Analysis on Blade of Wind Turbine System Load and Power of Tower Coupling System

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Abstract. The alternating load of aerodynamics, inertial force and elastic force of blade of wind turbine generator system can make elastic vibrator and tower generate coupling vibration to eliminate resonance. The paper takes the blade waving and bend of tower as an example. Firstly, the paper researches irrational tower and rotator wind wheel, and uses modal method to establish the operation equation of rotor hub and engine room tower. Then, the paper uses the deformation consistency condition of rotor hub tower system to couple the operation equation of rotor hub and engine room tower, for establishing complete operation formation of turbine rotor/tower system. Lastly, the paper introduces model coordinate to decouple coupled equations. The response curve the system is achieved. The stability of the system is analyzed, and the factors influencing the inherent frequency of the system is found out.

Introduction

Dynamics research of wind turbine generator system is to research the resonance and stability of the system. When the frequency of the external excitation force is the same with the inherent frequency of the system. Therefore, eliminating resonance needs to make the inherent frequency of the system avoid the frequency of the external excitation. The main content of researching the inherent frequency and response of the system ti to establish system model, which needs to write system parameters and operation status into mathematical model. And the coupling condition of rotor and tower is the most important.

In machinery design, the main purpose of researching elastic vibration problem is to avoid resonance. The machinery structure can be seen as multi-degree-of-freedom vibration system with many inherent frequencies. It is represented as many resonance regions in impedance test. The basic vibration feature of the structure for free vibration is called structural mode. Structural mode is determined by the feature of the structure and materials, and has no relationship with external load.

Establishment of Coordinate System

Figure 1 shows the coordinate system of establishing wind turbine system dynamic equation, and the definitions of the coordinate systems are as follows.

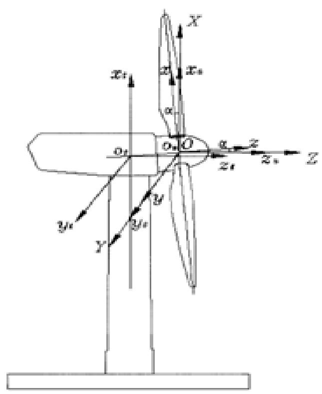

Fig1 The coordinate of wind turbine

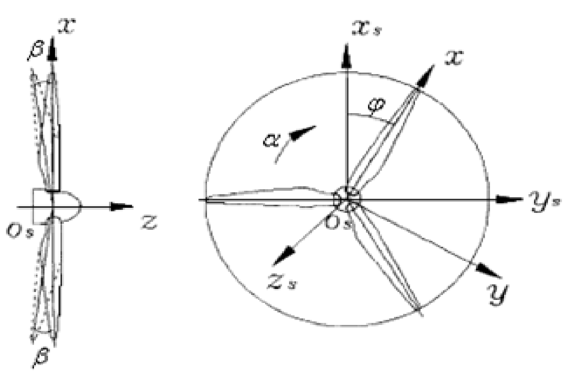

Fig2 The coordinate and elastic distortion of blade

When the hub doesn't move, the origin O of inertial coordinate system coincides with the inertial coordinate system. After the center of the hub translates for $q_x q_y q_z$, and reaches the origin O_s of the hub coordinate system, as shown in Figure 3, hub coordinate system doesn't rotate with the blades, and z_s axis is the rotation axis of rotor. The hub coordinate system rotates for α,φ,β angle, and becomes blade coordinate system. As shown in Figure 2, α is the inclination angle of rotation plane of wind wheel, β is the bending angle of blade, and φ is the azimuthal angle of blade rotating. When the balde is on the top of the wind wheel, the azimuthal angle of blade is 0°.

According to the above introduction, the total freedom degree of the system is:

Three displacements of the hub are q_x, q_y, q_z,

The blending angle of the blade is β.

The azimuthal angle of blade is $\varphi = \omega t$, ω is the rotating speed of wind wheel.

Elastic deformation of blade is r, s, u.

α,φ,β angle is rotated from inertial coordinate system to blade coordinate system, and the coordinate is transformed into

$$[i \;\; j \;\; k] = [I \;\; J \;\; K]T \tag{1}$$

$$T = T_\alpha T_\varphi T_\beta = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} = \begin{bmatrix} \cos\alpha\cos\varphi - \beta\sin\alpha & -\cos\alpha\sin\varphi & \sin\alpha + \beta\cos\alpha\cos\varphi \\ \sin\varphi & \cos\varphi & \beta\sin\varphi \\ -\sin\alpha\cos\varphi - \beta\cos\alpha & \sin\alpha\sin\varphi & \cos\alpha - \beta\sin\alpha\cos\varphi \end{bmatrix} \tag{2}$$

β angle is very small, the following simplification is applied in coordinate transformation, $\sin\beta \approx \beta, \cos\beta \approx 1$.

Establishment of Model

Motion equation of blade hub. (1) Energy expression of blade and hub. When lagrangian method is used to establish motion differential equation, the energy expression needs to be researched firstly. After the elastics of blade deforms, the place of any point x of the blade in inertial coordinate system is

$$R_1 = [I \;\; J \;\; K] \begin{bmatrix} X \\ Y \\ K \end{bmatrix} = [I \;\; J \;\; K] \begin{bmatrix} 0 \\ 0 \\ q_z \end{bmatrix} + [i \;\; j \;\; k] \begin{bmatrix} x \\ 0 \\ u \end{bmatrix} \tag{3}$$

The coordinate transformation formula (1) is introduced, and

$$R_1 = [I \;\; J \;\; K] \left\{ \begin{bmatrix} 0 \\ 0 \\ q_z \end{bmatrix} + T \begin{bmatrix} x \\ 0 \\ u \end{bmatrix} \right\} \tag{4}$$

The velocity vector of any point x of the blade at R_1 is

$$V_1 = \dot{R}_1 = [I \;\; J \;\; K] \left\{ \begin{bmatrix} 0 \\ 0 \\ \dot{q}_z \end{bmatrix} + \dot{T} \begin{bmatrix} x \\ 0 \\ u \end{bmatrix} + T \begin{bmatrix} x \\ 0 \\ \dot{u} \end{bmatrix} \right\} \tag{5}$$

The coordinate of hub center under inertial coordinate system is

$$R_2 = \begin{bmatrix} I & J & K \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ q_z \end{bmatrix} \tag{6}$$

The velocity vector is

$$V_2 = \dot{R}_2 = \begin{bmatrix} I & J & K \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \dot{q}_z \end{bmatrix} \tag{7}$$

The torsion of blades is not computed, the reason for which is that the torsional stiffness of blade is large, and the torque has little influence on researching the freedom degree of wind wheel rotor/tower system. The torsion generated by inertia is not computed. The blades are seen as elastic beam of quality on elastic axis. In view of the model, the kinetic energy of the single blade is

$$\begin{aligned} T_1 &= \frac{1}{2} V_1^2 \int_0^l m dx = \frac{1}{2} \dot{q}_z^2 \int_0^l m dx + \frac{1}{2} \dot{u}^2 \int_0^l m dx + \frac{1}{2} \int_0^l \begin{bmatrix} x \\ 0 \\ u \end{bmatrix}^T \dot{T}_a^T \dot{T}_a \begin{bmatrix} x \\ 0 \\ u \end{bmatrix} m dx \\ &+ \begin{bmatrix} 0 & 0 & \dot{q}_z \end{bmatrix} \left\{ \dot{T}_a \begin{bmatrix} x \\ 0 \\ u \end{bmatrix} \int_0^l m dx + T_a \begin{bmatrix} x \\ 0 \\ \dot{u} \end{bmatrix} \int_0^l m dx \right\} + \int_0^l \begin{bmatrix} x \\ 0 \\ u \end{bmatrix}^T \dot{T}_a^T T_a \begin{bmatrix} x \\ 0 \\ \dot{u} \end{bmatrix} m dx \end{aligned} \tag{8}$$

l is the length of blade, m is the quality of the quality of per unit blade length. The matrix transformation formula (2) is substituted into formula (8), which can achieve the kinetic expression of single blade

$$\begin{aligned} T_1 &= \frac{1}{2} \dot{q}_z^2 \int_0^l m dx + \frac{1}{2} \dot{u}^2 \int_0^l m dx + \frac{1}{2} (2\dot{\beta}^2 \cos^2 \varphi + \dot{\varphi}^2 \sin^2 \varphi) \int_0^l x^2 m dx \\ &+ \frac{1}{2} \dot{\beta}^2 \int_0^l u^2 m dx + \dot{\beta} \dot{\varphi} \sin \varphi \int_0^l u x m dx \\ &+ (\dot{\varphi} \sin \alpha \sin \varphi + \dot{\beta} \cos \alpha \cos \varphi - \dot{\varphi} \beta \cos \alpha \sin \varphi) \dot{q}_z \int_0^l x m dx \\ &+ \dot{\beta} \sin \alpha \dot{q}_z \int_0^l u m dx + (\cos \alpha + \beta \sin \alpha) \dot{q}_z \dot{u} \int_0^l m dx + \dot{\beta} \dot{u} \cos \varphi \int_0^l x m dx \end{aligned} \tag{9}$$

$M_1 = \int_0^l m dx$ is the mass of single blade.

$S = \int_0^l x m dx$ is the mass element of single blade.

$I = \int_0^l x^2 m dx$ is the rotary inertia of single blade.

$\omega = \dot{\varphi}$ is the revolving speed of wind wheel.

(2) Motion equation without aerodynamic force

For complicated constraint system, it has great advantages to use lagrange equation to establish oscillatory differential equation of the system, the reason for which is that it starts from the totality of the system, and uses the dynamics, potential energy and work under general coordinate to describe the relationship between exercise and acting force without considering the vector of detached body. Under the condition with dynamics, elastic energy and dissipation energy, lagrange equation can be used to establish the motion equation of the model.

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}_n}\right) - \left(\frac{\partial T}{\partial x_n}\right) + \left(\frac{\partial U}{\partial x_n}\right) + \left(\frac{\partial V}{\partial x_n}\right) = Q_n \tag{10}$$

x_n means the generalized coordinates, q_z●β●u , and Q_n corresponds to the generalized coordinate, Q_z●Q_β●Q_u . Expanding the equation can get

(3) Computation of generalized aerodynamic load

The computation of pneumatic thrust can make integral computation according to the following formula.

$$\begin{aligned}&(3M_1+M_2)\ddot{q}_z+3S\ddot{\beta}\cos\alpha\cos\varphi+3M_1\ddot{u}\cos\alpha-6S\omega\dot{\beta}\cos\alpha\sin\varphi\\&-3S\omega^2\beta\cos\alpha\cos\varphi+3S\omega^2\sin\alpha\cos\varphi=Q_z\end{aligned}\tag{11}$$

$$3M_1\ddot{q}_z\cos\alpha+3S\ddot{\beta}\cos\varphi+3M_1\ddot{u}-(6S\omega\sin\varphi+\frac{3}{2}M_1)\dot{\beta}+3\frac{k_b}{l}u=Q_u\tag{12}$$

$$F=\int_0^l B\rho cV_0^2C_n dr\tag{13}$$

Computing the work of pneumatic thrust needs to get the velocity of blades. The velocity of blades is the difference of absolute velocity V_1 and incident velocity v_{in} of air. In inertial coordinate system, the velocity of blade is

$$\begin{aligned}V_{xd}&=V_1-\begin{bmatrix}I&J&K\end{bmatrix}\begin{bmatrix}0\\0\\-v_{in}\end{bmatrix}=V_1+\begin{bmatrix}I&J&K\end{bmatrix}\begin{bmatrix}0\\0\\v_{in}\end{bmatrix}\\&=\begin{bmatrix}I&J&K\end{bmatrix}\left\{\begin{bmatrix}0\\0\\\dot{q}_z+v_{in}\end{bmatrix}+\dot{T}_a\begin{bmatrix}x\\0\\u\end{bmatrix}+T_a\begin{bmatrix}0\\0\\\dot{u}\end{bmatrix}\right\}\end{aligned}\tag{14}$$

Transforming the above formula into the blade coordinate system can get

$$V_{xd}=\begin{bmatrix}i&j&k\end{bmatrix}\left\{T_a^T\begin{bmatrix}0\\0\\\dot{q}_z+v_{in}\end{bmatrix}+T_a^T\dot{T}_a\begin{bmatrix}x\\0\\u\end{bmatrix}+T_a^TT_a\begin{bmatrix}0\\0\\\dot{u}\end{bmatrix}\right\}\tag{15}$$

Substituting thetransformation matrix formula (2) into the above formula can get. In relativistic velocity formula of blade, the incident velocity of air is $v_{in}=0$, and the expression of

$$\begin{cases}V_x=-\dot{q}_z\sin\alpha\cos\varphi+\beta\dot{q}_z\cos\alpha\cos\varphi-v_{in}\sin\alpha\cos\varphi+\beta v_{in}\cos\alpha\cos\varphi-u\dot{\beta}\cos\varphi\\V_y=\dot{q}_z\sin\alpha\sin\varphi-\beta\dot{q}_z\cos\alpha\sin\varphi+v_{in}\sin\alpha\sin\varphi-\beta v_{in}\cos\alpha\sin\varphi+u\dot{\beta}\sin\varphi+x\omega\\V_z=\dot{q}_z\cos\alpha+\beta\dot{q}_z\sin\alpha+v_{in}\cos\alpha+\beta v_{in}\sin\alpha+x\dot{\beta}\cos\varphi+\dot{u}\end{cases}\tag{16}$$

lastic deformation velocity is as follows.

$$\begin{cases}V_{xe}=-\dot{q}_z\sin\alpha\cos\varphi+\beta\dot{q}_z\cos\alpha\cos\varphi-u\dot{\beta}\cos\varphi\\V_{ye}=\dot{q}_z\sin\alpha\sin\varphi-\beta\dot{q}_z\cos\alpha\sin\varphi+u\dot{\beta}\sin\varphi+x\omega\\V_{ze}=\dot{q}_z\cos\alpha+\beta\dot{q}_z\sin\alpha+x\dot{\beta}\cos\varphi+\dot{u}\end{cases}\tag{17}$$

The work of pneumatic thrust in elastic deformation of blade is expressed as

$$\delta W=F\delta Z_e=FV_{ze}\delta t=F(\delta q_z\cos\alpha+\beta\delta q_z\sin\alpha+x\delta\beta\cos\varphi+\delta u)\tag{18}$$

Coupling equation of turbine rotors/tower system. With the consistence condition of hub deformation and tower cabin deformation, the rotor hub motion equation is combined with the motion equation of cabin tower, which can get the motion equation of turbine rotors/tower system.And the deformation consistence relationship of rotor tower system is established, which means to transform the deformation of cabin tower into inertial coordinate system from tower coordinate system.

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{Q\}\tag{19}$$

The tower coordinate system is transformed into inertial coordinate system

The displacement of cabin tower under inertial coordinate is w. From transformation formula (20), we can get $w = w_z + L$, which is substituted into formula (21) as follows.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x_t \\ y_t \\ z_t + L \end{bmatrix} \tag{20}$$

The cabin and hub is rigid connection, so $q_z = w_z$

$$\begin{aligned} &\frac{1}{12}M_3(a^2+b^2)\ddot{w}_z + \frac{1}{2}M_4(2R^2+t^2-2Rt)\ddot{w}_z + c_t\dot{w}_z + \frac{3\pi E}{256H^3}(2Rt-t^2)w_z \\ &= gS_zH + \frac{3\pi E}{256H^3}(2Rt-t^2)L \end{aligned} \tag{21}$$

Conclusions

The paper solves the mathematical model of turbine rotor/tower system, and get the characteristic root of the equation (the inherent frequency of the system) and the vibration condition of the system. And the rational simplification model is achieved by comparing with the calculation results of Bladed software. The achieved results are used to analyze the system, and it is judged if the system is stable. The established mathematical model is used to compute and analyze the dynamic stability of 1.5MW wind turbine system, and the kinetic feature of the design is verified. The inherent frequency of the system is achieved. The results show that there is not coincidence with 1-time frequency and 3-time frequency of turbine rotation frequency. However, when the rotor speed operates in the range of 9.6r/min-10r/min, it may coincide with the inherent frequency of the system. Therefore, the wind turbine system should not operate for long time in the range.

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