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Development of robust and adaptive controller for blade testing machine

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ABSTRACT

Nowadays, the majority of wind turbine blades are produced from composite materials which are subject to severe operational loadings. Thus, the composite material's behavior against in-service loadings is a great concern for wind turbine blade designers. This dictates the need for an experimental set-up for conducting real part experiments as similar as possible to in-service loadings. This research proposes a cost effective blade testing machine which is capable of conducting ultimate static and fatigue tests according to wind turbine blade standards. A new control unit is designed and implemented to track fatigue block loading in the frequency range of 1–3 Hz. The main focus is on designing a controller to perform desired block loading fatigue tests. The open loop transfer function is identified and the system uncertainty is calculated. PI, robust feedback and Two-Degree-of-Freedom robust controllers are designed and analyzed. Due to the poor robust performance, an adaptive feed forward controller is proposed based on the gain scheduling algorithm. Experimental results of the newly developed controller indicate a performance robustness. The proposed controller could be implemented for systems with large low frequency uncertainty at its operational frequency range, for example applications that the stiffness is variable during operation.

1. Introduction

Blades are one of the most critical components of a wind turbine as a failure of one blade can lead to the total destruction of a wind turbine and widespread damage to the turbine surroundings [1]. Nowadays, full scale blade tests must be conducted is order to ensure that blades can tolerate both ultimate and fatigue loads encountered during the designed service life. These tests also provide manufacturers and designers with the confidence of knowing their products have a defined reliability.

Wind turbines blades undergo intense loadings throughout their service life. The main source of mechanical loadings is originated from aerodynamic forces applied on the blade. The stochastic nature of the wind causes the load variations on rotor blades. In addition to aerodynamic loads, blades are also subject to gravity and inertial forces. The wind turbine blades have a resonance frequency that will be excited by turbulence. The wind shear and tower shadow could excite the blade mode shapes [1]. Further details of the wind turbine blade loadings could be found in Ref. [2].

Wind turbine blades are a specific usage of composite materials in the sense that they are subject to an unusual loading environment. The composite blades have been designed for high specific stiffness, outstanding fatigue properties, low density and tailored materials properties in different directions and locations. The mechanical behavior of the blade, such as stiffness, damping and strength along the blade length, is usually determined with large uncertainty. The calculations of stiffness, mass and inertia distributions along the blade length are performed using experimental data [3].

Wind turbine blades encounter a large number of cyclic loads throughout their targeted lifespan. A fracture of a structural member, as the result of repeated load cycles or fluctuating loads, is commonly referred to either *fatigue failure* or *fatigue fracture*. The corresponding number of load cycles or the equivalent time before observation of any fracture criteria is referred to as *fatigue life*. This depends on many factors, of which the load history, manufacturing method and blade size are among the most notable [4]. Moreover, the anisotropic characteristics of a composite blade can largely complicate fatigue analysis [5].

The stiffness and damping of composite materials, such as

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fiberglass composites, vary during the fatigue life. Abo-Elkhier et al. [6], measured composite parameters variations caused by the fatigue test. The experimental modal analysis was conducted on the specimens that were subject to fatigue loading in order to determine the modal parameters, such as natural frequency and damping ratio. For the laminated composites, the stiffness was reduced 25% and damping ration is increased by 10 times when the specimen endures 90% of its fatigue life.

Various forecast methods have been proposed and investigated for the lifespan of wind turbine blades, further details can be found in Ref. [7]. The load history could be approximated by wind turbine blade simulations [8,9]. The equivalent fatigue test load is obtained by matching the damage caused by 20-year-design load spectrum [7]. The number of load cycles is estimated up to 10^8 or 10^9 cycles for 20 years of service life [10]. These loads are always of variable amplitudes as depicted in Fig. 1. Fatigue analysis is usually characterized by amplitude, average and frequency. The variable load history can be converted to a series of constant amplitude loads, which could cause an equal damage accumulation as the actual loads [1]. The series of constant amplitude loads is usually referred to as *block loading* [11].

The accurate estimation of wind turbine blade fatigue life is a challenging task in practice [12]. This is due to the fact that a complicated time load history and small changes in the previously mentioned conditions may strongly affect fatigue life. Thus, designers are willing to rely on full-scale blade tests in similar conditions as those in the real operation [10,13]. In addition, there are globally accepted standards and certification procedures for full-scale rotor blade tests, such as IEC-61400-23 (2001) [14] and GL-2010 [15].

In order to perform wind turbine blade test according to IEC 61400-23(2001) [14], the design loads or design strength should be clearly specified, in order that the test loads can be determined. The purpose of the load-envelope testing is to demonstrate that the tested blade, within a certain level of confidence, has met the structural design requirements for operating or extreme load conditions. Strength-based testing uses as-manufactured blade strength data as its basis. The designed loads and design strength test types are normally used by the designer/manufacturer to determine the reserve strength by loading the blade to destruction which consist of static and fatigue test. For static testing, the blade should be loaded to the most severe design load condition, while for fatigue test the loading is computed based on the equivalent fatigue damage. The recommended sequence of static and fatigue test are: non-destructive static tests, fatigue test and residual strength test conducted according to IEC 61400-23(2001) standard [14].

The amplitude of the fatigue loading can be increased, which is inferred from standard test procedures. For example, J. Paquette et al. [16] conducted fatigue tests for 9-m wind turbine blades. After the first one million cycles, they increased the load amplitude by 10% for every 0.5 million cycles.

Most well-known international rotor blade test laboratories conduct single axial fatigue test experiments which are gradually upgraded to dual axial fatigue testing. In single axis experiments, flap wise and edge wise experiments are separately conducted [17]. Some advantages of the single axis experiment can be summarized as follows: simple hardware, well-tuned bending moment distribution and high frequency excitation [17].

A Comprehensive description of blade testing machines is presented in Ref. [18]. There are two types of fatigue testing machines for full-scale wind turbine blades: forced displacement and resonance excitation. The strain and deflection of the blade is measured during tests [10,13]. Strain measurement in these tests is a challenging experimental task. More information about the assessment of strain measurement in wind turbine blade tests is available in Ref. [19].

In the forced displacement type of fatigue testing machine, forces are commonly exerted on the blade by a servo hydraulic system. Fig. 2 shows a dual axis blade testing machine operated by a servo hydraulic system. Servo hydraulic actuators with a large stroke and velocity are usually very expensive. In addition, the forced displacement type cannot be employed for static tests, because of the large deformation of the full scale blade static test in comparison to fatigue test deformation.

The resonance excitation type of fatigue testing machine uses unbalanced masses attached to the blade that are moved by a servo hydraulic system. These unbalanced masses are excited near the first natural frequency of the blade, thus resulting in a large strain on the blade with low energy consumption [14]. It is an efficient and cost-effective method but has some limitations. The weight of the blade is a constant force applied to the blade which is maybe different from the in-service load. Thus, there is a significant difference between the applied set-up loads and the actual in-service loads. The average force distribution could be tuned by extra masses on the blade, but each extra mass will decrease the blade's natural frequency. Consequently, the frequency of cyclic loads is reduced and the required testing time increased. More importantly, it is not possible to adjust the average force during the fatigue test and, lastly, the above mentioned resonance type device cannot be used for static tests.

A dual axis blade testing machine is proposed in Ref. [20]. The

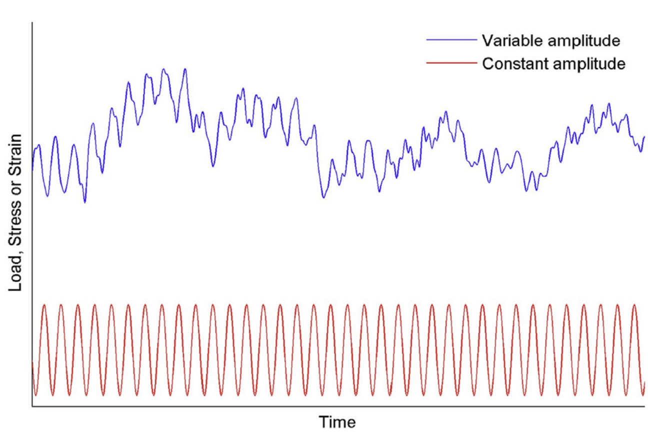

Fig. 1. Comparison between variable amplitude and constant amplitude load history [1].

Fig. 2. Dual axis blade testing machine [18].