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The vibration analysis of wind turbine blade–cabin–tower coupling system

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ABSTRACT

Renewable energy sources especially wind energy have gained much attention due to the recent energy crisis and the urge to obtain clean energy. To maintain the wind turbine in operation healthily, implementation of condition monitoring system and fault detection system is necessary. In wind turbine condition monitoring, vibration analysis is a common and affective way to apply in the feature extraction and fault diagnosis, especially in the rotation parts. The blade–cabin–tower coupling system is analyzed in this paper. At first, the coordinate system and the kinetic equation are established. The tower natural frequency is calculated based on the coordinate system and the random following wind vibration is analyzed. In the end, the total wind force in blade–cabin–tower coupling system is solved.

0. Introduction

Renewable energy sources like wind energy are copiously available without any limitation. Reliability of wind turbine is critical to extract maximum amount of energy from the wind [1,2]. Wind turbines have different types in size or capacity, on the whole structure aspect they can be divided into two types: gearbox speed-increase type and directly driven type. The directly driven wind turbine does not contain speed-increase gearbox, its blades are connected to the generator through the wheel hub. Most wind turbines have upwind rotors that are actively yawed to preserve alignment with wind direction. The three-bladed rotor is the most popular and, typically, has a separate front bearing with a low speed shaft connected to a gearbox which provides an output speed suitable for a four-pole generator [3]. Fig. 1 shows the main structure of a common speed-increase gearbox wind turbine [4].

As shown in Fig. 1, the wind turbine is consisted of several components such as main bearing, gearbox, generator, wind meter, control cabinet, and revolving motor. The main structure of the wind turbine can be simplified as a blade–cabin–tower system on the whole. To maintain the wind turbine in operation healthily, implementation of condition monitoring system and fault detection system is important and for this purpose ample knowledge of these two types of systems is mandatory [5].

In wind turbine condition monitoring, vibration analysis is a common and effective way to be applied in the feature extraction and fault diagnosis, especially in the rotation parts [6–8]. When the wind turbine is running, the blade–cabin–tower system is under the non-stationary wind force and brings some non-stationary and non-Gaussian vibration, which will affect the driving chain especially the gearbox. Therefore, before the condition monitoring processing of the wind turbine, it is necessary to analyze the vibration characteristic of the turbine structure, especially the blade–cabin–tower system.

There is no paper deal with the whole wind turbine blade–cabin–tower system before [9–11]. Some papers have established the tower system or the cabin system separately. Some papers deal with the blades under air turbulent flow and proposed some conclusions. The application of the non-ideal model to the gear rattling dynamics has been presented in a recent paper [12–14]. However, when combine the blade, cabin and tower together, the condition is so complex and hard to establish the condition function, especially a non-ideal vibrating system when the excitation is influenced by response of the system. A wind turbine tower with an unbalanced non-ideal generator suffers the Sommerfeld effect of getting stuck at resonance (energy imparted to the generator being used to excite large amplitude motions of the supporting structure). There are few results on non-ideal vibrating systems in the current literature. Based on the above analysis, this paper introduced some parameters which can affect the vibration of the whole wind turbine and analyzed the coupling vibration of the blade–cabin–tower system.

The structure of this paper is as follows: Section 2 gives some basic coordinate systems for simplification. Section 3 calculates the kinetic equation of the wind turbine tower and gives some results. The tower natural frequency is calculated in the 4th

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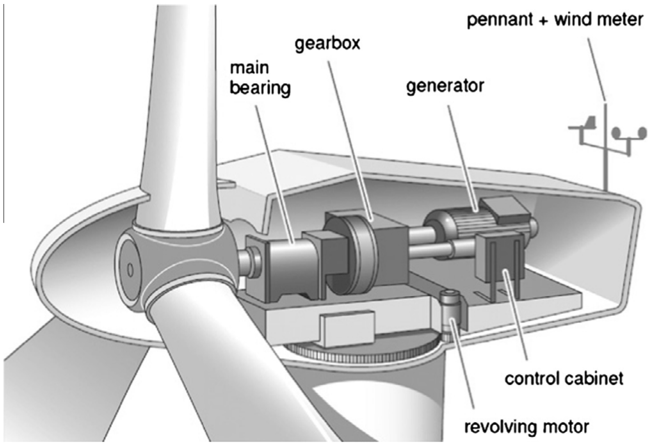

Fig. 1. Main structure map of the wind turbine system.

section. Section 5 discusses the simple and complex situation separately in order to analyze the random following wind vibration. Some conclusions are given in the last section.

1. Establish the necessary coordinate system

The coordinate system is important in the structure vibration analysis. The suitable coordinate can simplify the analyze process and reduce the calculation steps. Before the structure of the wind turbine, it is necessary to establish some important coordinate systems. According to the needs of the analysis and the structure of the wind turbine, this paper established 4 main coordinate systems, as shown in Fig. 2. The wind turbine is simplified as a blade–cabin–tower system. Some other structures such as wind indicator, handrail, or other additional parts outside the cabin are cut off in the analysis.

As shown in Fig. 2, there are mainly 4 coordinate systems have been established:

Inertial coordinate system $R_0(O_0x_0y_0z_0)$. The origin of coordinate O_0 is located in the center of the tower root, and the base vector is $[i_0j_0k_0]^T$.

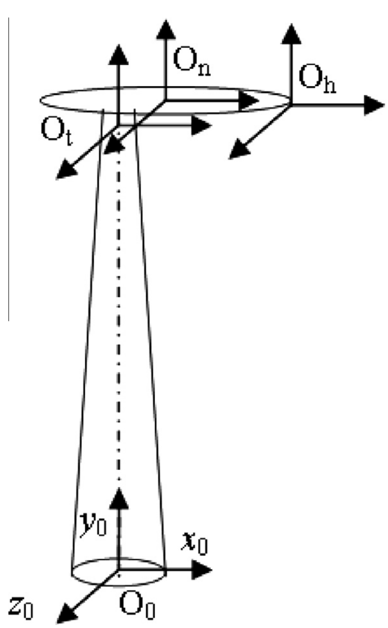

Fig. 2. Coordinate system of the wind turbine kinetic equation.

Tower coordinate system $R_t(O_tx_ty_tz_t)$. This system is fixed on the tower intersecting surface and its origin point O_t is in the center of joint face of cabin and tower, i.e., the tower top center. Its base vector is $[i_tcj_tk_t]^T$.

Cabin coordinate system $R_n(O_nx_ny_nz_n)$. This system is fixed on the cabin and its origin point O_n is located on the cabin barycenter, and z_n is perpendicular to the intersecting surface of the tower top. Its base vector is $[i_nj_nk_n]^T$.

Rotate coordinate system $R_h(O_hx_hy_hz_h)$. The origin of coordinate O_h is located in the center of the blade-hub system. This system rotates around y_n axis in the cabin coordinate system, in the angular velocity of Ω. Its base vector is $[i_hj_hk_h]^T$.

2. Kinetic equation of the tower

The tower kinetic equation is established in the inertial coordinate system $R_0(O_0x_0y_0z_0)$, and simplified as single degree of freedom (SDOF) system. This is the simplest idealized model and can be expressed as:

$$M\bar{y}(t) + C\dot{y}(t) + Ky(t) = P(t) \tag{1}$$

where M is the mass matrix of the tower unit, C is the resistance matrix, K is the stiffness matrix, $y(t)$ is the displacement vector of tower, $P(t)$ is the outside force.

Divided by M of the both side in Eq. (1), it can be changed into standard form:

$$\bar{y}(t) + 2\zeta_1\omega_1\dot{y}(t) + \omega_1^2 y(t) = F(t) \tag{2}$$

where $\omega_1 = \sqrt{\frac{K}{M}},\ \zeta_1 = \frac{C}{2\sqrt{KM}},\ F(t) = \frac{P(t)}{M}$.

Suppose the input force $F(t)$ is replace by pulse signal $F(t)\Delta t\delta(t-\tau)$ with continuous distribution, where $\delta(t-\tau)$ is the Dirac function and when $t = \tau$, $\delta(t) = \infty$ and $\int_{-\infty}^{\infty}\delta(t)dt = 1$. Then the response under $F(t)\Delta t\delta(t-\tau)$ is $F(t)\Delta th(t-\tau)$. The whole response of the system under every pulse can be calculated as

$$y(t) = \sum_{\tau=-\infty}^{t} F(t)\Delta\tau h(t-\tau)d\tau \tag{3}$$

When $\Delta\tau \to d\tau$,

$$y(t) = \int_{-\infty}^{\infty} F(\tau)h(t-\tau)d\tau \tag{4}$$

Generally, when $t < 0$, $F(t) = 0$, then

$$y(t) = \int_0^t F(\tau)h(t-\tau)d\tau \tag{5}$$

We can obtain the vibration function of the infinite degrees of freedom

$$m(z)\frac{\partial^2 y}{\partial t^2} + C\frac{\partial^2}{\partial t\partial z}\left[I(z)\frac{\partial^2 y}{\partial z^2}\right] + \frac{\partial^2}{\partial z^2}\left[EI(z)\frac{\partial^2 y}{\partial z^2}\right] = p(z,t) \tag{6}$$

Suppose the displacement is divided under vibration mode as

$$y(z,t) = \sum_{i=1}^{\infty} q_i(t)\varphi_i(z) \tag{7}$$

Then the function of generalized coordinate $q_i(t)$ can be obtained

$$\ddot{q}_j + 2\zeta_j\dot{q}_j + \omega_j^2 q_j = \frac{P_j^*(t)}{M_j^*} - F_j(t) \tag{8}$$

where $M_j^* = \int m(z)\varphi_j^2(z)dz,\ P_j^*(t) = \int p(z,t)\varphi_j(z)dz$.