Mechanical Systems and Signal Processing ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Feasibility study on a strain based deflection monitoring system for wind turbine blades

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ARTICLE INFO

Article history:
Received 6 September 2015
Received in revised form
27 March 2016
Accepted 6 May 2016

Keywords:
Deflection monitoring
Vibration monitoring
Strain monitoring
Wind energy
Wind turbine blades

ABSTRACT

The bending stiffness of the wind turbine blades has decreased due to the trend of wind turbine upsizing. Consequently, the risk of blades breakage by hitting the tower has increased. In order to prevent such incidents, this study proposes a deflection monitoring system that can be installed to already operating wind turbine's blades. The monitoring system is composed of an estimation algorithm to detect blade deflection and a wireless sensor network as a hardware equipment. As for the estimation method for blade deflection, a strain-based estimation algorithm and an objective function for optimal sensor arrangement are proposed. Strain-based estimation algorithm is using a linear correlation between strain and deflections, which can be expressed in a form of a transformation matrix. The objective function includes the terms of strain sensitivity and condition number of the transformation matrix between strain and deflection. In order to calculate the objective function, a simplified experimental model of the blade is constructed by interpolating the mode shape of a blade from modal testing. The interpolation method is effective considering a practical use to operating wind turbines' blades since it is not necessary to establish a finite element model of a blade. On the other hand, a sensor network with wireless connection with an open source hardware is developed. It is installed to a 300 W scale wind turbine and vibration of the blade on operation is investigated.

1. Introduction

The upsizing trend of wind turbines has been driven by needs to build a more cost-effective wind power system [1,2]. Since available power from the wind is proportional to the area of blades wiping, the longer blades are mounted on a wind turbine, the more input power can be captured. However, upsizing of the blade length causes a decrease in bending stiffness and leads to strike of a blade with its tower [3–5]. This kind of failure is more frequently occurred in mountainous countries, such as Japan. It is because the turbulence intensity of the wind condition is higher in mountainous terrain than in flat terrain. When the wind speed fluctuates, sometimes the periodic frequency of the wind could match the blades' natural frequencies, which forces the blades to oscillate extremely. If a wind turbine blade is damaged due to extreme vibration,

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http://dx.doi.org/10.1016/j.ymssp.2016.05.011
0888-3270/

Please cite this article as: K. Lee, et al., Feasibility study on a strain based deflection monitoring system for wind turbine blades, Mech. Syst. Signal Process. (2016), http://dx.doi.org/10.1016/j.ymssp.2016.05.011

repairing or changing the blade costs a lot and leads to long downtime. Therefore, some wind power operators stop the rotation of wind turbines when wind condition is not appropriate. However, since the vibration of blades is dependent not only on wind speed or fluctuation of speed, but also on other factors such wind shear, tower shadow effect, and so on, stopping a wind turbine on wind condition is only a temporary measure. Instead of that, a direct monitoring system for blade deflection can be a solution to avoid a blade smash up with its tower and also to improve availability [6]. Such monitoring methods can be established with various ways.

Park et al. [7] proposed a useful method to predict the vibratory behavior of the rotating blade. And a three bladed wind turbine vibration is examined to determine the presence of cracks using accelerometers [8]. Fleming et al. [9] calculated the parameters of the blade model to know the structural dynamic response of the blade.

Numbers of methods for monitoring using the fiber Bragg grating (FBG) sensors have been applied to the wind turbine blade since optical fiber sensors are less sensitive to electrical and magnetic interference and immune to the effects of lightning strikes. The aims of measurement by FBG sensor are, for instance, to detect damage [10] or monitor structural responses such as bending loads [11–13].

There are several methods of non-contact measurement. A single laser displacement sensor (LDS) system is installed in the tower to enable non-contact blade displacement monitoring [14]. Some studies have developed video metric technique to determine the blade deformation [15]. Photogrammetric 3D measurement systems using high-speed cameras are suitable as well to monitor the rotation status of the wind turbine blades. Digital image correlation (DIC) algorithm is used for 3D measurement such as the photogrammetric approach [16,17]. Additionally, a MEMS-based gyroscope sensor is proposed using a neural network model-based estimation method to estimate the blade tip deflection [18].

Also, in the following research, strain based deflection monitoring methods are studied. Strain sensors are installed on a cantilever beam, and a deflection estimation method is presented in [19–21]. Refs. [22,23] described strain based deflection estimation for a rotating cantilever beam and fixed wind turbine blades. In Ref. [24], strain gauges were installed at several places of the blade specimens for static structural testing. An error assessment of strain sensor signal interpretation was performed by comparing laboratory and numerical tests [25]. In these cases, sensor positioning is important because it determines the strain sensitivity, which affects the accuracy of deflection estimation. To arrange the sensor positions, strain sensitivity is investigated by a FE model [19–23].

As we see in the referenced research, the deflection monitoring system can be done in various ways. However, considering that strain information can be utilized not only to obtain deflection but also to estimate load conditions or detect abnormalities such as cracks by signal processing, strain based deflection monitoring method is worth to research. Moreover, other monitoring systems and wind turbine blades can be designed in a more optimized way through an analysis of monitored strain information.

To develop strain based deflection monitoring system, nevertheless some studies have been researched so far, still there are a lot of things remained to study for practical use. In the referenced research, a FE model of a wind turbine blade is utilized, however, typical wind turbine operating companies possess neither FE model nor detail designs of their wind turbines blades so that such methods are sometimes not applicable. Therefore, we develop a system easily installing to operating turbines without a FE model of a blade. The solution is calculating the strain distribution corresponding to the each vibration mode of the blade directly from a modal testing without a FE model. This can be done by interpolating mode shapes of the blade and differentiating the interpolation function. Also, a method to optimize the strain sensor locations is provided. Sensor locations are optimized by setting objective function that includes terms of the condition number of the transformation matrix and the calculated strain sensitivity. In order to test the feasibility of the strain based monitoring method, the accuracy under the wind is also evaluated. Finally the entire system is mounted on a 300 W scale wind turbine and, under wind blowing condition, the behavior of a blade was investigated. As a sequel to the experiments, the monitoring system enabled us to monitor the deflection of a blade in operation.

This paper consists of as follows: firstly theoretical verification of the algorithm is introduced, which describes the displacement estimation method and the optimal sensor positioning method without FE model. And then experimental studies are done to evaluate the proposed methods. The experimental study includes the modal testings to derive the correlation between the strain and the displacement of the blade. The estimation error evaluation for the algorithm is conducted not only by the impact hammer test but also under the wind. Using the developed system, the vibration of 300W scale wind turbine is measured. Finally, the conclusion of this research is given.

2. Theory

2.1. An estimation algorithm for strain based deflection

A deflection of wind turbine blades can be estimated by obtaining a transformation matrix which defines the correlation between strain and deflection of a blade. The size of the transformation matrix is dependent on how many numbers of vibration modes are targeted to be monitored. Then the matrix elements are determined by strain sensitivity at the position of strain sensors and a targeted point of deflection on the blade.

The transformation matrix can be derived from the equation of motion of a blade. Considering the shape and the boundary condition of a blade as well as the simplified equation of motion, the blade can be assumed as a tapered cantilever

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