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Damage detection method for wind turbine blades based on dynamics analysis and mode shape difference curvature information

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ABSTRACT

Blades are among the key components of wind turbines. Blade damage is one of the most common types of structural defects and can cause catastrophic structural failure. Therefore, it is highly desirable to detect and diagnose blade damage as early as possible. In this paper, we propose a method for blade damage detection and diagnosis. This method incorporates finite element method (FEM) for dynamics analysis (modal analysis and response analysis) and the mode shape difference curvature (MSDC) information for damage detection/diagnosis. Finite element models of wind turbine blades have been built and modified via frequency comparison with experimental data and the formula for the model updating technique. Our numerical simulation results have demonstrated that the proposed technique can detect the spatial locations of damages for wind turbine blades. Changes in natural frequencies and modes for smaller size blades with damage are found to occur at lower frequencies and lower modes than in the larger sized blade case. The relationship between modal parameters and damage information (location, size) is very complicated especially for larger size blades. Moreover, structure and dynamic characters for larger size blades are different from those for smaller sized blades. Therefore, dynamic response analysis for a larger sized wind turbine blade with a multi-layer composite material based on aerodynamic loads' (including lift forces and drag forces) calculation has been carried out and improved the efficiency and precision to damage detection by combining (MSDC) information. This method provides a low cost and efficient non-destructive tool for wind turbine blade condition monitoring.

1. Introduction

Renewable energy sources have attracted much attention due to their positive impact on society and environment. Wind energy is a fast developing clean renewable energy source. Wind turbines are being developed to enhance operational performance and yield through increasing blade size and improving structural design. It has been shown that blade crack may cause blade failure, and its repair is costly and requires substantial repair time [1]. To prevent severe blade damages and

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secondary failures, it is necessary to detect the early fault by regular monitoring, and continuing assessment of the structural health of wind turbine blades [2]. The purpose of this study is to develop a non-destructive testing method for wind turbine blade damage detection.

Over the past few decades, various sensors and non-destructive testing (NDT) methods such as fiber optics, acoustic emission, ultrasonic, X-ray, thermal imaging, laser Doppler vibrometer (LDV), strain memory alloy, and eddy current methods [3–9] have been explored for damage detection. Each of the methods has its own merits and limitations. In particular, their effectiveness for wind turbine blade condition monitoring and economic viability for such applications is yet to be investigated. In order to attain higher efficiency and lower cost, vibration-based approaches for damage detection have also received considerable attention in the literature [10–23].

Modal parameters (natural frequencies, mode shapes and modal damping) are functions of a structure's physical properties (mass, stiffness and damping). If any damage exists in a structure, the stiffness will be reduced. The reduction in stiffness may cause a decrease in the natural frequency and change the mode shape of the structure. Accordingly, many researchers have been using the decrease in natural frequency approach for damage detection in a structure [10–14]. By measuring or calculating the changes in natural frequencies, the presence of damage can be determined. However, to provide additional information to facilitate diagnosis, it is highly desirable to know the number, locations and severity (sizes) of damage(s). Such a task is challenge because two cracks of the same size may result in the same frequency but appear at different locations, and hence indistinguishable based on the frequency information alone. For this reason, some research has been directed towards using mode shapes to identify and locate damage in beams, plates and wind turbine blades. For example, Schulz et al. [15] present a damage detection method of constrained vibration deflection shapes (VDS) using a finite element model of a fixed-fixed beam. Larson et al. [16] have applied mode shapes to identify damage in a wind turbine blade using finite element analysis with a beam element model and experiments. Finite element method (FEM) is useful to analyze dynamic characteristics of structures and can be extended to simulate the static and dynamic parameters of wind turbine blades [17–19].

Damage detection by curvature mode shapes (CMS) has also been proposed in the literature. Pandey et al. [20] detected damage location according to the changes in curvature mode shapes. Their approach was based on FEM using a cantilever and a simply supported analytical beam model. Their study shows that CMS may sometimes be better than displacement mode shapes (DMS) in determining the damage location in a beam. Ratcliffe [21], and Cao and Qiao [22] introduced a modified Laplacian operator to CMS for structure damage identification. These studies have commonly utilized the numerical formula called "central difference approximation" for computing curvature mode shapes of beam. The CMS methods have some advantageous features such as the high sensitivity to the damage region and hence the ease of finding damage location. However, to enhance the accuracy of the CMS numerical formula for damage detection, it is necessary to determine the proper sampling interval. Sanzonov and Klinkhachorn [23] presented an optimal sampling interval for damage detection in a beam based on CMS and strain energy mode shapes, which could enhance the formula to reduce CMS calculation error for a beam. It is also noted that the changes in a uniform load surface (ULS) curvature have also been proposed to localize the damage for two-dimensional plane plate structures by Wu and Law [24].

For wind turbine blades with a bend-twist shape, especially larger sized hollow blades made of a multi-layer composite material, dynamic characters' changes depend on many factors such as structure, material, aerodynamic loads, or damages (including cracks and delamination) which occurred in the structure. The relationship between frequencies and mode shapes and the corresponding damage information (locations and size) is very complicated. Therefore, the single detection method using natural frequencies and mode shapes or CMS could not obtain robust and high efficient damage detection for wind turbine blades with complex structure and aerodynamic loads. In this paper, a novel damage detection technique for wind turbine blades is proposed. This technique combines the FEM based dynamics analysis (modal analysis and dynamic response analysis) and mode shape difference curvature (MSDC) information to detect single and multiple cracks, identify their locations, and diagnose their severity for wind turbine blades. Two types of wind turbine blades to be investigated have a complex 3D surface with a bend-twist shape. One of the wind turbine blades is 1.02 m in smaller size which is made of a fiber-glass, and the other one is 5.5 m which is made of a multi-layer composite material with a hollow structure. For the smaller wind turbine blade, a 3-dimensional (3D) solid model and a finite element model of the blade are developed using CAD and Finite Element software. To eliminate errors, the finite element model is modified (updated) by frequency comparison with experiment data obtained from the modal test. Based on the updated finite element model, the displacement mode shape difference between damaged blades (with single or multiple damages) and an intact blade, as well as the curvature of the mode shape difference can be calculated. The change in MSDC is then applied to detect locations of the cracks and examine their severity. For the larger sized wind turbine blade, the structure and dynamic characters are different from smaller size wind turbine blades. Therefore, we have also conducted numerical simulation for damage detection in a larger sized wind turbine blade. In this study, a finite element model of 5.5 m length wind turbine blade is built using shell elements with multi-layer composite material, aerodynamic loads (including lift forces and drag forces) are calculated, and then dynamics analysis (modal analysis and dynamic response analysis) is performed. By combining natural frequency and vibration response (frequencies and displacement at measurement points) changes, as well as mode shape different curvature information, the damage in blades can be efficiently and precisely detected. This integrated method is a reasonably good method to use for wind turbine blades. To the best of our knowledge, the detection of damage for wind turbine blades using this method has not been reported in the accessible literature.