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The inherent characteristics and vibration response analysis of 10KW small wind turbine tower

Yongzhi Xie[1, a], Lieping Zhang [1,b]

the Guang Xi Key Laboratory of New Energy and Building Energy Saving, Guilin University of Technology, Guilin, China, 541004;

[a]308530905@qq.com,[b]25761108@qq.com

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Abstract: The discrete structural dynamics equation is established for small wind turbine tower by means of Hamilton principle and the generalized displacement method, and the calculation model of natural mode, vibration mode and dynamic response of the wind turbine is also given. Four order natural frequency, corresponding vibration mode and the characteristics of vibration response on Wind turbine tower is simulated under the action of random wind. Research shows that, this will provide the basis for vibration control on the tower in the future .

Introduction

The deformation and vibration of the tower structure, not only influences the structure strength, but also affects its performance. Therefore, in the design of wind turbine, two problems of the wind tower system structure dynamics caused by the wind power must be analyzed: One is the analysis of the inherent characteristics of tower structure, namely the calculation of natural frequency and vibration model; the second is analysis and calculation of the tower structure dynamic response[1]. The maximum stress distribution of the wind turbine is simulated by NieSonghui [2] and XuErtao [3], and the modal analysis of the wind turbine is completed by using ANSYS software. ZhangFenghao[4]have studied in the rotating centrifugal force, while the wind speed increases the natural frequency of the wind speed increased significantly, Ignoring the quality of cabin, a wind wheel and hub Zhou Bo [5] has studied the inherent characteristic of wind turbine tower and vibration response characteristics by means of ANSYS software. Those scholars use the ANSYS software to analyze the dynamic characteristics of the method, this paper uses the analytical method to analyze the dynamic characteristics, to get better results.

Dynamic modeling of tower

Small wind turbine tower is tapered cylinder, its quality, stiffness, damping are changing continuously along with varied m(x), EI (x),C(x).The wind wheel and the hub, the cabin were regarded as the mass block M. Using the principle of virtual work and energy integration in Hamilton, the continuous system is discredited by the generalized displacement method, and the degree of freedom is reduced to a finite value N. On this basis, the system's motion equation is established, and modal analysis and motion response analysis are carried out.

Firstly, the moving coordinate system is established, and the center of the bottom of the tower is the origin of the coordinates, and the direction of the vertical to the plane of the wind wheel is X, and the axis of the tower is Y.

The bending vibration of the tower was described by a known shape function (x). Assuming that the tower height is h, the top end of tower is arranged unit value, namely phi (h) = 1, horizontal displacement Y(t)of the tower was regarded as the generalized coordinates, The bending deformation of the tower can be expressed as:

$$y(x,t)=\varphi(\mathrm{x})Y(t) \tag{1}$$

The tower system of Kinetic energy T and potential V are respectively expressed as :

$$\mathrm{T}=0.5\int_0^h m(x)\left[\dot{y}(x,t)\right]^2 dx+0.5M\dot{Y}^2(t) \tag{2}$$

$$\mathrm{V}=0.5\int_0^h EI(x)\left[y''(x,t)\right]^2 dx \tag{3}$$

the work done by thrust F (t) caused by the wind wheel and the damping force are respectively expressed as W_1 and W_2

$$W_1=F(t)Y(t) \tag{4}$$

$$W_2=\int_0^h -c(x)\dot{y}(x,t)dx \tag{5}$$

The following formula is available by the Hamilton principle of non conservative system:

$$\begin{aligned}&\int_0^{t_1}[\int_0^h (m(x)\dot{y}(x,t)\delta\dot{y}(x,t)-EI(x)y''(x,t)\delta y''(x,t))dx+M\dot{Y}(t)\delta\dot{Y}]dt\\&+\int_0^{t_1}[\mathrm{F}(\mathrm{t})\delta\mathrm{Y}(\mathrm{t})\text{-}\int_0^h (c(x)\dot{y}(x,t))\delta y(x,t)dx]dt=0\end{aligned} \tag{6}$$

Where :

$$\dot{y}(x,t)=\partial y/,\qquad \dot{Y}(t)=\partial Y/,\qquad y''(x,t)=\partial^2 y/\,\dot{c},\qquad \varphi''(x)=\partial^2\varphi/\,\partial.$$

The following equation of motion of the tower system can be deduced by formula (6) simplified:

$$\left(\int_0^h \mathrm{m(x)dx\varphi(x)+M}\right)\mathrm{\ddot{Y}}+\int_0^h \mathrm{c(x)dx\varphi(x)\dot{Y}}+\int_0^h \mathrm{EI(x)dx\varphi^{(4)}(x)Y=F(t)} \tag{7}$$

Dynamic analysis of tower

Inherent characteristic analysis. For free vibration, there exist $\mathrm{F^*(t)}$=0, and the effect of neglecting damping, and when EI and m are constant, the equation (7) is changed:

$$\mathrm{(m\varphi^2(x)+M)\ddot{Y}(t)+EI\varphi^{(4)}(x)Y(t)=0}\text{或}\frac{\mathrm{\ddot{Y}(t)}}{\mathrm{Y(t)}}=-\frac{\mathrm{EI\varphi^{(4)}(x)}}{\mathrm{m\varphi^2(x)+M}} \tag{8}$$

The right is a function of x, the left is a function of t. In order to make the equation set up, it must be:

$$\frac{\mathrm{\ddot{Y}(t)}}{\mathrm{Y(t)}}=-\frac{\mathrm{EI\varphi^{(4)}(x)}}{\mathrm{m\varphi(x)+M}}=-\mathrm{a}^4 \tag{9}$$

Assuming $\omega = a^2$,The formula (9) is equivalent to two following ordinary differential equations.:

$$\ddot{Y}(t) + \omega^2 Y(t) = 0 \quad (10)$$

$$EI\varphi^{(4)}(x) - m\omega^2\varphi(x) - M\omega^2 = 0 \quad (11)$$

The general solution of the formula (10) is:

$$Y(t) = A_1\cos\omega t + A_2\sin\omega t \quad (12)$$

The constant A_1 , A_2 are determined by the initial conditions.

When both EI and m are known, at the same time, the following equations was acquired in accordance with the boundary conditions:

$$\varphi(0) = 0, \varphi'(0) = 0, \varphi''(h) = 0, \varphi'''(h) = 0 \quad (13)$$

The general solution of the formula (11)was calculated, and then substituted into equation (12), each order natural frequency of tower and corresponding vibration mode curve function phi (x) is obtained.

Vibration response analysis. When EI, C and m are constant, the vibration differential equation can be got according to the form (7):

$$(m\varphi(x) + M)\ddot{Y}(t) + c\varphi(x)\dot{Y}(t) + EI\varphi^{(4)}(x)Y(t) = F(t) \quad (14)$$

Wind wheel load.

The axial force F_B can be derived Based on the Bernoulli Equation and theorem of momentum [6]:

$$F_B = 2\rho_0 U_\infty^2 Aa(1-a) \quad (15)$$

Where: ρ_0 : air density, U_∞ : the infinity upstream flow velocity at the center of wind wheel, A: wind wheel swept area, a :axial induction factor, θ :angular velocity rotating around the center of gravity.

By the blade element theory, the axial force F_B is :

$$F_B = N[C_l\rho_0(\Omega r)^2 / (2\cos\lambda) + C_d\rho_0 U_d^2(1-a)^2 / (2\sin\lambda)] \quad (16)$$

Where: N: blade number, λ :inflow angle, C_l :lift coefficient, C_d :drag coefficient, Ω :rotational angular velocity of wind wheel, r: the distance between the blade element and the root of the blade, U_d : the wind speed on the wind wheel.

If you need to solve the wind wheel load, then you need to first apply the simultaneous formula (16) and (15), and then calculate by means of adoption of the iterative approach. the axial inducing factor of the corresponding section are solved according to the different blade element section torsion angle and the specific airfoil, substituted into equation (15), and the axial thrust of the cross section , i.e the wind wheel load $F(t)$ are gained.

Examples and results analysis

The part of the parameter of small wind turbine tower structure and working condition[7,8]are: the rated wind speed V_1 is 8m/s, power is 10kw, rotating speed of the wind wheel 130, and tower height H=16m, Segmented cone tower is divided into five sections, followed by 4m, 4m, 4m, 2.5m, 1.5m from the top along length, wall thickness of 30mm.The top surface of diameter is 350 mm, bottom diameter of 710 mm. Airfoil blade for naca4412, wind wheel of 10 m in diameter, leaf number n is 3, the air density ρ_0 is 1.225 kg/m^3 total weight of blades, hub and generator M is 480kg,m=5881kg，EI=3045KN·m^2.

According to the above data, the natural frequency of tower can be calculated as follows in Table 1:

Table 1 Natural frequency of the tower

Order	first	Second	Third	Fourth
frequency	0.52	3.42	5.1	5.5

Various order modal function:

$$\varphi(x) = C[\cos a_n x - \cosh a_n x + \frac{(\cos a_n h + \cosh a_n h)(\sinh a_n x - \sin a_n}{(\sinh a_n + \sin a_n)} \quad (17)$$

Where C is a constant, n=1,2,.

The first four order mode curves corresponding to formula (17) are shown in Figure 1:

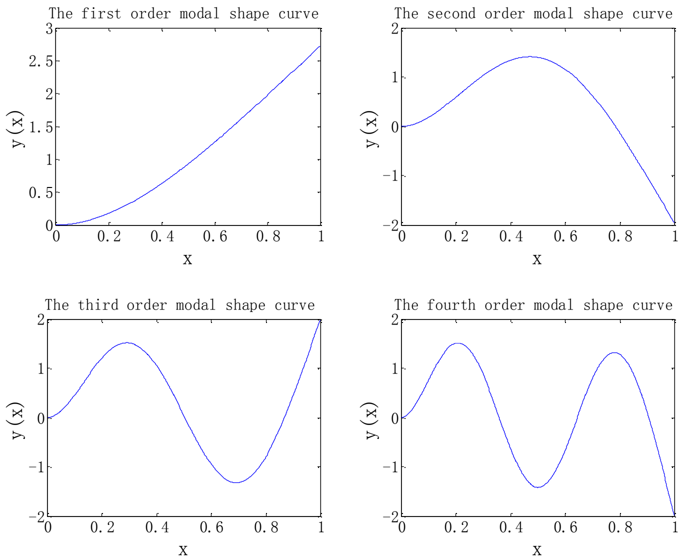
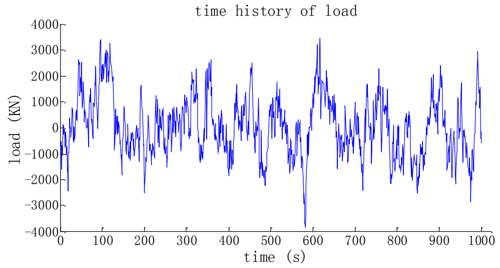


Fig 1 four order modal shape curve of tower



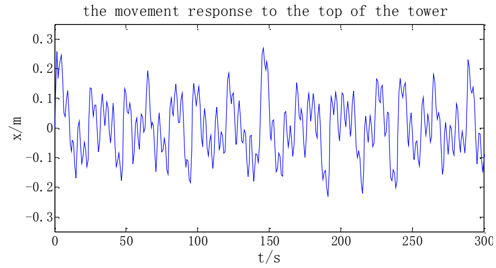


Fig.2 time history curve of the wind load Fig.3 response of the top of the tower

In this paper, the wind speed is 130r/min. According to the design standard, the natural frequency of the tower should be higher than the wind wheel blade passing frequency 20%. This example meets the requirements of the design standard from table 1。By the formula (15) and (16), the wind wheel load is obtained [9], as shown in Figure 2. This load will be substituted into the formula (14), vibration response can be obtained at the top of the tower, as shown in figure 3.We can see from Figure 4, the maximum amplitude at the top of the tower reaches 0.3m, and thus it is necessary for vibration control to ensure the security of the tower.

Conclusions

Taking 10KW small wind turbine as the research object, the model of random wind load is obtained by using the blade element momentum theory. According to Hamilton principle, the dynamic equations of the wind turbine structure are established. The dynamic analysis and structure vibration simulation of the 10kW wind turbine can be completed. Dynamic characteristics, such as displacement, velocity, acceleration and vibration mode, can be used to provide a basis for further vibration control of the wind turbine.

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