

Fig. 1: The airfoil of wind turbine blade

aerodynamic torque M under the air fluid will apply on the blade of wind turbine. The aerodynamic force can be divided into lift L and drag D which is vertical and parallel to the velocity of air fluid, respectively.

where, E is the aerodynamic center, G means the center of mass of airfoil, O is the center of stiffness, e denotes the distance between the center of mass and center of stiffness, α is angle of attack, δ means the distance between the aerodynamic center and the center of stiffness.

The differential equation of motion for the airfoil will be seen easily as Eq. 1:

$$\begin{bmatrix} J_0 & 0 \\ 0 & m \end{bmatrix}\begin{bmatrix} \ddot{\theta} \\ \ddot{x} \end{bmatrix}+\begin{bmatrix} k+e^2 s & -es \\ -es & s \end{bmatrix}\begin{bmatrix} \theta \\ x \end{bmatrix}=\begin{bmatrix} M \\ F \end{bmatrix} \quad (1)$$

where, J_0 is moment of inertia of the airfoil around the center of mass, m is the mass of airfoil, s is the stiffness of linear spring, k is the stiffness of torsion spring.

Considering the influence of viscous damping, the differential equation of motion for the airfoil will be changed as Eq. 2.

$$\begin{bmatrix} J_0 & 0 \\ 0 & m \end{bmatrix}\begin{Bmatrix} \ddot{\theta} \\ \ddot{x} \end{Bmatrix}+\begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix}\begin{Bmatrix} \dot{\theta} \\ \dot{x} \end{Bmatrix}+\begin{bmatrix} k+e^2 s & -es \\ -es & s \end{bmatrix}\begin{Bmatrix} \theta \\ x \end{Bmatrix}=\begin{Bmatrix} M \\ F \end{Bmatrix} \quad (2)$$

where, C_1, C_2 mean the controllable viscous damping coefficient of structure which can be adjusted to some extent. If C_1, C_2 are zero at the same time, the Eq. 2 will be simplified to Eq. 1.

THE AERODYNAMIC FORCE AND TORQUE BASED ON THE MODIFIED BLADE ELEMENTUM THOERY

The aerodynamic force F and torque M in Eq. 2 can be treated in very simplified way as Eq. 3 (Liao and Liu, 2004).

$$\begin{bmatrix} M \\ F \end{bmatrix}=-\begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix}\begin{bmatrix} \dot{\theta} \\ \dot{x} \end{bmatrix}-\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}\begin{bmatrix} \theta \\ x \end{bmatrix} \quad (3)$$

where, S_{11}, S_{12}, S_{21}, S_{22} mean the aerodynamic stiffness, d_{11}, d_{12}, d_{21}, d_{22} denote the aerodynamic damping.

In order to calculate the aerodynamic force and aerodynamic torque and to solve the Eq. 3, assume that there is no relation between the flap displacement, the rotate angle and the aerodynamic loads. That is to say, $S_{12} = S_{22} = 0$, $d_{11} = d_{21} = 0$. So the nonzero aerodynamic stiffness and aerodynamic damping can be expressed as Eq. 4 (Liao and Liu, 2004).

$$\begin{aligned}
S_{11}&=\frac{\partial M}{\partial \theta}=\frac{1}{2}\rho cBW_0\delta\left[\frac{dC_L(\alpha)}{d\alpha}\cos\alpha+\frac{dC_D(\alpha)}{d\alpha}\sin\alpha+C_D\cos\alpha-C_L\sin\alpha\right]\\
S_{21}&=\frac{\partial F}{\partial \theta}=\frac{1}{2}\rho cBW_0\left[\frac{dC_L(\alpha)}{d\alpha}\cos\alpha+\frac{dC_D(\alpha)}{d\alpha}\sin\alpha+C_D\cos\alpha-C_L\sin\alpha\right]\\
d_{12}&=\frac{\partial M}{\partial x}=\frac{\partial M}{\partial W}\frac{dW}{dx}+\frac{\partial M}{\partial \alpha}\frac{d\alpha}{dx}\\
d_{22}&=\frac{\partial F}{\partial x}=\frac{\partial F}{\partial W}\frac{dW}{dx}+\frac{\partial F}{\partial \alpha}\frac{d\alpha}{dx}
\end{aligned} \quad (4)$$

where, ρ is the density of air, c is the semi-chord length, B is the number of blades of wind turbine, C_L means the lift coefficient, C_D means the drag coefficient:

$$W_0=\sqrt{(R\Omega)^2+V_0^{\,2}}$$

means relative velocity, V_0 is the velocity of air fluid, r is the local radius of blade, Ω is the rotating angular velocity.

$$C_L, C_D, \frac{dC_L(\alpha)}{d\alpha}, \frac{dC_D(\alpha)}{d\alpha}$$

are the functions of the angle of attack and the axial induction factor, a and the tangential induction factor, b, can be calculated through the use of the blade element momentum theory (Hansen, 2008) which was modified with Prandtl's tip loss factor and Glauert correction for high value of axial induction factor, based on the fitting function of lift coefficient and drag coefficient.

Therefore, the calculation of aerodynamic stiffness and damping is calculated based on the modified blade element momentum theory. Equation 5 gives the flow angle and the local angle of attack based on the axial induction factor, a and the tangential induction factor, b.

$$\phi=\arctan\frac{(1-a)V_0}{(1+b)\Omega r},\ \alpha=\phi-\theta \quad (5)$$

where, ϕ is the flow angle which is the angle between the plane of rotation and the relative velocity, θ is the local pitch of the blade which is the local angel between the chord and the plane of rotation.

Equation 6 presents the Prandtl's tip loss factor, F, when the assumption of an infinite number of blade is corrected.

$$F = \frac{2}{\pi}\arccos[\exp(-\frac{B}{2}\cdot\frac{R-r}{r\sin\phi})] \quad (6)$$

where, R is the radius of wind turbine.

Equation 7 shows the normal force coefficient, C_n and tangential force coefficient, C_t , decided by the lift coefficient and drag coefficient.

$$\begin{aligned} C_n &= C_l\cos\phi + C_d\sin\phi \\ C_t &= C_l\sin\phi - C_d\cos\phi \end{aligned} \quad (7)$$

Considering the Prandtl's tip loss factor, F, the axial induction factor and the tangential induction factor can be calculated according to Eq. 8.

$$a = \frac{1}{\frac{4F\sin^2\phi}{\sigma C_n}+1}\ b = \frac{1}{\frac{4F\sin\phi\cos\phi}{\sigma C_t}-1} \quad (8)$$

where, σ is a solidity defined as the fraction of the annular area in the control volume which is covered by blades.

When the axial induction factor becomes larger than approximately 0.4, the simple momentum theory breaks down. Equation 9 gives the Glauert correction for high values of the axial induction factor.

$$\begin{aligned} &\text{when}\quad a > a_c \\ &a = \frac{1}{2}[2+k(1-2a_c)] - \sqrt{[2+k(1-2a_c)]^2 + 4(ka_c^2-1)} \end{aligned} \quad (9)$$

Where:

$$k = \frac{4F\sin^2\phi}{\sigma C_n}, a_c \approx 0.2$$

In order to calculate the aerodynamic stiffness and aerodynamic damping, the following algorithm is applied.

- **Step 1:** Initialize a and b, typically a = b = 0
- **Step 2:** Compute ϕ and α using Eq. 5
- **Step 3:** Calculate $C_L(\alpha)$,$C_D(\alpha)$,

$$\frac{dC_L(\alpha)}{d\alpha}$$

and

$$\frac{dC_D(\alpha)}{d\alpha}$$

from the curve-fitting functions of C_L,C_D

- **Step 4:** Compute C_n and C_t from Eq. 7
- **Step 5:** Calculate F from Eq. 6
- **Step 6:** Calculate a and b from Eq. 8, when a becomes larger, compute a from Eq. 9
- **Step 7:** If a and b has changed more than a certain tolerance , go to step 2 or else finish
- **Step 8:** Compute the aerodynamic force and aerodynamic torque based on Eq. 3 and 4

THE ALGORITHM OF THE AEROELASTICIY OF THE WIND TURBINE BLADE AIRFOIL

Considering Eq. 2 with damping, the four-order Runge-Kutta method can be utilized to calculate the aeroelastic responses of wind turbine blade. Let $y_1=\theta$, $y_2=\dot{\theta}$, $y_3 = x$, $y_4=\dot{x}$. Therefore, the first-order equation and the following order equation are seen as Eq. 5.

$$\begin{aligned} &y_1{}'=y_2 \\ &y_2{}' = \ddot{\theta} = \frac{M + esy_3 - (k+e^2s)y_1 - C_1y_2}{J_0} \\ &y_3'=y_4 \\ &y_4{}'=\ddot{x}=\frac{F\text{-}sy_3 - (S_{21}-es)y_1 - C_2y_4}{m} \\ &y_{1,n+1} = y_{1,n} + \frac{1}{6}(k_1+2k_2+2k_3+k_4) \\ &y_{2,n+1} = y_{2,n} + \frac{1}{6}(l_1+2l_2+2l_3+l_4) \\ &y_{3,n+1} = y_{3,n} + \frac{1}{6}(p_1+2p_2+2p_3+p_4) \\ &y_{4,n+1} = y_{4,n} + \frac{1}{6}(q_1+2q_2+2q_3+q_4) \end{aligned} \quad (10)$$

Where:

$$\begin{aligned} &k_1=hy_{2,n} \\ &l_1 = \frac{h}{J_0}[M_n + esy_{3,n} - (k+e^2s)y_{1,n} - C_1y_{2,n}] \\ &p_1 = hy_{4,n} \\ &q_1 = \frac{h}{m}[F_n - sy_{3,n} + esy_{1,n} - C_2y_{4,n}] \end{aligned} \quad (11)$$

$k_2, l_2, p_2, q_2, k_3, l_3, p_3, q_3, k_4, l_4, p_4, q_4$ are very similar to k_1, l_1, p_1, q_1, so they are omitted here.

If the tip speed ratio of the wind turbine blade under normal conditions is known, the aerodynamic stiffness and damping will be given. Before the initial moment, the blade stays stable. So the solution steps can be given as follows:

- **Step 1:** Initialize θ_0, $\dot{x}_0$ not be zeros at the same time
- **Step 2:** Compute the initial aerodynamic force and torque from Eq. 3
- **Step 3:** Calculate the new values of θ_1, $\dot{\theta}_1$, $\dot{x}_1$, x_1 at the next step from Eq. 10 and 11 by substituting the M_0 and F_0 into Eq. 1
- **Step 4:** Solve the new aerodynamic force and aerodynamic torque from Eq. 3
- **Step 5:** Repeat the (3) and (4) steps until the end condition was met
- **Step 6:** At last, the flap displacement and torsion angular displacement, the flap velocity and torsion angular velocity will be obtained

In order to solve the aeroelastic responses of the blade considering the viscous damping of structure, just substitute the Eq. 2 into the steps above for the Eq. 1. In addition, damping coefficients can be adjusted as required.

NUMERICAL SIMULATION AND RESULTS ANALYSIS

Parameters of the airfoil: The FX77-W-153 airfoil type will be applied in order to show the aeroelastic responses of the wind turbine blade without damping and with damping. The lift coefficient and the drag coefficients can be derived from software, their functions of angle of attack can be curve-fitted, so their derivatives can also be calculated correspondingly.

The structural parameters and the section parameters of Airfoil FX77-W-153 are as: elastic modulus = 22 GPa, shear modulus = 8.27 GPa, air density = 1.225 kg m^{-3}, axial moment of inertia = 17453 cm^4, mean radius = 10 m, mass = 185 kg, chord = 1.073 m , section area = 1093.1 cm^2, polar moment of inertia = 676010 cm^4, torsional center in chordwise = 0.35c, angle of incidence = 1.63 deg, moment of inertia =11.492kgm^2.

Numerical simulation and analysis: According to the algorithms mentioned above, the aeroelastic responses of the airfoil will be calculated, as a result, the flap vibration and the torsional vibration, that is to say, the torsional angular displacement, velocity and acceleration, the flap displacement, velocity and acceleration, will be given without damping and with damping respectively. The stability of the blade airfoil can be easily obtained without damping and with damping, that is, the divergence, critical condition and convergence of the blade airfoil aeroelasticity.

When the aeroelastic responses of wind turbine blade airfoil under different tip speed ratios without damping are calculated, it can be easily seen that the responses of the torsional angular displacement converge, so torsional motion always keep stable and the torsional motion will not cause the flutter. As for the flap responses of the wind turbine blade, that is to say, the flap displacement, velocity and acceleration of blade, will show the complicated responses, such as the convergence, critical condition and the divergence. And the flutter region of the wind turbine blade which the flutter occur, the tip speed ratio, $\lambda\in(0.5, 2.6)$, will be obtained correspondingly. λ = 0.5 and λ = 2.6 are the lower and higher critical tip speed ratios respectively, under the lower critical tip speed ratio, the flap displacement response will change from convergence to divergence and under the hither critical tip speed ratio, the flap displacement response will change from divergence to convergence. That is why λ = 0.5 and λ = 2.6 are called the critical tip speed ratio.

When the structural viscous damping is introduced into the aeroelasticity of the wind turbine blade, it can be seen that the six responses change very obviously. In the following part, the controllable viscous damping coefficient of structure, C_1,C_2 will be fixed as 0.1 and 0.1 at the same time.

On one hand, the torsional responses converge and very similarly, so the torsional motion will not cause the flutter of the wind turbine blade, the same as the conditions without damping. Figure 2 shows the torsional angular displacement response when λ = 0.4 without

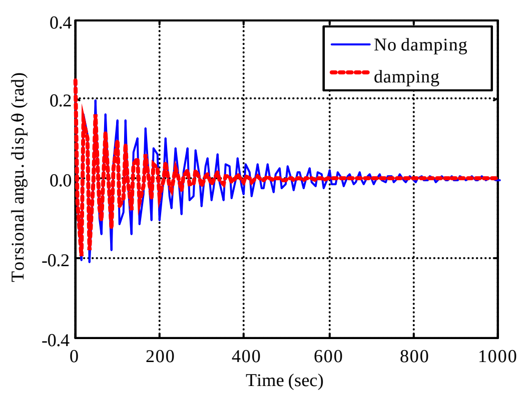

Fig. 2: The torsional angular displacement response when λ = 0.4

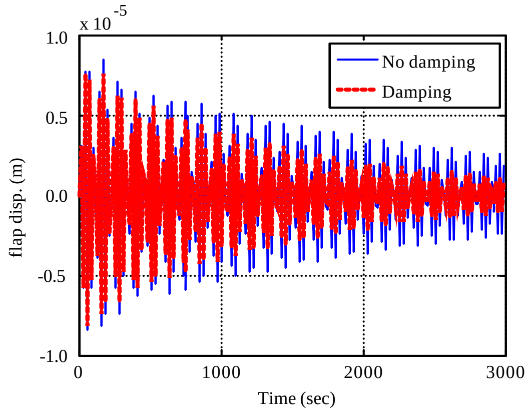

Fig. 3: The flap displacement response when λ = 0.4

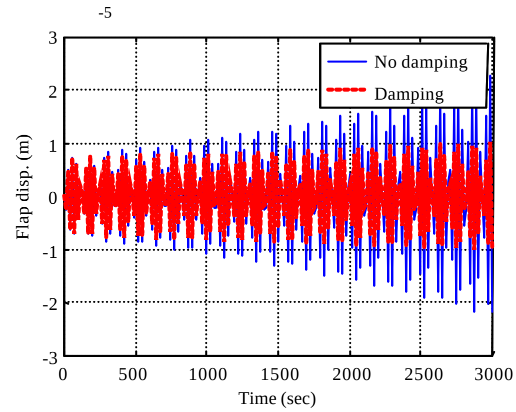

Fig. 5: The flap displacement response when λ = 0.6

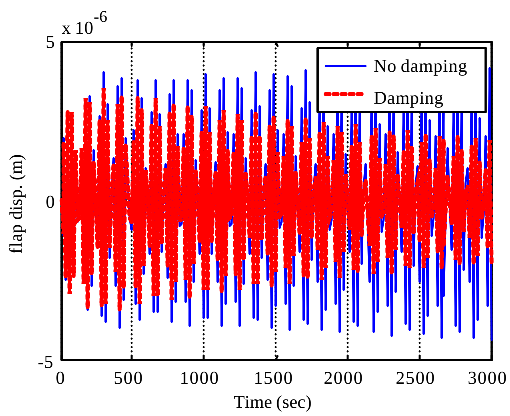

Fig. 4: The flap displacement response when λ = 0.5

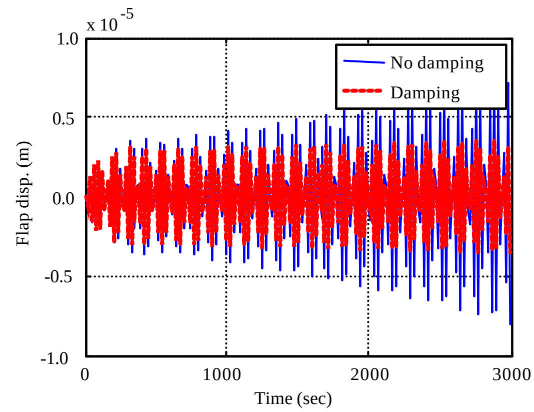

Fig. 6: The flap displacement response when λ = 2

damping and with damping. The torsional angular displacement with damping converges more quickly than that of the aeroelastic responses without damping. As the torsional angular velocity and accelertaion are very similar to the torsional angular displacement, their results are omitted. The flap motion response will be discussed in great detail. And because the flap displacement, flap velocity and flap acceleration show similar the changing treads, so the flap displacement will be treated in the following part.

On the other hand, although the flap motion shows complicated variations with the tip speed ratio changing, the introduced damping will suppress the flap responses, such as the flap displacement, velocity and the acceleration. Fig. 3 illustrates the flap displacement response when λ = 0.4. It can be seen the flap displacement converges without damping and the damping will cause the flap displacement converges more rapidly.

Figure 4 is the flap displacement response of the wind turbine blade when λ = 0.5 which is the lower critical tip speed ratio when there is no damping considered during the calculation of the blade aeroelasticity. When the viscous damping of structure is used, the flap displacement response will converge very obviously. So the critical tip speed ratio will change.

From the Fig. 5, the flap displacement response when the tip speed ratio is λ = 0.6. The response will diverge without damping, but when the damping coefficient is applied, the response will be critical, from λ = 0.6 on, the response will become divergent from convergence. So it can be seen that the lower critical tip speed ratio changes from 0.5 to 0.6 if the damping is considered in the wind turbine blade.

Figure 6 shows the flap displacement response of the wind turbine blade when λ = 2, Fig. 7 shows the flap displacement response of the wind turbine blade when λ = 2.6.

From Fig. 7, when the tip speed ratio is 2.6 which is the higher critical tip speed ratio, the aeroelatic condition will change from divergence to convergence without damping considered. However, when the viscous

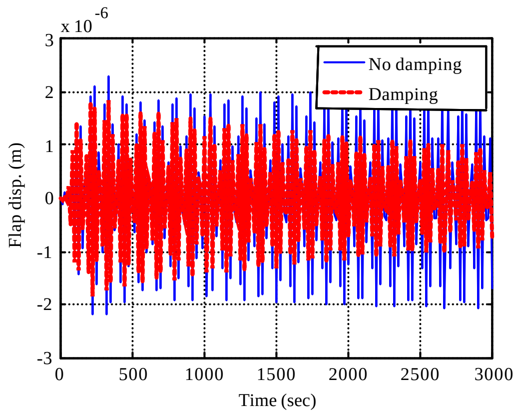

Fig. 7: The flap displacement response when λ = 2.6

damping is applied, the flap displacement response changes from critical condition to convergence. And from the Fig. 6, when the tip speed ratio is 2, the flap displacement response diverges and the flutter will occur, because that 2 is between the flutter region. When the damping is considered, the flap displacement response will become critical, for the response will become convergent from divergence. It can be easily seen that the higher critical tip speed ratio changes from 2.6 to 2 if the damping is considered in the wind turbine blade.

As a result, the flutter region when there is no damping, will be λ∈(0.5, 2.6). And the flutter region when there is damping, will be λ∈(0.6, 2) . That is to say, the flutter region will be shorten when the viscous damping of structure is applied. So the flutter will be controlled when the damping is added to the blade.

According to the time domain analysis of the wind turbine blade airfoil without damping and with damping respectively, the lower critical tip speed ratio without damping is 0.5 and the higher critical tip speed ratio is 2.6.When the damping coefficients are introduced, the lower critical tip speed ratio will be 0.6 and the higher critical tip speed ratio will be 2.0. Therefore, the flutter region will be shortened from λ∈(0.5, 2.6) to λ∈(0.5, 2.0) when the damping coefficients are applied. During the flutter region, the aeroelastic responses show that there are convergences as the tip speed ratio changes. That is to say, the flutter will occur.

What is more, when the viscous damping coefficients are increased, the flutter region will become much narrower than that of the smaller damping coefficients and even there is no flutter region at all when the damping coefficients become much larger. In the future, the flutter of the wind turbine blade will be suppressed or avoided easily if the structural viscous damping can be controlled.

CONCLUSION

In order to analyze the aeroelasticiy of the wind turbine blade, the differential equation of motion of the wind turbine blade was established, based on the viscous damping of structure. The Four-order Runge-Kutta numerical simulation method was used to solve the problem without damping and with damping. The time domain responses of flap and torsion motion were given correspondingly. There are similar changing treads when the tip speed ratio is changing. Compared with the aeroelastic responses without damping, there are also two critical tip speed ratios with damping. The flap motion plays a much more important role in the aeroelasticity of the wind turbine blade. There are two critical tip speed ratios, the lower critical tip speed ratio will become larger and the higher critical tip speed ratio will become smaller, as a result, the flutter region will be shorten when the viscous damping will be taken in account. And if the damping coefficients are increased, the flutter region will be controlled much more efficiently and even there is no flutter region at all when the damping coefficients become much larger.

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