

Operational Modal Analysis of Wind Turbine Speed-increase Gearbox

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Abstract

Speed increase transmission gear box is the primary vibration and noise source of wind turbine, Operational modal method was adopted to collect impact data and response data of each point based on the gearbox test model. ANSYS finite element model is established to simulate the wind turbine gearbox. Then the modal frequencies of the two methods were compared to ensure the test model is correct. The results show that operational modal method can be applied in wind turbine gearbox modal analysis and it has important guiding significance to gearbox fault diagnosis and reliability and maintainability improving.

Keywords: gearbox, wind turbine, operational modal, environment excitation

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1. Introduction

The operational state of speed-increase gearbox, as a key component, directly affects the whole performance of wind turbine and its failures usually were the important downtime factors. Along with the power increase of wind generator, the growth of gearbox size and quality was larger, so the losses caused by single turbine downtime were bigger. Tests and analysis of speed-increase gearbox has great realistic significance, it can provide reliable scientific basis for turbine operation maintenance and product design improving [1-3].

Operational modal method was using environmental loads or actual working conditions as the excitation source to test the modal of large complex structure. Compared with the traditional modal test method, it does not require a specific test conditions, the excitation device can modal experiment was carried out in actual working environment, greatly improved work efficiency and reduce the test cost [3-4]. In recent years, using the method of work modal was to study the actual conditions of various structures of the modal test has made important progress, but in the megawatt wind turbine gearboxes used has not been reported. Currently use environment to stimulate modal analysis method was varied, such as characteristics of realization algorithm (ERA), natural excitation technique (NEXT), random subspace method (SSI), etc. Natural excitation technique was applied in this paper, on the wind turbine gearbox its growth has confirmed the applicability of the proposed method [5-6].

The research of gearbox modal analysis and dynamic design has been conducted both at home and abroad. Wu etc. introduced detail analysis and calculation on gearbox failure, and then summarized some common reasons and influences of manufacturing process on gear life and reliability according to the actual situation in factory; improving design measures were proposed for raw materials and main process [7]. Zheng studied intrinsic characteristics of gear transmission system with complex modal theory to gain the inherent frequency and vibration model of gearbox transmission system, analyzed dynamic excitation of gear mesh based on primary causes of gearbox system vibration, this paper analyzes the, simulated the gear mesh internal incentives with finite element numerical analysis method, and obtained the dynamic exciting forces of meshing gear transmission system [8]. Xiao studied gearbox transmission system design problems, and the return, analyzed major sources of errors, established finite element vibration theory model in view of the defects of vibration and the noise, discussed influence on transmission accuracy of main shaft under torsion, bending, and other forms of main vibration [9]. Kumar etc. established virtual prototype of gearbox in ADAMS, analyzed deflection of the gearbox body under different temperature conditions, conducted dynamic

simulation and analysis for the gearbox transmission system in the different operational temperature environment [10]. Reference [11] used traditional modal analysis to study large-scale ship driving gear transmission system, analyzed the lower stages vibration modal of gearbox, showed characteristic parameters and potential damage parts. Many scholars had carried out large amount of related research of gear transmission system of the wind turbine.

Vibration monitoring and analysis methods had characteristics of high diagnosis speed, high accuracy rate and achievable online diagnosis etc., so it was the most effective fault test and diagnosis method for gearbox, and modal test the theoretical model of 2 due to the one of the most commonly used method [12-13]. The modal test analysis method was an important way applied to fault diagnosis and operational condition monitoring. When the structure failure occurs, cracks, looses, damages of components and so on, structural physical characteristic parameters, natural frequencies, modal damping, vibration mode and frequency response function, etc., usually will be changed subsequently. According to the changes of these characteristic parameters, the fault types can be judged and sometimes the damaged position can also be confirmed of gearbox. The fault statistics of large scale wind turbine gearbox showed that the largest failure parts were gear and bearing, about 60% and 19% proportion respectively [14]. Due to the power of large-scale wind turbine was bigger, the loss caused by a downtime unit was bigger, Increasing reliability of wind turbine components was essential. It had increasingly become an effective method and safety testing of fault diagnosis that conducting modal analysis and using modal parameters as fault Identification results on wind turbine gearbox.

2. The Vibration Modal Theory Algorithm

The vibration of the wind turbine gearbox can assume as a linear time invariant systems with n degrees of freedom movement. If whole structure was discretization, the basic dynamic equation for free vibration was:

$$M\ddot{X} + C\dot{X} + KX = 0 \quad (1)$$

Where the M , C and K were structural mass matrix, damping matrix and stiffness matrix respectively; Vector X was node displacement vector, and it was the basic solutions of finite element problem; \dot{X} , \ddot{X} were node velocity and acceleration vectors respectively, and it was derived solutions of finite element. Assumed that solution for the equation was $X = \phi e^{\lambda t}$, placed in Equation (1), then:

$$(\lambda^2 M + \lambda C + K)\phi = 0 \quad (2)$$

So the vibration dynamic problem was converted into an eigenvalue problem, the eigenvalue λ_i were the solutions of Equation (1), each eigenvalue corresponded to a feature vector, namely modal vibration mode. The information of frequency and modal damping were contained in eigen value λ_i , that was $\lambda_i = \sigma_i + j\omega_i$. Where the real part was damping factor, the imaginary part was inherent circular frequency (rad/s).

The relation of discrete time system and the eigenvalue of for continuous time systems:

$$\lambda_i^c = \frac{\ln \lambda_i}{\Delta t} \quad (3)$$

The modal damping ratio ζ_r was depended on nature frequency ω_r , modal quality M_r and modal damping c_r according to the following:

$$\zeta_i = \frac{c_r}{2M_r\omega_r} \quad (4)$$

Natural frequencies, vibration modes and modal damping of structure was three basic volume dynamic characteristics. When excitation vibrations were at the i coordinates of, frequency response function was measured at j coordinates was:

$$H_{ji}(\omega) = \sum_{r=1}^n \frac{\phi_{jr}\phi_{ir}}{\omega^2 M_r + j\omega C_r + K_r} \quad (5)$$

In the actual test, frequency response function of system was generally obtained by power spectral density as follows:

$$H(\omega) = \frac{G_{PX}(\omega)}{G_{PP}(\omega)} \quad (6)$$

Cross power spectrum analysis technology was adopted in above function, and the noise can be greatly reduced after multi-times average. Its basic idea was constructing a polynomial, and then deriving the autoregressive (AR) model of system, after solving from autoregression coefficient, gradually identifying out the modal parameters of system.

3. The Experiment Test Analysis

This experiment gearbox object which was 3.75 meters long and up to 21 tons weight was operated in a 1.5Mw wind turbine, it has characteristics of large structure size and complicated shape. So it was difficult to use conventional methods to motivate and unable to use traditional hammer experiment modal parameter identification method for the speed-increase transmission gearbox. As it was difficult to effect direct external excitation for wind turbine gearbox, the operational modal technology method adopted to apply the ambient excitation, and then stochastic subspace method was used to identify the modal parameters. Signal testing and acquisition location was nearly hundred meters in the engine room, field test used rotor rotation as environmental incentive, that wind load excitation equal or more than rated wind speed. Wind turbine of this experiment measurement had variable blade pitch function, so in the measuring process speed-increase transmission gearbox can keep guaranteeing the rated input speed and cyclic loads.

Modal test step of wind turbine speed-increase transmission gearbox was shown in Figure1. As gearbox has in large size and complex structure, and the quantity of Vibration acceleration sensors was limited, this test adopted grouping and mobile measurement method under the same rated working condition. This method was able to satisfy the premise of operational modal testing and ensure a better testing result.

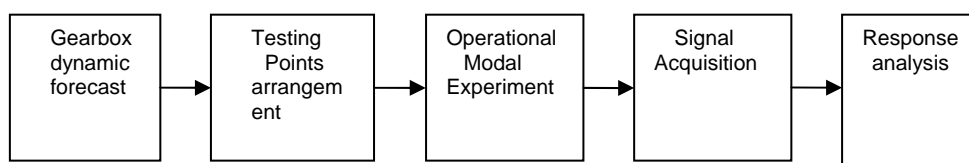


Figure 1. Test Steps of Wind Turbine Gearbox Operational Modal

The test equipments were laptop computer and LDS PHOTON II portable 16 channel acquisition instrument, acquisition software was RTPro PHOTON signal collection and analysis software, sensors were PCB2 unidirectional vibration acceleration sensor. The signal collection and acquisition devices were shown in following Figure 2. The whole body of wind turbine speed increasing gearbox was set up 76 points, including supporting position of gearbox where was laid out 2 three-direction acceleration sensors as reference points. In order to accurately simulate the shape of gearbox body, eight measuring points were arranged circular layout and total 72 measuring points to record the vibration response signal of speed increasing gearbox.

Each measuring point was repeated measurements twice and each time measuring the 50s to avoid human operational error in test under rated the measurement condition. More appropriate average number of the signal sections was used to eliminate or reduce the random signal error under rated wind loads, and Hanning window was used to inhibit the leakage of time domain signal. The quality of acceleration sensors used in this experiment compared to quality of speed increasing gearbox was negligible, it will not affect the test accuracy and the frequency calculation result also showed the estimates was right. In the experiment, support way was original operational support of speed increase gearbox, so it was maximum limit to get real working conditions of vibration data of measuring points and was ready for operational modal analysis of next step.

4. The Test and Data Processing

Vibration modal analysis was a method of studying structure dynamic characteristics, and it was system identification method application in the field of engineering vibration. It can be gotten the natural frequencies and modal vibration mode in various frequencies through modal analysis of mechanical structure. The purpose of finite element modal analysis method analysis was the natural modal frequencies and its corresponding modal vibration mode of wind turbine speed-increase transmission gearbox, at the same time measuring points and test sensors can be arranged of based on the modal frequency response type vibration modal.

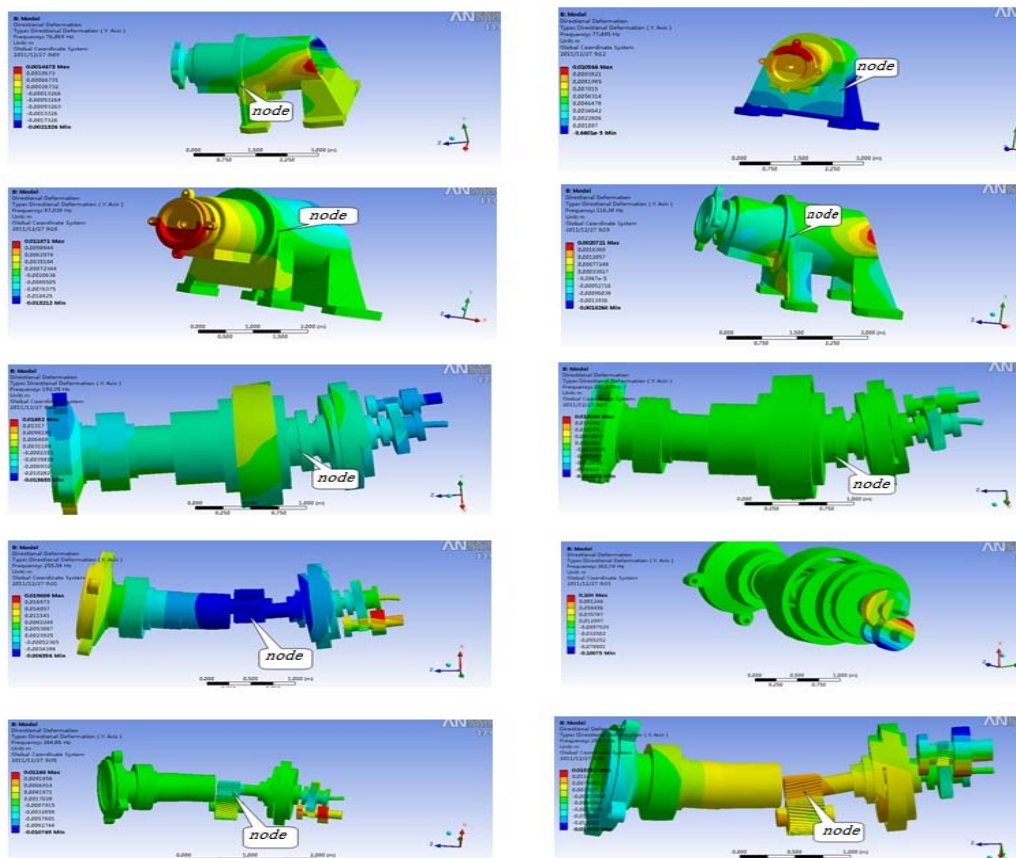


Figure 2. The First 10 Order Modal Vibration Modes of 1.5Mw Wind Turbine Speed-increase Transmission Gearbox

The resonance was Likely to occur, when working frequency was close to an order of natural frequency mechanical structure. Frequencies of vibration modes will be calculated according to the vibration resonance state, so most frequently operational fault states can be

predicted through these calculated data with working frequency was close to an order of natural frequency in the mechanical structure. At same time, necessary increase or reduce measures should be taken to avoid close to the natural frequency in design and installing of a mechanical structure. So in the design and operational of the wind turbine speed-increase gearbox, the most important jobs were to avoid resonance with the external sources of wind loads and wheel input vibration and reduce the chances of structure faults. ANSYS software was applied to aid modal analysis in the modeling simulation step. Considering the relatively weak model function of ANSYS software, for it finished the model step by step, from points, lines, faces and then body. The CAD system was most suitable for introducing model, so this paper choose UG software to build the entity model, achieve rapid finite element entity model by setting of seamless connection of UG software and ANSYS software. The first 10 order modal vibration modes of 1.5Mw wind turbine speed-increase transmission gearbox were shown at Figure 2.

The vibration modal mode can be clearly shown in above Fig.2. It can clearly see that blade dangerous sections appear in modal node section position of all the order. The so-called modal node, structure under a certain order natural frequency, was intersection node of vibration mode and original form. The cross section that vibration mode node located was called vibration modal node section. Vibration mode node section bears more frequent alternating load than other position, it was more vulnerable to damage.

Vibration mode was the nature characteristics of structure, and the modal of gearbox depend on the box-body structure, mass distribution, etc. From the perspective of the modal vibration mode of gear box, was the direction of Y direction of the swinging, reverse swing and turn around. The torsion vibration of box-body was various, it would cause the instability of the whole performance, cause the gear in fault states, fatigue damage, cause the body to accelerate the destruction of box-body. Vibration along the Y direction of gearbox wall will drive the basic reciprocating motion and fix affecting gear box-body, and will affect the whole transmission performance of the gearbox. Gearbox body reverse bending oscillation along the Y direction will compress air in the box to produce large noise.

Then test data processing was conducted according to the derived Equation (12) above by computer program, output the element modal strain energy change ratio as shown in Table 1.

Table 1. Comparison of Modal Frequencies between Experiment and ANSYS

Modal orders	Test results	ANSYS results	Vibration mode performance
Order1	165Hz	176.79 Hz	Whole vibration of the Y direction
Order 2	172 Hz	177.19 Hz	Whole vibration of the X direction
Order 3	181 Hz	184.91 Hz	Whole vibration of the X direction
Order 4	197 Hz	187.24 Hz	Whole vibration of the Y direction
Order 5	334 Hz	325.87 Hz	Whole vibration of the Y direction,high-speed level vibration of the X direction
Order 6	345 Hz	349.29 Hz	Spindle and high-speed level vibration of the Y direction
Order 7	355 Hz	350.19 Hz	Whole vibration of the X direction,bigger amplitude of spindle and high-speed level
Order 8	377 Hz	372.41 Hz	Spindle torsion vibration
Order 9	408 Hz	407.19 Hz	Spindle vibration of the X direction , torsion vibration of middle-speed level and high-speed level
Order 10	419 Hz	417.64 Hz	opposite direction of vibration of Spindle, low-speed, middle-speed and high-speed level in axial direction

From above Table 1, it can be clear known that test conclusion analysis results were accordance with the results of the finite element calculation of each vibration modal order. The first 4 modal orders of gearbox transmission system mainly vibrate in radial of X direction and Y direction; in the 8th and 9th orders spindle and high-speed level appear torsion vibration and in the 10th order the whole key components appear axial vibration. It should try to stay away from these 3 order modal in the practical operation of wind turbine gearbox and the operational frequency does not fall within the half power bandwidth in a certain order modal.

The modal also show that casing joint severe vibration, box-body stiffness need to be appropriately increased to reduce casing deformation in the design stage, reduced the adverse effects on the structure of the gear box due to the large deformation. Periodic inspection and maintenance should be implemented to gearbox fix and coupling centering, avoid bolt loosening and position deviation caused by vibration and swing gearbox body.

The bigger vibration amplitude of box-body also greatly affected operation and centering of the gear, take vibration and noise caused by shocks to gear tooth surface, which was an important cause roots to produce fault of gearbox. It can get the gear-mesh frequency of high-speed level, middle-speed level and low-speed level in ANSYS model in combination with the practical rated operational situation of gearbox. The modal parameters and vibration response data suggest that dynamic model established of gearbox was correct.

5. Conclusion

The realistic engineering methods of operational modal parameters identification and modal computation analysis were combined in this paper, and can effectively solve the modal analysis of large complicated mechanical structure. The methods not only ensured the accuracy of modal parameters results, but also were able to ensure integrity of modal parameter matrix. At the same time, the signal decomposition preprocessing method effectively solved decomposition modal in the operational modal parameter identification. The identified vibration modes of the finite element model of wind turbine gearbox has a symmetry characteristics, whole gearbox-body modes appeared in low frequency band and large numbers of transmission system modes appeared high frequency band.

It can be seen that operational modal method based on environmental excitation was feasible for natural frequency vibration test of wind turbine speed-increase gearbox according to the results.

(1) The type of vibration sensors was reasonable and accurate in the actual testing process. The arrangement of measuring points can well meet the needs of test and can be a good base for acquiring vibration response signal under the environment excitation. That processes greatly improve the results reliability of the subsequent data analysis.

(2) The environment excitation methods were used to test natural frequencies of a large mechanical structural. They were simple and reliable and did not produce any vibration and noise. The more reliable natural frequencies can be obtained in subsequent data analysis, and it can be widely used in the similar test work. On the other hand, the methods were needed to decorate a large number of sensors and restricted by the surrounding environment. So the methods were not suitable for application in more complex vibration environment.

(3) The nature characteristics of the transmission gearbox were obtained based on the response data modal identification technique. The finite element model was verified correctness by comparing the ANSYS results and test results. The conclusions of this paper provided dynamic design and analysis methods for megawatt wind speed-increase transmission gearbox and were able to reduce the vibration, noise of gear box, optimize its structure, provided a theoretical basis to improve its reliability.

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