Crack Diagnosis of Wind Turbine Blades Based on EMD Method

CUI Hong-yu\textsuperscript{1}, DING Ning\textsuperscript{1,2}, HONG Ming\textsuperscript{1}

\textsuperscript{1}School of Naval Architecture, Dalian University of Technology, Dalian 116024, China
\textsuperscript{2}COSCO-SHIPYARD, COSCO Ship DESIGN CENTER, Dalian 116600, China

E-mail address: cuihongyu@dlut.edu.cn

Abstract. Wind turbine blades are both the source of power and the core technology of wind generators. After long periods of time or in some extreme conditions, cracks or damage can occur on the surface of the blades. If the wind generators continue to work at this time, the crack will expand until the blade breaks, which can lead to incalculable losses. Therefore, a crack diagnosis method based on EMD for wind turbine blades is proposed in this paper. Based on aerodynamics and fluid-structure coupling theory, an aero-elastic analysis on wind turbine blades model is first made in ANSYS Workbench. Second, based on the aero-elastic analysis and EMD method, the blade cracks are diagnosed and identified in the time and frequency domains, respectively. Finally, the blade model, strain gauge, dynamic signal acquisition and other equipment are used in an experimental study of the aero-elastic analysis and crack damage diagnosis of wind turbine blades to verify the crack diagnosis method proposed in this paper.

1. Introduction

Wind turbine blades are the key component for energy conversion in a wind power generation system\cite{1,2}. It is possible for cracks to occur on the blade surface under poor service conditions or following long running times, and fatigue damage will accumulate until the blade breaks, which leads to incalculable losses\cite{2,3}. Therefore, accurately monitoring the blade surface condition before crack growth is a prerequisite and is necessary for wind power generation systems\cite{3,4}.

Blades operate under the coupling of gravity, aerodynamic and centrifugal forces, and the vibration signal is characterized as nonlinear, stochastic and coupling\cite{5}. Presently, there are many blade structure analysis methods for analyzing the signal characteristics during blade operation in the time or frequency domains. Empirical mode decomposition (EMD) is a signal analysis method in the time-frequency domain proposed by Norden E. Huang in 1999. EMD can decompose a signal into a series of intrinsic mode functions (IMF) with different time characteristics and smooth processing\cite{6}. Linear and nonlinear signals can be analyzed by the EMD method due to its adaptability. Therefore, EMD is advantageous for analyzing the vibration signals of rotating machinery and other structural characteristics signals.

Once cracks occur on a blade, the structure stress near the cracks will change. The structural stress signal is obtained from numerical simulations without any noise pollution, but the actual signal that is acquired cannot be used in crack recognition because of the pollution. Therefore, we propose a crack damage diagnosis method in which collected signals are decomposed based on the EMD method and an energy method is applied to recognize crack damage.

2. Wind turbine blade aero-elastic analysis
In this paper, a fluid-structure coupling method is used for the aero-elastic analysis of blades. Computational fluid dynamic and structural dynamic theory are used to calculate the flow domain and structure, respectively[7,8].

The structure dynamic equation of wind turbine blades is as follows:

\[ M \ddot{u} + C \dot{u} + K u = F_s + F_a \]  

(1)

where \( M \) is the mass matrix; \( C \) is the damping matrix; \( K \) is the stiffness matrix; \( u \), \( \dot{u} \), and \( \ddot{u} \) are displacement, velocity and acceleration, respectively; \( F_s \) is the loading on the blades; and \( F_a \) is the fluid loading, which is a function of displacement, velocity and acceleration.

Computational Fluid Dynamic (CFD) is applied to simulate the flow phenomena of fluid. The equations of fluid mechanics are continuity equation, momentum equation and energy equation.

According to the law of conservation of mass, the continuity equation of fluid is obtained as follows:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \]  

(2)

where \( \nabla = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \) is the Hamilton operator; \( \rho \) is the fluid density; and \( \mathbf{V} \) is the fluid velocity vector.

According to the law of conservation of momentum, the momentum equation of fluid or Navier-Stokes (NS) equation, is obtained as follows:

\[
\begin{aligned}
\rho \frac{du}{dt} &= \rho f_x + \frac{\partial p_x}{\partial x} + \frac{\partial p_y}{\partial y} + \frac{\partial p_z}{\partial z} \\
\rho \frac{dv}{dt} &= \rho f_y + \frac{\partial p_x}{\partial x} + \frac{\partial p_y}{\partial y} + \frac{\partial p_z}{\partial z} \\
\rho \frac{dw}{dt} &= \rho f_z + \frac{\partial p_x}{\partial x} + \frac{\partial p_y}{\partial y} + \frac{\partial p_z}{\partial z}
\end{aligned}
\]  

(3)

where \( f_x \), \( f_y \), and \( f_z \) are the components of fluid mass force in the normal direction and \( \rho \) is the fluid stress tensor.

According to the law of conservation of energy, the energy derivative with respect to time is equal to the sum of the net inflow of heat per unit time and the acting of mass force and surface forces on the fluid infinitesimal. The integral form of the energy equation is as follows:

\[ \rho \frac{d}{dt} \left( e + \frac{\mathbf{V} \cdot \mathbf{V}}{2} \right) dV = \nabla \cdot (\sigma \cdot \mathbf{V}) + \mathbf{V} \cdot \rho \mathbf{f} + \nabla \cdot \mathbf{q} \]  

(4)

where \( e \) is the internal energy of fluid infinitesimal; \( \sigma \) is the surface force of fluid infinitesimal; \( \mathbf{f} \) is the mass force of fluid infinitesimal; and \( \mathbf{q} \) is the thermal conductivity.

In this paper, a fluid-structure coupling calculation method is applied in aero-elastic analysis of wind turbine blades. Computational fluid dynamics and structural dynamics theory are used to calculate the flow domain and structure, respectively, and thereby generate two sets of finite elements and boundary conditions, including coupling parameters that are specially defined. In the calculation, the coupling amount will be exchanged through the middle platform, and the computing parameters will be transferred through the fluid-solid coupling boundary. Specifically, during the fluid-structure coupling iterative calculation, the structure and fluid domains are calculated once at each time step, and their results are exchanged for another calculation until the results converge to achieve the fluid-structure coupling calculation analysis.

3. Numerical simulations of blades aero-elastic analysis based on ANSYS Workbench
ANSYS Workbench is applied to analyze the aero-elasticity of blades. The geometry model of blade, which is based on the initial blade profile design, is built in ANSYS Workbench and meshed into finite elements. Then, the FE model is imported into ANSYS Workbench to obtain the response in the time domain based on bi-directional flow-solid coupling method to achieve a numerical simulation of the blades’ aero-elastic analysis.

The basic parameters of a wind turbine blade are designed by using Bates theory and blade element theory[9]. The basic parameters are shown in Table 1.

| Basic design parameters       | Value       |
|-------------------------------|-------------|
| rated power $P$               | 1200kW      |
| designed wind speed $V$       | 15 m/s      |
| wind energy utilization factor $C_p$ | 0.4        |
| generator efficiency $\eta_g$ | 0.9         |
| mechanical transmission efficiency $\eta_t$ | 0.8 |
| air density $\rho$            | 1.225 kg/m$^3$ |

Based on the parameters in Table 1, the chord and twist angle for each location are obtained as shown in Table 2.

| Location | $l_i$ (m) | Twist angle $\gamma_i$ (°) | Location | $l_i$ (m) | Twist angle $\gamma_i$ (°) |
|----------|-----------|-----------------------------|----------|-----------|-----------------------------|
| 0.1R     | 6.2       | 55.2                        | 0.6R     | 1.3       | 87.1                        |
| 0.2R     | 3.7       | 72.4                        | 0.7R     | 1.1       | 88.2                        |
| 0.3R     | 2.6       | 79.5                        | 0.8R     | 1.0       | 89.1                        |
| 0.4R     | 2.0       | 83.2                        | 0.9R     | 0.9       | 89.7                        |
| 0.5R     | 1.6       | 85.5                        | 1.0R     | 0.8       | 90.0                        |

Based on the parameters of a designed wind turbine blade, PROFILI is applied to design blade profiles. Then, the profiles are imported into ANSYS to create a geometry model, as shown in Figure 1.

**Figure 1.** Three-dimensional geometric model of wind turbine blade

Because CFX was the first fluid dynamics analysis software in the world, ANSYS+CFX is applied to analyze the aero-elasticity of the designed blade. The calculation process is as follows:

a. Import the created blade model and create flow model.
b. The blade and fluid model parameters are set, and the models are meshed, as shown in Figure 2.
c. The elements of the blade and fluid are imported into CFX to make the bi-directional flow-solid coupling calculation and obtain the pressure on the blade surface in the time domain. The distribution of the pressure on the blade surface and the air speed in the longitudinal profile of the fluid domain at 3 s are shown in Figure 3.

![Figure 2. Mesh for wind turbine blade and fluid domain](image)

![Figure 3. Surface pressure distribution and air flow rate in longitudinal section diagram at 3 s](image)

![Figure 4. Stress and displacement response of blade at 3 s](image)

d. The pressure calculated in CFX is used as the load on the blade surface, and the structural dynamics are solved to obtain the response in the time domain to achieve an aero-elastic analysis of blades. The stress and displacement response at the 3 s moment are shown in Figure 4.

4. Crack diagnosis method of wind turbine blade based on numerical simulation

In this paper, a crack diagnosis method based on a numerical simulation of the blade aero-elastic analysis is proposed. A crack is created 10 m from the blade root on the blade geometry model. The length of the crack is fixed at 0.1 m. The width of the crack is fixed at 0.01 m. The depth of the crack is designed as 0.004 m, 0.005 m, 0.01 m, and 0.02 m. The aero-elasticity of the blade containing a
crack is analyzed, and the responses of selected points as a characteristic signal of crack diagnosis are obtained. The crack location and distribution of feature points are shown in Figure 5.

Figure 5. Extracted feature points’ distribution of crack signal

In this paper, the energy method, which is widely applied in the extraction of signal characteristics, is used to identify the crack of a wind turbine blade. The response of feature point $i$ is collected first. Then, the stress response energy of point $i$ is calculated based on formula (5) as follows:

$$E_i = \sum_{k=1}^{n} x_{ik}^2 \quad (k = 1, 2, 3L n)$$  \hspace{1cm} (5)

where $k$ is number of sampling points. The energy $E_i$ of feature point $i$ is used as the eigenvalue to identify the crack in the wind turbine blade. The variation in the energy values for each feature point with varying depths of the crack is shown in Figure 6, where “D” represents the crack depth and “B” represents the crack width.

Figure 6. Energy feature point of crack variation with depth

It can be seen from Figure 6 that the energy eigenvalue of the feature point at the crack is much lower than the energy of the same point in healthy conditions. Further, the energy eigenvalue of a feature point reduces gradually with increases in the crack depth.

The EMD method is very effective in handling both non-stationary and nonlinear signals. Signals are decomposed into several IMFs from high to low frequency, and a residual by EMD method. The collected signal $x(t)$ is decomposed by EMD as follows:

$$x(t) = \sum_{i=1}^{N} c_i(t) + r(t)$$ \hspace{1cm} (6)

where $c_i(t)$ are IMF components and $r(t)$ is the residual.
In this paper, signals at different locations are decomposed by the EMD method to obtain the first two IMF components, and the energy eigenvalue of each IMF is calculated. The energy eigenvalues of the first two IMF components in different crack states are shown in Figure 7.

**Figure 7.** Energy feature point of crack variation with breadth of IMF1 and IMF2

Figure 7 shows, for the first two IMF components decomposed by EMD, that the energy eigenvalue of the feature point at the crack is much lower than that of the same point in healthy conditions. Further, the energy eigenvalue of a feature point reduces gradually with increasing crack depths.

5. Experiment of crack diagnosis of wind turbine blade

The structural stress signals obtained from numerical simulation calculation are ideal, whereas the actual collected signals are difficult to use in the diagnosis of cracks due to noise pollution of the signals. Crack diagnosis experiments are performed to prove the validity, efficiency and feasibility of the method proposed in this paper. Variable wind power, as surface loading, is controlled by adjusting an electric fan during the experiment, and the stress signals at different positions are collected by strain gauges connected to signal acquisition instruments. The wind turbine blade, crack and strain gauges are shown in Figure 8.

**Figure 8.** Wind turbine blade, crack and strain gauges

The collected blade stress signal in the time domain is shown in Figure 9.

**Figure 9.** Time domain distribution of stress signal at point 1 of crack 1

Each feature extraction was obtained using the energy method to obtain the stress crack state at different measuring points. To compare the energy characteristics of each measuring point effectively,
the energy eigenvalue of each measuring point is normalized. The energy eigenvalues of cracks at different depths after the normalization process are shown in Figure 10.

Figure 10. Energy feature point of crack variation with width

Figure 10 shows that the energy eigenvalues of the feature point at the crack are much lower compared with the energy of the same point in healthy conditions, which is same as the conclusion obtained from numerical simulations. The variation in the energy eigenvalues with increasing crack depth is not significant enough, which is in large contrast to the conclusion obtained from numerical simulations.

The EMD-based energy method is used to diagnose the crack damage of wind turbine blades. The variation in the energy eigenvalues with increasing crack depth for the IMF1 and IMF2 components is shown in Figure 11.

Figure 11. Energy feature point of IMF1 and IMF2 with variations in crack width

Figure 8 shows that the stress signal obtained from the experiments can be decomposed into several IMFs based on EMD method; thus, the first two IMF components are taken as the original signals in the diagnosis. The energy eigenvalues of the feature point at the crack are much lower than the energy of the same point in healthy conditions, and the energy eigenvalue of feature points reduces gradually with increasing crack depth.

The experimental conclusions are similar to the results of numerical simulations that used the crack diagnosis method based on EMD, as proposed in this paper. This proves the validity, efficiency and feasibility of the method.

6. Conclusions
In this paper, according to the basic theory of fluid-solid coupling, ANSYS Workbench is applied to analyse aero-elasticity, and an EMD-based energy method is used to diagnose the crack damage of...
wind turbine blades. The results show that the energy eigenvalues of a feature point at the crack are much lower than the energy of the same point in healthy conditions and that the energy eigenvalues of feature points decrease gradually with increasing crack depth. Ideal diagnosis results can be obtained in either numerical simulation research or experimental research to verify the correctness, validity and feasibility of the method proposed in this paper.

Acknowledgments
This work was funded by the Natural Science Foundation of China (Grant No. 51109034)

References
[1] Ying Wang, Xiaojing Sun, Xiaohua Dong, Bing Zhu, Diangui Huang and Zhongquan Zheng 2016 Energy Conversion and Management vol 108, Numerical investigation on aerodynamic performance of a novel vertical axis wind turbine with adaptive blades pp 275-286.
[2] Ruizhen Yang, Yunze He and Hong Zhang 2016 Renewable and Sustainable Energy Reviews vol 60, Progress and trends in nondestructive testing and evaluation for wind turbine composite blade pp 1225-1250.
[3] N. Dervilis, M. Choi, S.G. Taylor, R.J. Bar thorpe, G. Park, C.R. Farrar and K. Worden 2014 Journal of Sound and Vibration vol 333, On damage diagnosis for a wind turbine blade using pattern recognition pp1833-1850.
[4] Julián Sierra-Pérez, Miguel Angel Torres-Arredondo and Alfredo Güemes 2016 Composite Structures vol 135, Damage and nonlinearities detection in wind turbine blades based on strain field pattern recognition. FBGs, OBR and strain gauges comparison pp 156-166.
[5] H. Hamdi, C. Mrad, A. Hamdi and R. Nasri 2014 Applied Acoustics vol 86, Dynamic response of a horizontal axis wind turbine blade under aero-dynamic, gravity and gyroscopic effects pp 154-164.
[6] Huang NE, Shen Z, Long SR, Wu MC, Shih HH, Zheng Q, Yen NC, Tung CC and Liu HH 1998 Proceedings of the Royal Society A: Mathematical Physical and Engineering Sciences vol 454, The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis pp 903-995.
[7] Cui Peng and Jinglong Han 2011 Journal of Fluids and Structures vol 27, Numerical investigation of the effects of structural geometric and material nonlinearities on limit-cycle oscillation of a cropped delta wing pp 611-622.
[8] Dong Ok Yu and Oh Joon Kwon 2014 Renewable Energy vol 70, Predicting wind turbine blade loads and aeroelastic response using a coupled CFD-CSD method pp184-196.
[9] SM Habali, IA Saleh and Local design 2000 Energy Conversion & management vol 4, testing and manufacturing of small mixed airfoil wind turbine blades of glass fiber reinforced plastics, Part I: Design of the blade and root pp 249-280.