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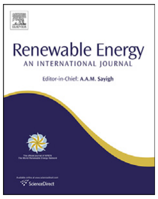

Development of fatigue life prediction method and effect of 10-minute mean wind speed distribution on fatigue life of small wind turbine composite blade

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A B S T R A C T

This study aims to develop a fatigue life prediction method and to identify the effect that a 10-minute mean wind speed distribution has on the fatigue life of a small-scale wind turbine composite blade. First, combining the von Karman isotropic turbulence model and the Weibull distribution for a 10-minute mean wind speed provided us with the 1-Hz full wind history for a specific time period. Accordingly, the fatigue stress spectra at the blade's fatigue-critical locations (FCLs) were created by applying a stress tensor, in which the interaction between flapwise and edgewise bending moments was taken into consideration. The fatigue life of a composite blade can be predicted with a reliability $R = 95\%$ by applying the P–S–N curve obtained from the constant amplitude fatigue tests and rainflow cycle counting, and cumulative damage rule to the fatigue stress spectra. To acquire the second-order regression equation, nonlinear regression analysis was performed on the fatigue lives, which were simulated by using the proposed fatigue life prediction method. In this equation, the variables were the shape parameter, K, and the scale parameter, C, of the Weibull distribution for a 10-minute mean wind speed. The effects of the Weibull parameters on fatigue life were evaluated through the sensitivity analysis of the equations.

1. Introduction

Generally, wind energy conversion systems (wind turbines) are fatigue-critical systems: therefore, their main components (especially, the blades) should be designed to have higher fatigue resistance [1,2]. The fatigue load on a blade is generated by winds that were random in nature. Under such loading conditions, a blade should have more than 20 years of design life [3]. In particular, fiber reinforced plastics, which are used to improve the weight reduction of a blade, exhibit significantly different fatigue behavior with respect to other existing metal materials [4].

Many studies have been conducted on the fatigue behavior and life prediction of wind turbine composite blades [5–8]. Kensche [5] reviewed some of the fatigue and life aspects of wind turbine composite rotor blades, including the required S–N curves, and the influence of environmental effects on fiber content and architecture. Sutherland and Kelley [6] analyzed the effect of mean stress on the prediction of damage, resulting from the typical wind turbine load spectra, using a detailed Goodman diagram for characterizing the behavior of composites used in wind turbine blades. Sutherland and Kelley [7] analyzed the site dependence on the loading spectra using the well-known WISPER load spectrum and showed that there are fundamental differences in the fatigue damage resulting from the loading spectra. Mandall et al. [8] summarized important findings related to the strength and fatigue resistance of composite materials and the substructural elements intended for application in wind turbine blades. Even though these studies showed positive results for the fatigue of composite blades in various ways, it remains of the utmost importance to continue the study of the fatigue behavior of composite blades because the behavior is affected by various factors such as material characteristics, structural architecture, environmental conditions, and loading spectrum.

Considering the intrinsic mechanism of a wind turbine that generates electric energy from the kinetic energy of wind, the most important environmental factor is the wind conditions at the specific site where the wind turbine is installed. A wind turbine should be designed to maximize the annual energy production with a given 10-minute mean wind speed, expressed in the two parameters Weibull distribution [3]. Such wind conditions significantly affect not only the performance of the wind turbine but also its safety. In particular, the

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fatigue loading spectrum exerted on a blade also varies significantly according to the wind conditions. Studies on the structural integrity of blade or the effect of wind conditions—wind speed distribution in particular—on fatigue life have been conducted previously, Epaarachchi and Clausen [9] developed a methodology to create a fatigue loading spectrum using the blade stress cycles determined by detailed measurements made in conjunction with 18 long-term wind datasets measured by the Australian Bureau of Meteorology. They [10] also created an annual fatigue loading spectrum for the blades by using short-term, detailed aeroelastic and measured wind conditions, and developed an accelerated full-scale fatigue test method for a small composite blade. Also, Lange and Winterstein [11] proposed a three-moment-based quadratic Weibull load distribution to overcome some of the deficiencies found in the standard Weibull models by using a power–law relationship and wind measurements. Noda and Flay [12] developed a procedure to generate a flapwise fatigue loading spectrum for a medium scale blade. They utilized the cumulative fatigue damage model and a synthetic wind spectrum to estimate the damage in the blade root. These studies have evaluated the fatigue damage on a blade or have developed a fatigue loading spectrum using wind speed. It is thought that a 10-minute mean wind speed distribution, expressed by a Weibull distribution, has a significant effect on the fatigue life of a blade. However, few studies have been conducted on the dependence of the fatigue life of a blade on the wind speed distribution.

This study developed a procedure for the fatigue life prediction of a small-scale composite blade and determined the effect of wind conditions on the blade's fatigue life. First, combining the von Karman isotropic turbulence model and the Weibull distribution for a 10-minute mean wind speed provided us with the 1 Hz full wind history for a specific period. Accordingly, the fatigue stress spectra at the blade fatigue-critical locations (FCLs) were created by applying a stress tensor, in which the interaction between the aerodynamic force and the flapwise and edgewise moment were taken into consideration. Then, rainflow cycle counting and the cumulative damage rule were applied to the fatigue stress spectra to predict the fatigue life of a blade by considering the uncertainty of the composite materials utilized in blade. Also, based on the above procedure, the fatigue life according to the wind speed distribution was obtained, and nonlinear regression and sensitivity analyses were performed.

2. Analysis and experiment procedure

This study was conducted to develop a fatigue life prediction method and to determine the effect of the wind speed distribution on the fatigue life of a composite blade of a small wind turbine system whose specifications are listed in Table 1. Also, Fig. 1 shows the procedure used in this study for fatigue life prediction and the sensitivity analysis of wind speed distribution on fatigue life.

2.1. Development of fatigue life prediction procedure

2.1.1. Wind history

To predict the fatigue life of a composite blade, at least 0.5 Hz data, rather than 10-minute mean data, are required. However, it is almost impossible to measure 0.5 Hz wind data for period of time enough to a fatigue life prediction. Thus, this study used a von Karman isotropic turbulence model [13] to obtain a 1-Hz unit wind history at a specific wind speed and turbulence intensity, as specified in the IEC 61400-2 [2].

Table 1
Specifications for small wind turbine.

Rated power	1.5 kW
Cut-in wind speed	3.0 m/s
Cut-out wind speed	22.5 m/s
Rated wind speed	10.5 m/s
Rated rotational speed	300 rpm
Blade length	1.42 m

In addition, wind speed distributions at various sites were studied to evaluate the effect of Weibull distribution for 10-minute mean wind speed on fatigue life. In this paper, the Weibull distributions for 10-minute mean wind speed [14–18] obtained from 25 sites located in the Republic of Korea, China, Nigeria, Yucatan Peninsula, Turkey, Canada, Brazil and Algeria were used. The full wind speed history at each site was reproduced using the above-mentioned 1-Hz unit wind history and the Weibull distribution, as shown in Fig. 2. Table 2 lists the Weibull parameters for the 10-minute mean wind speed at each site.

2.1.2. Aerodynamic forces

The blade used in this study is utilized a small wind turbine with a rated power of 1.5 kW and wind speed of 10.5 m/s. The open source code PROPID [19] based on blade element momentum theory (BEMT), was used to calculate the aerodynamic forces exerted on this blade. In this manner, the flapwise and edgewise moments resulting from the wind speed at each section were obtained.

2.1.3. Fatigue test

Fatigue tests were performed to determine the fatigue behavior of the blade material. The blade material was DBL 600E triaxial glass/epoxy composite, and the specimens were processed in the 0° and 90° directions with respect to the fiber orientation. The test was conducted under the conditions of a stress ratio of $R = 0.1$ and at 60%, 50%, 40%, and 35% of the blade material's tensile strength. The test frequency was 2 Hz, the infinite life was set to 10^6 cycles, and the testing machine was an Instron model 8801 hydraulic fatigue-testing machine.

2.1.4. Finite element analysis

Structural analysis was performed using commercial software ABAQUS [20], and the blade was modeled using shell elements such as S4R and S3R, as shown in Fig. 3. The number of elements and nodes were 19,035 and 19,074, respectively, and the boundary conditions were the translations in the X, Y, and Z directions and the rotation along the Y and Z directions at the blade root.

In addition, we used two types of loading conditions. First, the aerodynamic forces, calculated by using the BEMT-based software, were applied to the nodes of the blade to identify the FCLs. Also, 25 types of unit loads were applied to the blade tip, as listed in Table 3, to determine the effect that the mutual interaction between the flapwise and edgewise loads has on the local stress in blade.

2.1.5. Fatigue life prediction

The bending moment spectrum was derived from the 1-Hz full wind speed history, which was obtained by using the method described in Section 2.1.1 and the moment–wind equation in Section 2.1.2. Furthermore, the P_E/P_F spectrum, which represents the ratio of the flapwise moment to the edgewise moment, was generated to determine the interaction when the flapwise and edgewise bending moments were exerted at the same time.

We obtained the fatigue stress spectra at the FCLs of the blade by combining the above. Finally, the fatigue life of the composite blade was predicted using rainflow cycle counting, the Goodman equation, and Miner's cumulative damage rule.

2.2. Nonlinear regression and sensitivity analysis

To analyze the effect of the Weibull distribution for a 10-minute mean wind speed on the fatigue life of the composite blade, nonlinear regression and sensitivity analyses were performed.