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Based on Theory of Random Wind Load Wind Turbine Transmission System Structure Reliability Analysis

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Abstract

As structure wind turbine is influenced by wind load in the run, and property of wind load is strong randomness which is a great influence on the reliable operation. In this paper, the theory of random vibration analysis is applied to analysis of the wind load and calculation of wind turbine. Mathematics method of wind load analytic calculation is detailed discussed, meanwhile simulating method of the structure is combined, which is applied for simulation analysis of wind turbine transmission system. Combining result of numerical simulation and in actual working condition, We can thought it value that analysis method can be used for engineering application and it is put forward that new analysis thought of wind load.

Keywords: *Random, Wind Load, Transmission System, Reliability, Wind Turbine*

1. Introduction

In recent years, many experts and scholars at home and abroad has carried on further research of the wind turbine transmission system. For example, building nonlinear dynamic model of the gear - drive shaft - body system coupled with multi-gear transmission of large wind turbine, and studying on the dynamic characteristics of the coupling system [1]; building multi-gear contact finite element model of large wind turbine transmission system, put forward calculation method that the actual contact gear pair, distributed gear load in the process of inside and outside gear pair meshing [1]; building and putting forward analysis method of planetary gear system kinetic model in variable load excitation [2]. These methods is built based on steady or very small change outside environment, actually transmission system of wind turbine is affected by external environment and by wind load obviously [2]. It is considered that external wind load affects wind turbine, and should be certain engineering value for research on running reliability of the whole wind turbine and transmission system.

2. Wind Load Randomness Vibration Analysis

2.1 Random Process

As structure, intensity of wind load which is one of wind turbine load always changes with time. Characteristics of wind load are that not only changes complicatedly with time but also load waveform don't show same style in two time. It is exhibit complex and changes with time not only waveform of wind load but also frequency and duration. As a random process, random vibration can be not a function of time t, but it used to be function of spatial coordinate.

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Even in the same environment, it total impossible to be predict that the actual waveform generated, but it is occurred by Probability. Sample function may be produced in the condition of each waveform. Random vibration of non-deterministic phenomena is to be solved by analyzing the actual function of statistics.

2.2. Wind Load Stationary Random Process and Continuity

When it is provided that all actual sample function of wind load random process $x(t_1)$, $x(t_2)$, ...,$x(t_n)$, or when it is provided that total probability density function and probability density function, these statistics should be solved. Of course, complex stochastic processes of wind load cannot explain fully by only these statistics used. It is the most important and the most basic random process that stationary random process. In the actual wind power project, It is simulated by stationary stochastic process that many phenomenon is controlled by the probability.

When all statistics x (t) in random process does not change with time, it is known as strictly stationary random process. Therefore, n time of x (t) probability density function should satisfy:

$$f(x_1, x_2, \cdots, x_{n,}) = f(x_{1+r}, x_{2+r}, \cdots, x_{n+r}) \tag{2.1}$$

Based on probabilistic basic formula, mathematical expectation of x_1 are as follows:

$$\mathrm{E}[x(t_1)] = \int_{-\infty}^{\infty} x_1 f(x_1) dx_1 = \lim_{n\to\infty} \frac{1}{n} \sum_{k=1}^{n} x_k(t_1) \tag{2.2}$$

So the meaning of x_1 and $x(t_1)$ in equation (2.2) is consistent, namely $x_{1+r}=x(t_{1+r})$.

According to equation $f(x_1, x_2, \cdots, x_n) = f(x_{1+r}, x_{2+r}, \cdots, x_{n+r})$, the probability density function of $x(t)$ as follows: $f(x_1) = f(x_{1+r})$. because it is right for each r, the $f(x_1)$ has nothing to time t. So it can be showed $f(x_1) = f(x)$, equation $E[x(t)] = \int_{-\infty}^{\infty} x f(x) dx =$ constant.

Meantime wind load as two-dimensional distribution of random process x_1, x_2, the quadratic probability density function is:

$$f(x_1, x_2) = f(x_{1+r}, x_{2+r}) \tag{2.3}$$

In project, in addition to the strictly stationarity above, when $x(t)$ only satisfy equation (2.1) and (2.3), it is known as stationary random process. Except it is noted in engineering project, which is to satisfy equation (2.1) and (2.3) is known as stationary random process.

2.3. Random Gauss Process

Random process n times of x (t) probability density function obey laws of gauss distribution, x (t) is called as a gauss random process. That is: $x_1 = x(t_1), x_2 = x(t_2), \cdots, x_n = x(t_n)$

And probability density function is given:

$$f(x_1, x_2, \cdots, x_n) = \frac{1}{(2\pi)^{n/2} |S|^{1/2}} \exp\left[-\frac{1}{2|S|} \sum_{j=1}^{n} \sum_{k=1}^{n} |S|_{jk} \times (x_j - E[x_j])(x_k - E[x_k]) \right] \tag{2.4}$$

$|S|$ in the equation is determinant of the covariance matrix as follow:

$$S=\begin{bmatrix} \sigma_{x_1}^2, & k_{x_1x_2}, & k_{x_1x_3}, & \cdots & k_{x_1x_n} \\ k_{x_{21}x_1}, & \sigma_{x_2}^2, & k_{x_2x_3}, & \cdots & k_{x_2x_n}, \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ k_{x_nx_1}, & k_{x_nx_2}, & k_{x_nx_3}, & \cdots & \sigma_{x_n}^2, \end{bmatrix} \tag{2.5}$$

When n=2, equation (2.5) is:

$$f(x_1,x_2)=\frac{1}{\sqrt{2\pi}\sigma_{x_1}\sigma_{x_2}\sqrt{1-\rho_{12}^2}}\exp\left\{-\frac{1}{2(1-\rho_{12}^2)}\left[\frac{(x_1-E[x_1])^2}{\sigma_{x_1}^2}-\frac{2\rho_{12}(x_1-E[x_1])(x_2-E[x_2])}{\sigma_{x_1}\sigma_{x_2}}\right]+\frac{(x_2-E[x_2])^2}{\sigma_{x_2}^2}\right\} \tag{2.6}$$

in equation

$$\rho_{12}=\frac{k_{x_1x_2}}{\sigma_{x_1}\sigma_{x_2}}=\frac{R_x(t_1,t_2)-E[x(t_1)]E[x(t_2)]}{\sigma_{x_1}\sigma_{x_2}} \tag{2.7}$$

ρ_{12} is correlation coefficient of $x(t_1)$ and $x(t_2)$x (t1).

3. Single Degree of Freedom System Vibration Analysis

When structure is applied by external force and it can be regarded as random process, the dynamic analysis method is called random vibration theory. Change of wind load, because of its non repetitive, is shown as random process, and that grasping reaction of wind turbine structure system is reliable safety method of Quantitative evaluating structure.

Originally, it is regarded as limited duration problem that vibration response of wind turbine for wind load, so it should be considered to non stationary random process. But the actual aim is different, we can consider it as stationary random process. in addition, when static wind turbine start running, especially in the initial stage of the movement, we can serve it as a non-stationary random process for analyzing.

Random vibration theory can be divided into two types. one is that considering the structure material and mechanical properties of nonlinear, large deformation effects vibration analysis, the other is that considering idealized linear vibration analysis. In addition, structure itself also can't be considered as random structure if statistical properties of structures is considered.

Random vibration is most important that evaluating reliability problem of the dynamic load. When structure is designed and reliability is considered, boundary limited and deform should be defined. For example, when wind turbine structure stress exceeds allowable stress. From angle of reliability, it should be thought that wind turbine has entered into a dangerous range. When solving problem of dynamic load by applying random vibration theory, we think that it more high that reaction value it more safe that wind turbine runs in entire duration. If the numerical value of probability has been obtained, we can think it as quantitative evaluation of reliability. it is called random damage problem when reaction value is higher than limited value, and we think it as criterion. In theory, it is problem of first time misregistration probability. It is not considered that elasto-plastic properties, accumulation fatigue, strength degradation of wind turbine, but because of providing the more important problem of dynamic reliability theory.

3.1. Single Degree of Freedom System Vibration

For single degree of freedom, particle-spring system can be illustrated by the following equation:

$$m\ddot{x} + c\dot{x} + kx = g(x) \tag{3.1}$$

$$x(t) = z(t) - y(t) \tag{3.2}$$

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{y}(t) \tag{3.3}$$

In equation, m= quality, c= viscous damping coefficient, k=spring constant. motion equation of particle displacement *x*(t) is shown when particle m is disturbed by external force g(T). meanwhile motion equation of foundation displacement x(t) in absolute coordinate *z*(t) and relative displacement *x*(t) is shown as equation (3.2).

The single degree of freedom system vibration model is that changes the most complex structure into the simple idealization model, it will become the basis of multi degree of freedom system vibration analysis.

Equation (3.1) and (3.2) is transformed into a standard form:

$$\ddot{x} + 2\beta\omega_0\dot{x} + \omega_0^2 x = f(x) = \begin{cases} g(t)/m \\ \text{或} \\ -\ddot{y}(t) \end{cases} \tag{3.3}$$

In equation: ω_0 =single degree of freedom intrinsic circular frequency; β =damping ratio; $\omega_0 = \sqrt{k/m}$ ； $\beta = c/2\sqrt{mk}$

If on initial condition $x(0) = \dot{x}(0) = 0$,we can solve:

$$x(t) = \int_0^t h(t-\xi) f(\xi) d\xi \tag{3.4}$$

In equation:

$$\left.\begin{aligned} h(t) &= \frac{e^{-\beta\omega_0 t}}{\overline{\omega_0}} \sin \overline{\omega_0} t; \quad t \geq 0 \\ &= 0; t < 0 \end{aligned}\right\} \tag{3.5}$$

Studying on harmonic motion condition of the damping ratio $0 \leq \beta < 1$. wind load disturbance *f*(t) is considered as absolute value 1 of instantaneous force when $t=t_0$ .That is,

$$f(t) = \delta(t - t_0) \tag{3.6}$$

Substitute it into equation (2.4)

$$\begin{aligned} x(t) &= \int_0^t h(t-\xi)\delta(\xi - t_0) d\xi = h(t - t_0) \\ &\left.\begin{aligned} &= \frac{e^{-\beta\omega_0(t-t_0)}}{\overline{\omega_0}} \sin \overline{\omega_0}(t - t_0); \quad t \geq t_0 \\ &= 0; \quad t < t_0 \end{aligned}\right\} \end{aligned} \tag{3.7}$$

Therefore, physical significance of function h(t) is reaction displacement $h(t-t_0)$ in single degree of freedom system when surging force $\delta(t-t_0)$ in t=t_0, it is called unit impulse reaction function.

Secondly, we research on wind load disturbing as stationary harmonic function. Suppose $f(t)=e^{i\omega t}$, $x(t)=H(\omega)e^{i\omega t}$,substitute it into (2.3)

$$H(\omega)=\frac{1}{\omega_0^2-\omega^2+i2\beta\omega_0\omega} \tag{3.8}$$

$H(\omega)$ is called wind turbine (transmission) system frequency reaction function or (transmission) system transfer function. in other word, it is displacement reaction of wind load input f(t).

3.2. Random Vibration Analysis

Considering input of equation (3.3), wind load disturbance $f(t)$, as stochastic process. At this time, $f(t)$ is not all sampling function, but should be regarded as collection of functions. For reaction x(t) of input is meaning and becomes random process.

Suppose $f(t)$ is

$$f(t)=g(t)f_s(t) \tag{3.9}$$

$g(t)$ is non-stationary confirm function, $f_s(t)$ is stationary random process. When $g(t)\neq$ constant, $f(t)$ is non-stationary random process. As $f(t)$ is represented by equation (3.9), it is used to mathematical model of wind load vibration and its frequency component distribution proportion of power spectral density is nothing to time t.

If we take solution of equation (3.3), expected value of equation (3.4) is

$$E[x(t)]=\int_0^t h(t-\xi)E[f(\xi)]d\xi \tag{3.10}$$

If $E[f(\xi)]=0$, reaction expected value $E[x(t)]$ will be 0.

On the basis of equation (3.4)

$$x(t_1)x(t_2)=\int_0^{t_1}\int_0^{t_2} h(t_1-\xi_1)h(t_2-\xi_2)f(\xi_1)f(\xi_2)d\xi_1 d\xi_2 \tag{3.11}$$

Solution will be given, in fact expected value of wind load two-dimension steady random mathematic is

$$E[x(t_1)x(t_2)]=\int_0^{t_1}\int_0^{t_2} h(t_1-\xi_1)h(t_2-\xi_2)E[f(\xi_1)f(\xi_2)]d\xi_1 d\xi_2 \tag{3.12}$$

And working out two-dimension random probability of wind load is

$$R_x(t_1,t_2)=\int_0^{t_1}\int_0^{t_2} h(t_1-\xi_1)h(t_2-\xi_2)E[f(\xi_1)f(\xi_2)]d\xi_1 d\xi_2 \tag{3.13}$$

4. Multi-Degree of Freedom System Linear Reaction Analysis

In order to infer dynamic properties of wind turbine structure by using analysis method, wind turbine structure is needed to be modeled when it analyzed. Now, it is aim to analyze mechanical behavior of wind load in wind turbine, so wind turbine model and displacement should be linked up. Due to analysis result calculated under ideal conditions, if its result is correct or not will depend on whether ideal model is appropriate.

In order to model wind turbine, at first, according to mechanical property component must be divided into elastomer, rigid body, viscoelastic body, elastic plastic body, visco-elasticity plastic body and it must be defined clearly. After structure is divided into several units and each unit is defined, force transfer mechanism is simplified and component is regard as which rod piece, board or stereo. Binding condition and boundary conditions between components is given boundary conditions, then mechanical model of wind turbine structure of wind turbine is completed. The mechanical model of wind load system given is analyzed. we can deduce dynamic phenomenon of wind turbine.

Wind turbine structure is modeled for arbitrary shape system, and linear matrix method is used. Therefore, wind turbine structure should be assumed as the following aspects:

(1) Linear elastic body

(2) Replace wind turbine into finite partial-spring system, and act inertia force on one partial only.

When this kind of problem is defined, for the structure mechanical model, line-surface equation is established.

$$P = KU\text{或}\begin{Bmatrix} P_1 \\ \cdots \\ P_i \\ \cdots \end{Bmatrix} = [K]\begin{Bmatrix} U_1 \\ \cdots \\ U_i \\ \cdots \end{Bmatrix} \tag{4.1}$$

In equation, P is external force vector, U is displacement vector, K is stiffness matrix.

In the case of three-dimensional structure, in each node, external force vector P is composed of 6 components. External force Pi of node *i* is

$$P_i = \begin{Bmatrix} X \\ Y \\ Z \\ M_x \\ M_y \\ M_z \end{Bmatrix} \tag{4.2}$$

In equation, X, Y, Z is absolute coordinate system (x, y, z), direction force of x, y, z. M_x, M_y, M_z are torque of around *x, y, z* axis.

Similarly, displacement vector U of node i is

$$U_i = \begin{Bmatrix} u_x \\ u_y \\ u_z \\ \theta_x \\ \theta_y \\ \theta_z \end{Bmatrix} \tag{4.3}$$

Analysis method of random vibration theory applies on the condition of usual final conclusion. Extend in meaning, That studying on node force P_P and supporting displacement U_0 of multi-degree of freedom system as stochastic process is given. The study:

(1) Analysis of all supporting suffers identical displacement reaction in x direction.

(2) All supporting fixed, reaction analysis of wind pressure node P_P.

In case (1), basic equation is that element model equation(3.3) and optimize part of polynomial, that is:

$$y_k + 2\beta_k \omega_k \dot{y}_k + \omega_k^2 y_k = r_{xk} \ddot{x}_0 \tag{4.4}$$

In case (2), basic equation is that element model equation (3.3) and optimize part of polynomial, that is:

$$\ddot{y}_k + 2\beta_k \omega_k \dot{y}_k + \omega_k^2 y_k = p_k \tag{4.5}$$

5. Dynamic Reliability Theory

5.1. Spectrum Parameters (Stationary Random Process)

Wind turbine structure is affected by external disturbance, random process of wind load acting on wind turbine foundation, which is known as random vibration theory based on statistical probability inferring dynamic properties of random vibration theory. The fundamental objective and idea of random vibration theory has been repeated many times, in general it can be summarized as follows.

(1) The actual load of wind turbine structure often has very complex statistical changes, and more wind loads are non-repeatability vibration. In statistical probability theory, final conclusion is applied for analyzing structure in engineering before a period of time. But we analyze structure of statistical characteristics with final conclusion theory, its result can't reflect truly the actual situation. As a result, what dealing more correctly with the wind load of statistical features in theory is fundamental objective for random vibration theory.

(2) As ultimate object of wind turbine structure analysis—evaluation reliability method, it is to make statistical structure on quantitative evaluation of probability reliability. Ever final conclusion is determined to rely on the designer's experience too much, therefore, it only basis of reliability evaluation that "current reliability" starting from compromise of theory and experience. And destructive probability P_f or non-destructive probability $P_i=1-P_f$ take place of probability above-mentioned.

Reliability of structure is for dynamic loading—dynamic reliability, which can come down to work out the first deflection probability with theory.

In initial conditions $x(0)=\dot{x}(0)=0$, the time which random process $x(t)$ reach amplitude λ_1 or $-\lambda_2$ is random variable. Supposing probability distribution function is $F_{Tj}(t)$, and dynamic reliability is defined as follow:

$$P_{S_2}(\lambda_1,-\lambda_2)=P\{\max x(t)\le \lambda_1 \cap \min x(t)\ge -\lambda_2 \quad 0\le t\le T\}=1-F_{Tj}(T) \tag{5.1}$$

As standard for safety dynamic reliability is within a certain time [0, T], the maximum value of x(t) is smaller than λ_1, and the minimum value is larger than $-\lambda_2$. For example, if the x (t) is taken as any stress of wind turbine structure, in [0, t] of dynamic load acting, tensile stress changes within λ_1 (allowable stress) and compressive stress changes within $-\lambda_2$ (allowable stress). when value do not exceed threshold, it can be thought of basic security, meantime you can use it to evaluate dynamic reliability with equation (5.1).

If first offset time T_f of probability distribution function is used, the F_{Tf}(T)is in [0, T] and probability of x(t) is larger than λ_1 or smaller than $-\lambda_2$, then 1 subtract F_{Tf}(T) get equation (5.1) which polynomial is equal each side. Therefore, solving dynamic reliability and solving the first offset probability distribution function is one thing. In equation (5.1), if take $\lambda_1 = \lambda_2 = \lambda$:

$$P(\lambda,-\lambda) = P\{\max|x(t)| \le \lambda \quad 0 \le t \le T\} \tag{5.2}$$

When only considering unilateral allowable limit:

$$P_f(\lambda) = P\{\max x(t) \le \lambda \quad 0 \le t \le T\} \tag{5.3}$$

Take the maximum value of x (t):

$$x_m = \max|x(t)| \quad 0 \le t \le T \tag{5.4}$$

With probability distribution function $F_{x_m}(\lambda)$ of the maximum value of $|x(t)|$, equation (5.2) and equation (5.3) can be written:

$$P_f(\lambda) = F_{sm}(\lambda) \tag{5.5}$$

The basis dynamic reliability theory and theoretical analysis is form by probability distribution function $F_{T_f}(t)$ or $F_{x_m}(t)$. By equation (5.1) - (5.5), dynamic reliability is defined which is used to evaluate random destructive reliability, without structure fatigue and strength reduction considered. Although this idealized method is restricted in practical application, but it gives the basic ideas of dynamic reliability.

5.2. Spectrum Parameters of Stationary Random Process

When dynamic reliability is analyzed, it is convenient of random process power spectral density function of x (t) - spectrum parameters by utilizing random process. if the mean value of random process x(t) in $\omega \ge 0$ is 0,power spectral density function $G_x(\omega)$ and autocorrelation function $R_x(\tau)$ have the relationship as following:

$$G_x(\omega) = \frac{2}{\pi}\int_0^\infty R_x(\tau)\cos\omega\tau d\tau \tag{5.6}$$

$$R_x(\tau) = \int_0^\infty G_x(\omega)\cos\omega\tau d\omega \tag{5.7}$$

Therefore, the most important thing is that determining the maximum value of $|x(t)|$ which is probability distribution function $F_{x_m}(\lambda)$ or first offset probability distribution function $F_{T_f}(t)$, and dynamic reliability can be obtained. The method of solving approximate solution is that based on the Poisson distribution theory. When considering boundary value λ (or λ_1, λ_2) of $x(t)$ is large, because it is little intersection chance between $x(t)$ and λ, they can be independent of time, and be applied with Poisson distribution rule. Stationary random Poisson process should be stated.

6. Random Structure Analysis

6.1. Introduction

In random vibration theory, structure system is showed normally by deterministic model, and input is as stochastic process and statistic of analysis reaction. In wind power engineering, input of wind load input often is uncertain, and by contrast uncertain factor in the structure of wind turbine system can be thought of negligible levels. If wind turbine structure system is as random quantity, complexity of analysis should increase. Considering requirements of precision, wind turbine structure is looked as deterministic model.

However, when uncertainty factor can't be neglected compared with the input which wind turbine structure system contains or in order to study variable quantity, wind turbine is analyzed as random quality by modeling. So materials often have statistically discreteness or from study dynamic characteristics of wind turbine structure, quality, stiffness and damping factors would be looked as determining quantity and input would be look as random quantity properly.

6.2. Random Continuum Analysis of Intrinsic Value

When wind turbine structure system is analyzed as continuum model, it should be solved base on free vibration theory. In inherent value problem, the basic equations containing small parameter perturbation method is seemed as sum of small parameter.

For the problem of one-dimensional or two-dimensional inherent value, W is take for function of 1 or 2 spatial coordinates.

$$L[W] = A_1 W + A_2 \frac{\partial W}{\partial x} + A_3 \frac{\partial W}{\partial y} + A_4 \frac{\partial^2 W}{\partial x^2} + A_5 \frac{\partial^2 W}{\partial x \partial y} + \cdots\cdots \quad (6.1)$$

$$M[W] = B_1 W + B_2 \frac{\partial W}{\partial x} + B_3 \frac{\partial W}{\partial y} + B_4 \frac{\partial^2 W}{\partial x^2} + B_5 \frac{\partial^2 W}{\partial x \partial y} + \cdots\cdots \quad (6.2)$$

In equation, A_1, A_2, $\cdots$ or B_1, B_2, , $\cdots\cdots$is as function of space coordinates x, y, L and M if for differential operator.

The eigenvalue problem of differential equations and boundary conditions are given as following.

$$L[W] = \lambda M[W] \quad (6.3)$$

And

$$U_i[W] = 0 \qquad i = 1,2,\cdots,2n \quad (6.4)$$

In equation, λ is for unknown constants.

Now, the solution of equation (6.3) is:

$$W(\underline{x}, \lambda) = \sum_{i=1}^{2n} C_i W_i(\underline{x}, \lambda) \quad (6.5)$$

Substitute into boundary conditions (6.4):

$$U_i\left[\sum_{j=1}^{2n} C_j W_j(\underline{x},\lambda)\right] = \sum_{j=1}^{2n} C_j U_i\left[W_j(\underline{x},\lambda)\right] = 0 \qquad i = 1,2,\cdots,2n \tag{6.6}$$

In equation, $\underline{x}$ is spatial coordinate, and one-dimensional is for x, two-dimensional is for x and y.

Therefore, according to 2n simultaneous equations (6.6), coefficient C_j can be obtained. The right side of equation (6.6) is 0, in order to ensure nonzero solution existence, matrix $2n \times 2n$ is must be equal to 0.

$$\left|U_i\left[W_j(x,\lambda)\right]\right| = 0 \tag{6.7}$$

From (6.7), we can get eigenvalue of λ, corresponding $W(\underline{x},\lambda)$is inherent function. In structural mechanics, the basic method of free vibration and buckling stability is constitute by type (6.3) and (6.4). In the domain of $D = L - \lambda M$, function $u(\underline{x})$ can be second-order differential, and satisfy boundary conditions function (6.4).

Above is the basic content of eigenvalue problem, and the random eigenvalue problems is its extension, finally random eigenvalue equations can be gotten:

$$\int_D L_0[W_{00}]W_{10}dD + \int_D W_{00}L_1[W_{00}]dD = \lambda_{00}\int_D M_0[W_{00}]W_{10}dD + \lambda_{10}\int_D M_0[W_{00}]W_{00}dD \tag{6.8}$$

6.3. Random Continuum Analysis

The average eigenvalue is :

$$E[\lambda] = \lambda_{00} + E[\lambda_{10}\alpha] + E[\lambda_{01}\beta] \tag{6.9}$$

The quadratic mean is:

$$E[\lambda^2] = \lambda_{00}^2 + 2\lambda_{00}E[\lambda_{10}\alpha] + 2\lambda_{00}E[\lambda_{01}\beta] \tag{6.10}$$

Variance value is:

$$V_{ar}[\lambda] = \sigma_\lambda^2 = E[\lambda^2] - E[\lambda]^2 \tag{6.11}$$

When in order to solve random eigenvalue problems by simulation method, a large number of extraction operator would be gotten with deterministic method, at final it is processed by statistical method.

7. Gear Transmission System Analysis

7.1. Whole Shaft Structure Dynamic Analysis

Through ANSYS processor, carve of equivalent stress changing which is shaft structure of wind turbine transmission system can be drawn. as follow Figure 7.1.

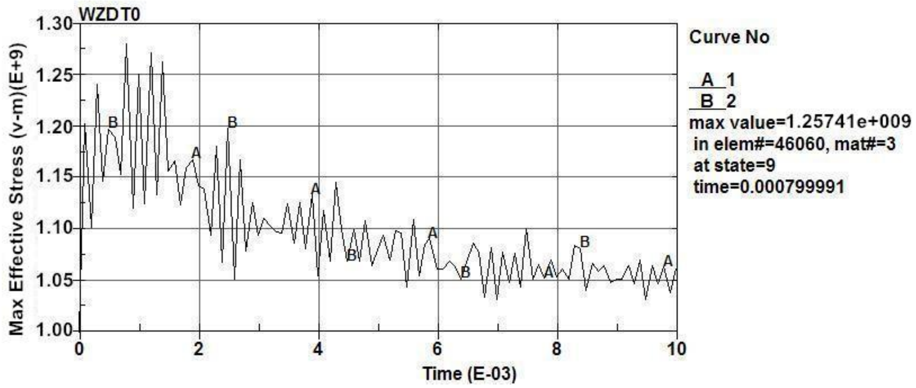

Figure 7.1. The Equivalent Stress Changes with Time

Figure 7.1 shows that on the condition of wind turbine gear running, that wind turbine shaft structure running is meshing process which is from impact meshing to stable meshing. It can be seen that the value of dynamics analysis stress is bigger than the one of static analysis, and vibration and dynamic load in addition.

Through software LS-DYNA [5] we simulate transient equivalent stress of wind turbine gear running process, as shown in Figure 7.2.

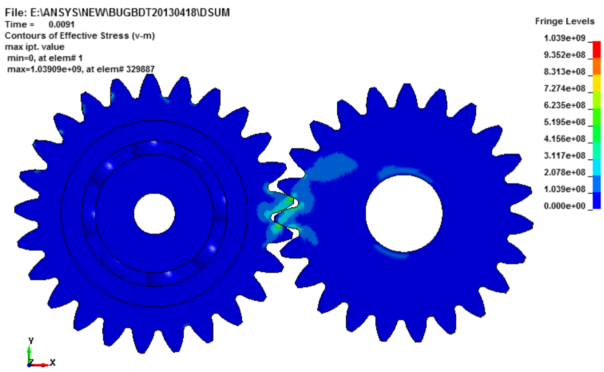

Figure 7. 2. Transient Equivalent Stress of Gear Transmission Movement Process

In figure 7.2, the transient dynamic simulation result of wind turbine gear transmission running process is very fit with actual situation.

7.2. Gear Tooth Structure Dynamic Analysis

In order to analyze change of the equivalent stress which is random vibration of wind turbine gear meshing process in different positions, we can take three different units a pair of meshing gears in the middle of a tooth, tooth root, as shown in Figure 7.3.

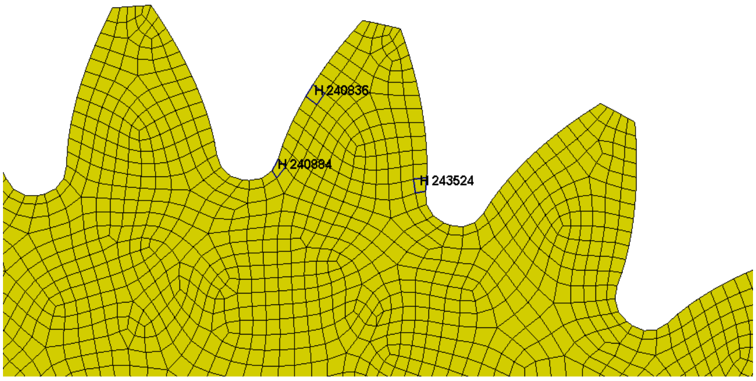

Figure 7.3. Part of Gear Surface Schematic Diagram

The equivalent stress of three units change in the process of meshing as shown in Figure 7.4.

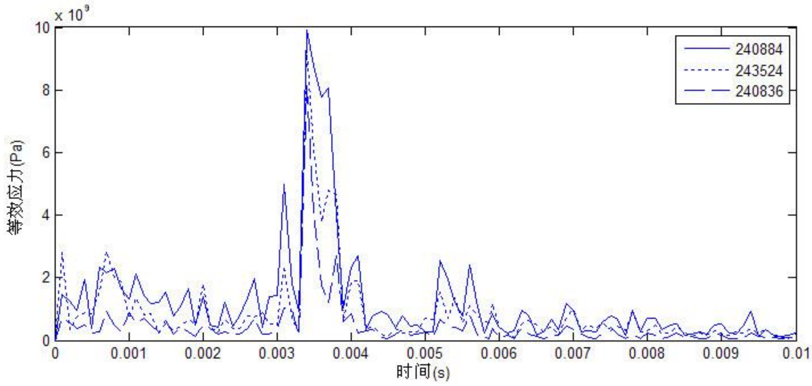

Figure 7.4. Units Curve of Equivalent Stress Changes over Time

As Figure 7.4 shows that when entering the meshing position, the equivalent stress increases gradually. The largest equivalent stress is where near line of contact in the process of contact. When gear retreat from meshing, the equivalent stress will reduce to zero, which is in accord with actual process of gear meshing. Meanwhile, harmonic vibration can be seen in equivalent stress curve from figure 6.4, it explains that wind turbine gear transmission system is affected by the wind load of random vibration in the process of meshing, and preliminary judgment is correspond to actual situation.

8. Conclusion

(1) It is more significant that wind turbine is affected in actual process of wind turbine running, so not only the whole wind turbine but also transmission system is analyze in structure load, dynamic load or stationary load, it must be considered that effect of external load (wind load). Wind load has strongly randomness, so it is practical application value that using theory of random to determine wind load.

(2) According to operation characteristics of wind turbine gear transmission system and theory of wind load random, model of dynamic analysis with external excitation is established. In paper, mathematic modeling method of wind load random model is stated with gear rigid motion of wind turbine transmission system and flexible vibration as the research object.

(3) Example shows that wind turbine transmission system is affected by simulation random external wind load, and the energy of wind turbine suffered is increasing and in addition its vibration stress, which affects energy distribution

between impact of wind power gear. It is for the foundation of dynamic optimization design of wind turbine gear box.

References

[1] W. Jun-Gang, W. Yong and H. Zhi-pu, "Estabilishment of mathematic model and study of vibration modes of multi-stage planetary gear train of wind turbine gearboxes[J]", journal of Sichuan university(engineering science edition), 5, 189 **(2013)**

[2] Z. Cai-chao, H. Ze-hao and T. Qian, "Analysis of nonlinear coupling dynamic characteristics of gearbox system about wind-driven generator. Chinese journal of mechanical engineering", 41, 203 **(2005)**

[3] Z. Cai-chao, H. Qi and T. Qian, "Study on multi-teeth contact and load distribution of speed increase gearbox transmission system for the wind-driven generator[J]", Journal of agricultural machinery, 37, 86 **(2006)**

[4] G. Xin, S. Zhi-li and Z. Yan, "Based on theory of aerodynamic excitation wind turbine blade unsteady flow effect analysis[J]", Science technology and engineering, 27, 224 **(2014)**

[5] Z. Yang, M. Ahmat, S. Shu-dou and H. Yong-ming, "Dynamic nonlilnear analysis of helical planetary gear system for wind turbine gearbox", Renewable energy resource, 8: 45-50 **(2013)**

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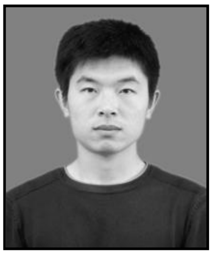

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