Composite Structures 119 (2015) 677–684

Contents lists available at ScienceDirect

Composite Structures

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

Improved methodology for design of low wind speed specific wind turbine blades

R.H. Barnes, E.V. Morozov *, K. Shankar

School of Engineering and Information Technology, University of New South Wales at the Australian Defence Force Academy, Canberra, Australia

ARTICLE INFO

Article history:
Available online 11 October 2014

Keywords:
Wind turbine blades
Finite element method
Composite materials
Low wind speed
Design

ABSTRACT

The majority of wind power is currently produced on high wind speed sites, and the standard design of wind turbine blades has evolved to be structurally efficient under these conditions. Recently, sites with lower quality wind resources have begun to be considered for new wind farms. This study confirms the expectation that the standard high wind speed design process results in less efficient structures when used for low wind speed conditions, and that a low wind speed specific design process is able to yield structural improvements. A comparative structural analysis of generic blades from high and low wind speed turbines quantifies the differences in structural performance between high and low wind speed blades, and indicates the ways in which the standard design process should be modified to suit a low wind speed specific design. An improved design method specifically for low wind speed blades is proposed, with more emphasis on stiffness than in the standard high wind speed design. The improved design process results in a lighter and cheaper blade than the conventionally designed one, whilst still fulfilling the design requirements.

1. Introduction

Sites with very high quality wind resources (Class I, according to Electrotechnical Commission definitions — see Table 1) are becoming scarcer as more wind farms are installed each year. Low and medium wind speed sites (Class II–IV) are more common than high wind speed sites, meaning there are opportunities for wind farms to be located closer to existing electrical grid, transport and manufacturing infrastructure. These factors have the potential to lower development costs, and offset some of the inherent economic disadvantages of the lower quality wind resource. Utilising low and medium wind speed sites also enables wind power resources to be more geographically dispersed which assists in smoothing the variability of wind generation, an effect that is well established [1].

Government and industry research anticipates that increasing numbers of low wind speed sites in the United States [2–4], Canada [5], Europe, China [6], India and Brazil will be developed in the near future [7]. In addition, wind turbine manufacturer Siemens has stated that it "expects that one-third of global wind-power development in coming years will take place in areas with low to medium wind speeds." [8].

There has been a moderate amount of research published regarding low wind speed turbines, mainly in the following categories: wind resources [1,9], aerodynamics [6,10] and structural design/ analysis [11,12]. Qualitative comparisons have been made between traditional high wind speed turbines and low wind speed turbines, for example the observation that in low wind speed turbines, "blade stiffness and the associated tip deflections become increasingly critical [13]." One study [14] made quantitative comparisons of blade root moments for low and high wind speed blades, but the design implications were not investigated. No other quantitative comparison studies were found. Structural design information for low wind speed blades was presented in [11,12], but both were much smaller than the utility-scale turbines considered in this study. Of the few utility scale low wind speed blades in the literature [15,16], none were found that presented either detailed structural design information or rigorous stress analysis, nor did the low wind speed designs differ from the basic structural design of high wind speed blades or the standard design methodology.

Structural design and analysis of high wind speed blades is better accounted for in the literature than low wind speed blades. The majority of studies considered conceptual wind turbines, typically performed by government-sponsored research groups such as the USA's National Renewable Energy Laboratory and the EU's UpWind project. The amount of design information provided

* Corresponding author.
E-mail address: E.Morozov@adfa.edu.au (E.V. Morozov).

http://dx.doi.org/10.1016/j.compstruct.2014.09.034
0263-8223/

ranged from very basic [17–20] to more detailed [21,22]. There were very few cases where sufficient design information was included to reproduce the blade model, however. The design presented in [21] was the closest to a complete design found, although some geometry and materials information was still missing. Very little has been published using commercial wind turbine blade designs, and in the few cases where they were used [23–26], no design details were given.

Recent studies containing structural analysis mainly used the finite element method. The most common approach was to create a 2D shell model of either the full blade [27–30] or of just the structural spar [26,31], neglecting the effect of the aerodynamic shell which has minimal effect on stress and deflection results for flapwise bending [26,32–34]. Some studies, in particular those concerned with non-linear effects, used a sub-modelling approach where a 3D model of the critical blade section was analysed [32,35,36], and others used 3D elements to model adhesive bonds and sandwich cores in an otherwise 2D model [24,37].

Wind turbine blade lengths have been steadily increasing over the past few decades. The longest blades currently in production are 75 m long, and lengths of over 100 m are expected in the near future. Innovations proposed for very long wind turbine blades include thickened profiles [18,38] or flatback aerofoils [18] as a means to improve the structural properties of the blade at the potential expense of compromised aerodynamics. Materials innovations that have been considered include the selective use of carbon fibre in blade spars [13,18,39,22,29]. Increased use of sandwich structures was investigated in [32,34,40] by adding a sandwich construction to the spar caps. Innovative spar geometry was examined in [17], a conceptual design study of a 100 m long GFRP blade in which a third web was added to the spar in order to increase flapwise bending stiffness. In [20], 5 alternative spar cross-sections were analysed for a 48 m long GFRP blade. The geometry varied in the number of webs, the location and orientation of the webs, but the structures were not compared quantitatively.

The objectives of this study are to quantitatively compare high and low wind speed blade structures and to use these results to improve the design process for low wind speed blades. The standard wind turbine blade design methodology is used to generate a typical high wind speed (Class I (C1)) blade design and a low wind speed (Class III (C3)) blade design of equivalent power output. Finite element models are created and the models are analysed under several loading cases in order to quantify the differences, and to examine the ways in which the standard design process should be improved in order to create an efficient low wind speed blade structure. An alternative design procedure is then applied to the low wind speed problem.

2. Blade structural design

2.1. Low wind speed versus high wind speed blade structures

Low wind speed (LWS) and high wind speed (HWS) wind turbine blades differ in two major ways: the blades' lengths and the magnitude of aerodynamic loads. The power generated by a wind turbine is proportional to the square of the blade length and proportional to the cube of wind speed. To maintain the same rated power at lower wind speed, the blade length needs to be increased. For this reason, blades for LWS turbines are longer than similarly-rated HWS blades. The maximum chord remains the same, resulting in long slender blades. Commercial Class I (C1) and Class III (C3) variations of the same turbine family have C3 blade lengths around 130%-140% of the corresponding C1 blade [7,41–43]. The longer blades have increased mass, which leads to larger deflections and stresses due to self-weight. The greater length also increases the distance over which loads are transferred to the hub and therefore causes larger moments at the root. The aerodynamic loads are smaller per unit length for the LWS blades, but the increased span means that total forces are closer to or may be larger than an equivalent HWS blade.

The structural design challenges of low wind speed blades share some similarities with the very long blades of turbines with high rated power. Stiffness and self-weight are important to both, which suggests that the LWS design problem may be solved by some of the innovations currently being researched for large HWS turbines. The design challenges are not fully equivalent, however, because in LWS cases only the length (l_0) is increased while the other dimensions remain the same. A blade's deflection is determined by its length, mass and second moment of inertia. The mass and length of the LWS blade are 130% of the original blade, whereas the second moment of inertia remains unchanged. In contrast, a HWS blade of the same length as the LWS blade would have the chord and thickness increased as well as the length. So for a 30% increase in length, the blade's mass would be approximately $(1.3)^3$, i.e. 2.2 times greater. The second moment of inertia is related to the 4th power of the cross sectional dimension, so an increase of 1.3 times would result in an increase of second moment of inertia of 2.9 times, acting to decrease deflection and stresses.

Table 1
Wind class definitions [46].

Parameters (m/s)	Class I	Class II	Class III	Class IV
Average wind speed	10	8.5	7.5	6
50 year return gust speed	70	59.5	52.5	42

2.2. Blade description

The external geometry and basic internal structure of the baseline blade used in this work are those of a 30 m blade from a typical C1 1.5 MW turbine published in a design study[21]. The blade is made of glass fibre reinforced plastic (GFRP), with some balsa core sandwich sections. The blade's geometry is representative of commercial designs, blending from a circular cross section at the blade root to a thickened S818 aerofoil at 25% span ($l/l_0 = 0.25$). The thickness and chord taper from a maximum at the 25% span to a minimum at the tip. The twist of the blade varies according to aerodynamic specifications, decreasing from the root to the tip. The blade contains a structural spar with webs located at 10% and 60% chord at the blade root and 15% and 45% chord from 25% span outwards. Details of the chord, thickness and twist are given in Table 2. The geometry of the full blade is illustrated in Fig. 1, which shows the shape and location of the six aerofoils used to generate the geometry, each with different chord, thickness and twist.

An equivalent C3 blade design was created by lengthening the baseline blade to maintain the 1.5 MW power rating under C3 conditions. This is representative of the approach in industry, where blades for low wind speed sites are typically lengthened versions

Table 2
Baseline blade geometry.

Span	Chord, m	Thickness	Twist	Aerofoil	Spar location
0%	1.56	100%	29.5°	Circle	10–60%
25%	2.58	28%	13°	S818	15–45%
35%	2.28	24%	8.8°	S818	15–45%
55%	1.71	22%	4.4°	S818	15–45%
75%	1.2	20%	1.9°	S818	15–45%
100%	0.6	18%	0°	S818	15–45%