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Supercritical and subcritical dynamic flow-induced instabilities of a small-scale wind turbine blade placed in uniform flow

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ABSTRACT

There is a growing interest in extracting more power per turbine by increasing the rotor size in offshore wind turbines. As a result, the turbine blades will become longer and therefore more flexible, and a flexible blade is susceptible to flow-induced instabilities. In order to design and build stable large wind turbine blades, the onset of possible flow-induced instabilities should be considered in the design process. Currently, there is a lack of experimental work on flow-induced instabilities of wind turbine blades. In the present study, a series of experiments were conducted and flow-induced instabilities were observed in wind turbine blades. A small-scale flexible blade based on the NREL 5 MW reference wind turbine blade was built using three-dimensional printing technique. The blade was placed in the test section of a wind tunnel and was subjected to uniform oncoming flow, representing the case of a parked wind turbine blade. The blade's tip displacement was measured using a non-contacting displacement measurement device as the oncoming wind speed was increased. At a critical wind speed, the blade became unstable and experienced limit cycle oscillations. The amplitude of these oscillations increased with increasing wind speed. Both supercritical and subcritical dynamic instabilities were observed. The instabilities were observed at different angles of attack and for blades both with and without a geometric twist. It was found that the blade twist had a significant influence on the observed instability: a blade without a twist experienced a strong subcritical instability.

1. Introduction

Among the well-established sources for clean energy production, wind energy is one of the most critical ones. Onshore wind energy has been the world's fastest growing energy source for more than a decade (Watson et al., 2005), and there is an increasing interest in using offshore wind turbines, especially in deep water (Henderson et al., 2003; Jonkman, 2007; Twidell and Gaudiosi, 2009). One of the major benefits of the offshore wind turbines is the possibility of using larger blades, which will lead to higher power generation. With the relatively high construction and installation cost of the offshore platforms, being able to use larger blades is a key in making the offshore wind turbine designs feasible. Ideally one would want to make the blades as large as possible to increase the generated power – but how large?

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Large wind turbine blades are susceptible to various flow-induced dynamic instabilities. These are instabilities that occur due to the highly nonlinear interaction between the structure and the flow around it. In the case of a large wind turbine blade, the blade behaves as a flexible structure due to its large aspect ratio, and therefore can have very large deflections. The deflection of the structure results in a change in flow forces that act on the structure, which in turn results in a change in the structure's deflection, yet again.

A thorough understanding of the fundamental physics of possible blade instabilities is crucial for designing new generations of wind turbines with higher efficiency, hence reducing the wind energy cost. Although various instabilities have been considered extensively for several dynamical systems, the instabilities of wind turbine blades are not well understood (Hansen, 2007), mainly because of their complicated geometry and their highly nonlinear interaction with flow.

Hansen (2007) has reviewed the major studies on aeroelastic instabilities of wind turbines. The two major aeroelastic instabilities of wind turbine blades are stall-induced instability for stall-regulated turbines, and flutter for pitch-regulated variable-speed turbines. Another major source of instability in wind turbines is controller-induced instability (Hansen, 2007). Stall-regulated turbines can experience stall-induced vibrations leading to undesired large-amplitude vibrations of blades (e.g., Rasmussen et al., 1999; Chaviaropoulos, 1999, 2001; Thomsen et al., 2001; Hansen, 2003; Liu et al., 2013). Larsen and Nielsen (2006, 2007) have used a nonlinear model to study stall-induced oscillations of a wind turbine blade. They have observed quasiperiodic and chaotic oscillations for a wind turbine blade, using their two-degree-of-freedom system. Pitch-regulated turbines, however, operate in attached flow and may have the risk of flutter. There have been some numerical studies on flutter instability in wind turbine blades, using linear models (Lobitz, 2004, 2005; Hansen, 2004a, 2004b). These models have been used to estimate the possible blade instabilities. In general, various tools have been developed for stability analysis of wind turbine blades (e.g., Chaviaropoulos, 2001; Riziotis et al., 2004), but the experimental studies are lacking (Hansen, 2007).

Linear models can be used to understand the qualitative nature of the possible instabilities. Using a linear numerical analysis, Lobitz (2004) showed that flutter occurs at lower speeds for larger and more flexible blades, by focusing on two specific blades. He also showed that including twist and aeroelastic tailoring in innovative blade designs increases the blades proclivity for flutter. Using an eigenvalue approach, Hansen (2004a, 2004b) predicted the critical values for flutter, both for a single blade and a full turbine, showing that a single-blade model can predict the flutter limit rather accurately – at least from a linear point of view. It is also shown numerically that in general the onset of flutter decreases for increased flapwise deflection (Lobitz, 2005).

The subject of limit cycle oscillations of wings placed in uniform flow has been studied extensively in the aerospace community. While the majority of studies are for a flexibly-mounted rigid wing, there are some studies on flexible wings. For example, Patil and Hodges (2000), Patil et al. (2001) and Tang and Dowell (2004) discussed the nonlinear aspects of the limit cycle oscillations for a high-aspect-ratio wing. Tang and Dowell (2001, 2002) conducted a series of experiments and observed subcritical limit cycle oscillations for a wing with a constant cross-sectional area along its length, with no twist and with a slender body attached to its tip. They used these experimental results to confirm their theoretical prediction. Patil et al. (2001) studied limit-cycle oscillations of a high-aspect-ratio wing numerically and using a nonlinear model.

Flow-induced instabilities of helicopter blades have been the subject of several studies as well. For example, Fulton and Hodges (1993a, 1993b) discussed a finite-element stability analysis tool to study a hingeless, composite, isolated rotor blade in hover. Cesnik and Hodges (1997) expanded the method to generally represent anisotropic and inhomogeneous materials. Friedmann (2004) provided a detailed review and comparison of different structural models of helicopter rotor blades. Recently, methods to study flow-induced instabilities of helicopter blades using Computational Fluid Dynamics have been investigated (e.g., Yeo et al., 2010; Morillo et al., 2012; Reveles and Smith, 2014).

In the present work, a series of experiments on a small-scale wind turbine blade subjected to uniform oncoming flow were conducted, in which dynamic flow-induced instabilities were observed experimentally for the first time for wind turbine blades. From an applied point of view, the instability of wind turbine blades could be a concern for “parked” blades. In an extreme event, when the wind speeds are predicted to go beyond a safe threshold, the wind turbines are stopped. In these cases the oncoming flow that the blade sees has a uniform flow profile. The presented experimental results can also be used to validate the existing as well as the future numerical methods for predicting these flow-induced instabilities, in the case of a non-rotating blade, before an analysis of a rotating blade is considered. It ought to be mentioned here that the goal of the present work was not to scale down any specific wind turbine blade exactly. The external geometries of the NREL 5 MW blade were used in the experiments, but there was no attempt to match its structural properties as well. The main goal of the present work was to investigate how a variable cross section and a continuous twist influence the onset and the type of instability of a flexible wind turbine blade, rather than providing predictive tools for any specific wind turbine blade.

2. Experimental set-up

In this work, a series of tests were conducted in order to observe flow-induced instabilities in a flexible wind turbine blade placed in uniform flow. The blade model used for the experiments was a small-scale version of the NREL's baseline 5 MW wind turbine, provided for use in various offshore analysis concept studies (Jonkman et al., 2009). The actual 5 MW turbine blade has a length of 61.5 m. The small-scale version of the blade had a length of 0.4 m, but its aspect ratio was the same as the full-scale blade: 13.5. The airfoil profile of the blade used in the present experimental study varied as listed in Table 1. The blade was built using the digital three-dimensional printing techniques. The commercial name for the blade