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Design studies of swept wind turbine blades

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ABSTRACT

The growth of wind energy is sustained by innovation that lowers the cost of energy. One recent innovation is the swept blade, which deflects in operation and lowers loads. With sweep, a design rotor diameter can increase, capturing more power, with the loads remaining within limits. This concept has been demonstrated in a U.S. program and is in commercial production. This paper describes a parametric study of swept blade design parameters for a 750 kW machine. The amount of tip sweep had the largest effect on the energy production and blade loads; other parameters had less impact. The authors then conducted a design study to implement a swept design on 1.5 MW, 3 MW, and 5 MW turbines. An aeroelastic code, previously described, was developed to model the behavior and determine the loads of the swept blade. The design goal was to increase annual energy production 5% over the straight blade, without increasing blade loads. Successful designs were developed for the 1.5 MW and 3.0 MW turbines. The swept 5 MW turbine exhibited a twist instability at high wind speeds. Further study is required to determine if sweep can be implemented for larger turbines, which are approaching flutter boundaries in unswept designs.

1. Background

1.1. Introduction

Given the static policy environment, lowering the cost of energy (COE) is the primary means for continued growth of the wind energy industry. One method for lowering the COE is to increase the rotor diameter to capture more power; however, the loads on the blades and turbine increase. Turbine components must be strengthened to withstand the increased loads, raising costs. There are several methods to lower the loads on blades, and they fall into two categories: active and passive load control.

Active load controls implies that energy (actuation) be provided to control load. Active methods include individual pitch control [1], and active aerodynamic control [2,3]. The disadvantages with active control are added complexity, potential reliability problems, and added power requirements.

Passive load control implies that the system acts in a manner which reduces loads when disturbed. Two examples are bend-twist coupling [4] and blade sweep. With all methods, the rotor diameter can be increased given the same load envelope as a baseline design.

A swept blade is more complex to manufacture and increases cost; however, the cost of energy overall is lowered because more power is produced. The loads are reduced because in turbulent winds the blade tip twists and lowers the aerodynamic forces (passive load control). Fig. 1 illustrates the concept, with the tip of the loaded blade (dashed line) twisting counter-clockwise, lowering its angle of attack which lowers the aerodynamic forces.

Liebst [5] and Zuteck [6] proposed using swept blades on wind turbines for passive load control. Liebst analyzed a model of a 10 kW turbine with swept blades. His objective was to lower the loads for a given rotor diameter. The analysis showed that lowering the torsional rigidity (flexibility in twist) of the blade would be necessary for effective load relief. Zuteck proposed sweep as an alternative to bend-twist coupling, and conducted design studies with sweep on a 1 MW wind turbine. He also found that lowering the torsional stiffness would be necessary to obtain sufficient twisting; on the order of 5°. He also proposed increasing the rotor diameter to lower the cost of energy.

As a follow-on to Zuteck's work, a team led by Knight & Carver produced the STAR (swept-twist adaptive rotor) [7] for a U.S. Department of Energy program. The STAR program included the design and manufacture of a swept blade rotor with increased

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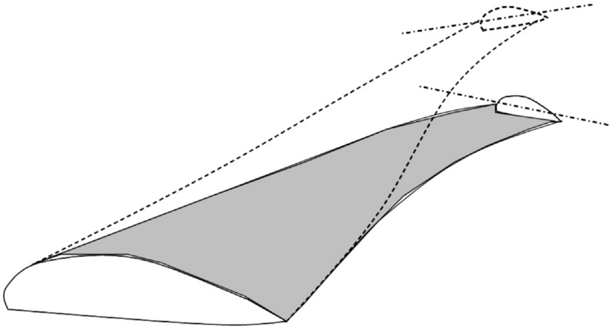

Fig. 1. Swept blade concept: solid line represents unloaded, dashed line represents loaded with tip twisting.

diameter for a 750 kW turbine. Two blades were constructed for laboratory tests, and a complete rotor set was installed on a Zond Z-48 turbine in Tehachapi, California, as shown in Fig. 2. The STAR turbine showed a 12% increase in energy capture over similar turbines in the wind plant. The measured loads on the STAR turbine were below the design loads for the Z-48 turbines, and were similar to loads measured on Z-48 turbines at other wind plants.

Verelst and Larsen [8] described parametric modeling of swept blades on a 5 MW turbine with 120 variations in the sweep parameters. Their study included forward sweep of the blades. They found load benefits in backward swept blades but instabilities in forward swept blades. Siemens started large scale production on 53 m swept blades (with the name Aeroelastic Tailored Blade) for a 3 MW turbine in 2012.

The current work is an extension of the lead author's dissertation [9]. For this work, the authors performed a parametric study of swept blade design parameters for the STAR blade. The results show that amount of tip sweep is the most sensitive parameter for load reduction. The authors used this information to design swept blades for 1.5 MW, 3.0 MW and 5.0 MW wind turbines. The design goal was to increase annual energy production (AEP) by 5% over a baseline straight blade and lower the lifetime flapwise bending loads (Fig. 1 shows the blade in flapwise bending). The 1.5 MW and 3 MW designs show successful increase in AEP and lowering of flap bending loads. The swept 5 MW turbine exhibited a twist instability at high wind speeds. Further study is required to determine if sweep can be implemented for larger turbines, which are approaching flutter boundaries in unswept designs.

Fig. 2. STAR swept blade rotor in Tehachapi, CA 2008 (photo by H. Shiu).

2. Methods

Fig. 3 shows the blade sweep parameters for this analysis. The sweep curve starts a specified distance along a blade, at about 40% of the radius for the STAR blade [7]. The authors expected that sweeping the entire blade increases manufacturing complexity with no benefit. The tip sweep is the distance from the pitch axis of the blade (about which the entire blade rotates while being pitched) to the sweep curve. The sweep curve as established by Zuteck in the STAR program was:

$$y = d_{\text{tip}}\left(\frac{x - x_{\text{start}}}{L_{\text{blade}} - x_{\text{start}}}\right)^{\gamma} \tag{1}$$

where y is the local distance from the pitch axis to the sweep curve, d_{tip} is the distance from the pitch axis to the sweep curve at the blade tip, x is the local distance along the blade measured from the blade root, x_{start} is the position of the beginning of the blade sleep, L_{blade} is the length of the blade, and γ is the sweep exponent. Another design parameter is the torsional stiffness, which is a measure of the twisting flexibility of the blade about the elastic axis.

For the swept blade analysis, the authors used CurveFAST, which is an extension of the National Renewable Energy Laboratory's (NREL) FAST [10] wind turbine analysis code. CurveFAST models the swept blade motions and aerodynamics (aeroelastic modeling) under turbulent wind conditions.

The blade model allows for four mode shapes, which are the blade shapes when vibrating at the particular mode's natural frequency. Fig. 1 is an example of the first mode shape, which is mostly flap bending in addition to twisting. The three other mode shapes are called first edge bending, second flap bending, and first torsion. Edge bending is mostly in-plane motion, transverse to that shown in Fig. 1. The mode shapes are determined by a finite element code called CurveFEM, which models the blade under rotation. These mode shapes are then input to CurveFAST.

Larwood and van Dam [11] report on verification and validation of CurveFAST. 'Verification' is defined as comparison with results from other software programs/solutions (are the equations solved correctly), and 'validation' is defined as comparison to test data (are the correct equations being used). The verification used the multibody code Adams™and showed agreement to within 5% on power, flap bending, and edge bending loads. Validation with field test results were inconclusive due to uncertainties in the wind speed measurements and the turbine controller.

The current design study includes modeling that is similar to the normal turbulence model (NTM) for the IEC (International Electrotechnical Commission) 61400–1 Design Requirements for Wind Turbines [12]. Each model run was a 10 min turbulent simulation, which had a nominal 10 min average wind speed varying from 3 m/s to 25 m/s in 2 m/s steps. The NREL program TurbSim [13] generated the wind files with the Kaimal spectrum for the IECA normal turbulence model. Each wind speed step consisted of five 10-min simulations with the random seed equal to the computer