



Modal-based damage identification for the nonlinear model of modern wind turbine blade



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ABSTRACT

In this paper, the modal-based indices are used in damage identification of the wind turbine blade. In contrast of many of previous researches, the geometric nonlinearity due to the large structural deformation of the modern wind turbines blade is considered. In the first step, the finite element model (FEM) of the rotating blade is solved to obtain the modal features of the deformed structure under operational aerodynamic loading. Next, the accuracy and efficiency of the various modal-based damage indices including the frequency, mode shape, curvature of mode shape, modal assurance, modal strain energy (MSE) and the difference of indices (between the intact and damaged blades) are investigated. To adapt the MSE index calculation in nonlinear modeling, a new approach is introduced to include the effects of the structural nonlinearity. Furthermore, the effect of the damage length, its location and severity and also the effect of rotational speed and amplitude of loading are studied. The generic 5-MW NREL blade is used for the simulation study. The results show enough sensitivity of the mode shape curvature and MSE indices to the local damages. Moreover, the importance of geometric nonlinearity in the damage detection of the modern wind turbines is demonstrated.

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1. Introduction

The global statistics of investment rate in the wind sources indicates their progressive importance in the future of the worldwide energy sources. Global installed wind power capacity for the IEA countries has doubled since 2011–2013 [1]. Many countries are planned to provide 10% of total electricity demand from the wind resources until 2020 [2]. Considering the wind as a reliable source of energy, requires more improvement of the cost and reliability of current wind turbine (WT) machines. This necessity makes many researches to be focused on developing specialized structural health monitoring (SHM) techniques for the WT application. The great wind resources are usually located in offshore and inaccessible regions with harsh environment condition. Moreover, the accessibility problem and the high cost of modern multi-megawatt WT makes the use of the infield and online SHM more essential. The blades are usually the most susceptible part of the wind turbine

structures to apply the online monitoring techniques. This is because of high failure rate and repairing expenses of the WT blade [3] and moreover the possibility of catastrophic secondary damage to the total of the WT system [4].

In the literature, different strategies have been proposed for SHM of the wind turbine blade. Principally, these methods can be divided into two groups. First, those strategies which use advanced measuring instruments such as: fiber optics sensors as a strain gage in the prototype [5] and the field application [6], network of advanced piezoceramic [7] or MFC (Macro-Fiber Composite) sensor/actuator patches [8], thermal and ultrasonic based approaches [9]. In addition, other possible techniques to be used in wind turbine SHM have been reviewed extensively by Ciang et al [4].

In contrast, the second group of strategies uses the conventional vibration accelerometer and develops the damage indices to accommodate with the WT blade application. The second group is greatly interested in industry due to its more reliability, accessibility, lower cost of instruments and also the rich documentation in the field of SHM. The most important indices of this group are based on the modal features that their applications for recent

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flexible WT blades are focused in this paper. Due to the limited research in the application of the WT blade, certain additional related works including the fixed and rotating beam application are additionally reviewed in the following.

Pawar et al. [10] applied the finite element approach for a composite rotating blade with crack which is modeled by the reduction of the elasticity module of the composite. The variation of the frequency and the tip response of the blade revealed that the torsional frequency is more sensitive to the severity of stiffness reduction. Adams et al. [11] used an FEM model of a wind turbine blade which is updated with the experimental test case (9 m length) to simulate the WT blade dynamics. They showed the low damage sensitivity of the frequency index (less than 4% for the case of 25% damage at the blade root) but the acceptable sensitivity of the MAC and modal contribution coefficients. Jassim et al. [12] investigated the different damage indices for a typical cantilevered beam model and reported that the indices based on CoMAC and MSC (mode shape curvature) are efficient for localizing the damage in beam-like structures.

Wang et al. [13] used the mode shape difference curvature (MSDC) index for damage detection in a FEM model of WT blade and showed that it had a better performance than the MSC index. In some other researches, more advanced MSC-based damage indices have been proposed to localize the damage in the beam-like structures without the requirement to the corresponding undamaged data; either by applying the wavelet analysis [14] or more complementary techniques [15]. However, due to the complex structure of the wind turbine blade and uneven variation of the structural properties along the blade span, it is expected that the approaches that use both damaged and intact blade are more efficient and robust.

Another recent index is the MSE index which is more advantageous in identification of the local damages. Dutta and Talukdar [16] used MSE index in damage identification of the FEM model of a bridge. In some researches, the accuracy and efficiency of damage detection using the MSE-based indices were experimentally examined for the cantilever beam model; e.g. the results of an aluminum beam with saw cuts damage [17] and the damage in face and core of composite sandwich beam [18]. Liu et al. presented a MSE-based approach for the damage localization in the tripod of a jacket-type offshore wind turbine [19]. Guan et al. [20] considering a uniform cantilevered beam investigated more aspects of the in-field application of the damage identification indices. In that work, some techniques were presented for improving the results of mode shapes derivatives which are required for evaluation of MSC and MSE indices. In similar work by Sazonov et al. [21], it was shown that the introduced techniques for taking derivatives of the mode shapes are more efficient and less sensitive to the noise effect than the customary used central difference methods.

On the other hand, during the past decades, the performance objectives have continually increased the structural dimensions and flexibility of the WT blades. This fact introduces certain nonlinearity due to the large deformation of the blades under aerodynamic operational loading. This is usually called as the geometric nonlinearity, which makes the nonlinear dynamic analysis of the WT blade more crucial [22,23]. Larsen and Nielsen investigated the effect of this nonlinearity in change of dynamic behavior [24] and stability boundary [25] of the simplified wind turbine blade. Otero et al. [26] used the VABS (Variational Asymptotic Beam Section Analysis) approach for the structural modeling to determine the modal properties of the 5MW-NREL blade in pre-stressed condition; under steady-state aerodynamic loading. Rezaei et al. [27] presented the relatively comprehensive nonlinear formulations and investigated the associated nonlinear effects on the modal properties and dynamic response of the

mentioned blade. They demonstrated that the geometrical nonlinearity causes the modal properties such as the frequency and mode shapes of the blade to be dependent on the deformation gradient of the blade under operational loading. Furthermore, since the local stiffness reduction in the damaged region of the blade, imposes a more severe structural local rotation, it would be predicted that the geometric nonlinearity effect is intensified for the case of the damaged blade; this consequence is confirmed in the results of this paper. The variation of the modal parameters due to the geometrical nonlinearity may cause inconsistency in the application of the current damage detection algorithm which is not mostly investigated in previous studies.

In this paper, a modal-based damage identification method is presented for a nonlinear model of modern wind turbine blades. In this approach, the modal properties of the damaged blade in pre-stressed deformation aerodynamic loadings are obtained using the ANSYS commercial finite element software. The specification of 5-MW NREL blade is used for structural modeling and simulation studies. Various modal-based damage indices including the frequency, mode shape, curvature of mode shape, modal assurance, modal strain energy (MSE) and the difference of indices (between the intact and damaged blades) are investigated. Their accuracy and efficiency in the damage detection problem is evaluated and compared. Thereafter, a parametric study is performed to investigate the effect of the damage length, location and severity (the depth of the damage). In addition, the effects of rotational speed and amplitude of loading on the performance of proposed damage detection approaches are studied.

2. Basic formulations & modeling

2.1. Structural modeling

The structural model of a three bladed wind turbine is shown in Fig. 1 demonstrating the large deformation concept and the blade with the local damage.

The blades are dominantly deformed due to the aerodynamic loading, as schematically demonstrated for the one of the blades in Fig. 1a. The detailed formulation of the aerodynamic loading is presented in the next section. The structural deformation of the blade is defined by three translational components of u , v , w and the angle of ϕ which are corresponding to the blade deformation along the longitudinal, edgewise, flapwise and torsional directions, respectively. In Fig. 1b, the length of damage and its location from the blade root are denoted by L_d and L_m , respectively. In this paper, the specification of the 5-MW reference wind turbine blade of the National Renewable Energy Laboratory (NREL) [28] is used for the simulation as depicted in Fig. 2. As it is shown, the distributions of the real wind turbine blades parameters are non-smooth function along the span.

The damage (Fig. 1b) is modeled with the local reduction of the blade stiffness specifications of Fig. 2b; at the associated region of the damage. Moreover, the damages are characterized by the stiffness reduction coefficient $\text{Coff}_{EI} = (EI)_{\text{damaged}}/(EI)_{\text{intact}}$, the damage length coefficient $\text{Coff}_{Ld} = L_d/L$ and the damage location coefficient $\text{Coff}_{Lm} = L_m/L$; L is the total blade length.

As the most of the previous studies on WT blades, the Euler-Bernoulli beam theory is considered for the structural modeling. This model is conveniently efficient and accurate enough for the beam-type structures with high slenderness ratio (L/D for considered blade is more than 20). The finite element model of the blade is developed by the commercial finite element software of ANSYS using the element type of BEAM188. In FEM of the blade, root boundary is rigidly connected to the support; rotating with the constant rotational speed Ω .

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