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An efficient procedure for the calculation of the stress distribution in a wind turbine blade under aerodynamic loads

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ABSTRACT

In the current state-of-the-art, computational fluid dynamics (CFD) analysis and Blade Element Momentum (BEM) based models are used to analyse and design a wind turbine blade. CFD code simulations are accurate but very time consuming. Instead, BEM based codes are quick but they are not able to calculate the local stress/strain that appear at different positions on the blade. This paper presents the development of an automated procedure for aero-structural analysis that calculates the global and local stress/strain results on a wind turbine blade for different wind conditions. The pressure distribution along the blade due to the wind loading is calculated based on a two-and-a-half-dimensional aero-elastic analysis. With this methodology, the wind loads depend on blade deformations, that is, wind loads are coupled with blade deformations. As a practical example, the whole procedure is applied to the 5 MW UpWind wind turbine blade. The methodology is validated against FAST and Bladed codes giving good agreement. This methodology saves time and provides the necessary data in order to perform subsequent studies such as blade structural behaviour analysis.

1. Introduction

The necessity of reducing fossil fuel dependency has become an important issue all over the world. To achieve this goal, the renewable energy production, in particular wind energy generation, has seen a dramatic expansion. It is known that the energy harvested by a wind turbine is proportional to the swept area of the rotor. Larger turbines lead to higher mean wind speeds which go with increased tower height and in addition, the influence of the wind gradient due to the ground is reduced. Since the 1980's, the size of commercial wind turbines has increased from a rated power of approximately 50 kW and a rotor diameter of 10–15 m up to today's commercially available 5 MW machines with a rotor diameter of more than 120 m (Vázquez Hernández et al., 2017; Serrano-González and Lacal-Arántegui, 2016). However, the increase of the size of wind turbines has led to significant design challenges. Wind turbine mass should be kept low which requires more slender and flexible blade designs. On the other hand, the aeroelastic deformation due to the design produce unsteady vibratory loading and reduced performance of the blades (Dong and Kwon, 2014). Furthermore, repair and maintenance of large wind turbines, especially those that are remotely located as offshore wind turbines, require an efficient organisation for 20 years or more in order to decrease their cost while maintaining competitiveness. Currently, a typical wind turbine averages 2.6 component failures per year, within the first 10 years of operation (Echavarria et al., 2008). All these issues and the fact that the blades of a wind turbine rotor are generally regarded as the most critical component of the wind turbine system (Brøndsted et al., 2005), require an upgrade of the design tools from simple calculations to more sophisticated procedures.

The main sources of wind turbine blade loading are the aerodynamic, gravitational and centrifugal loads. A number of comprehensive models have been developed for the analysis of wind turbine aerodynamics (Rasmussen et al., 2003; Hansen and Sørensen, 2006). In general, they can be divided into engineering models and computational fluid dynamics methods. Most engineering models are based on the Blade Element Momentum (BEM) theory and the majority of computer codes for wind turbine analysis are based on this theory. A comparison between several aero-elastic codes used in the USA and Europe for wind turbine certification is described in (Buhl and Manjock, 2006). On the other hand, the Computational Fluid Dynamics (CFD) is based on numerical solutions to the Euler and Navier-Stokes equations. CFD has the potential to provide a consistent and physically realistic simulation of the turbine flow field. However, the high computational costs and numerous numerical issues associated with CFD methods lead to limited-used in wind turbine applications. There are several investigations regarding wind

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turbine analysis. Some major contributions are briefly described below.

Jensen et al. (2006) investigated the failure of a 34 m composite blade under flap-wise loading. A numerical model was developed using a commercial solver modelling the blade by brick and composite shell elements. A non-linear analysis was performed due to the large deflections experienced by the blade. In this study, the box girder region was looked at in detail.

A Fluid-Structure Interaction (FSI) model of a wind turbine rotor was developed by (Bazilevs and Hsu, 2011). The rotor was modelled using non uniform rational B-splines (NURBS) and the structure was governed by the rotation-free Kirchoff-Love shell theory with the aid of the bending strip method.

Motta-Mena et al. (2014).developed a wind turbine FSI model from an existing actuator line method solver and an author-developed structural dynamics solver to evaluate the deformation of a wind turbine's blades in response to uniform inflow.

A FSI model of a full turbine structure (including tower and nacelle) was built by Hsu et al. (Hsu and Bazilevs, 2012). The interaction between wind and flexible blades was carried out using a non-matching interface discretization approach. The aerodynamics were computed using a low-order finite-element based Arbitrary Lagrangian-Eulerian Variational Multiscale (ALE-VMS) technique and the rotor blades were modelled as thin composite shells using NURBS-based isogeometric analysis (IGA).

Despite substantial scientific progress in methodology development, wind turbine designers in industry still commonly use the BEM theory for wind turbine performance prediction exploiting its advantages in computational speed (Clifton-Smith, 2009; Lanzafame and Messina, 2010) and ease of implementation. The BEM theory, generally attributed to Betz and Glauert, actually originates from two different theories: blade element theory and momentum theory (Manwell et al., 2009; Burton et al., 2001; Brøndsted and Nijssen, 2013). Blade element theory assumes that a blade can be divided into small elements. These elements are assumed that act independently of the surrounding elements and operate aerodynamically as two-dimensional airfoils. The elemental forces calculated based on the local flow conditions are summed along the span of the blade, obtaining the total forces and moments exerted on the turbine. The momentum theory, on the other hand, assumes that the loss of momentum in the rotor plane is caused by the work done by the airflow passing through the rotor plane on the blade elements. The calculated induced velocities affect the inflow in the rotor plane and therefore also affect the forces calculated by blade element theory. The coupling of the two theories gives the blade element momentum theory and sets up an iterative process to determine the aerodynamic forces and also the induced velocities near the rotor.

Although BEM based codes are quick, they have some disadvantages. Common used codes such as FAST (Jonkman and Buhl, 2005) and Bladed (Bossanyi, 2012) are not able to calculate the local stress and strain that appear at different components and composite layers of the blade. These code are only able to deliver 2-dimensional loads (lift, drag and aerodynamic moment) acting at the aerodynamic centre of a certain profile section. Some researchers have combined 3D finite element (FE) models with results from BEM based codes (Griffith and Ashwill, 2011), applying forces and moments in specific zones of the FE model. However, this approach may lead to peaks in the stress field which do not correspond to physical behaviour, leading to imprecision and errors (Knill, 2005).

A wind turbine blade is an assembled structure, with shear webs and spar caps which are typically connected to each other using adhesive joints. These joints introduce discontinuities in the blade, which inevitably lead to stress concentrations that can lead to premature blade failure. What is more, due to the fact that blades are composed of composite materials, it is significant if each layer can be investigated separately. For this reason, it seems necessary to develop a methodology that can calculate loads quite fast and accurately to afterwards introduce them in a 3D finite element (FE) blade model. This is why one of the main objectives of this paper is to develop an automated methodology which introduces the loads on the FE blade model and gives a detailed stress-strain map on a composite structure. The major advantage of the proposed procedure is that as the wind loads are introduced as a smooth pressure distribution, undesirable stress concentrations are avoided.

In this paper, Section 2 is devoted to the description of the wind turbine blade model which is used as practical example. This blade is modelled with the finite element method (FEM) and a detailed model is obtained. In Section 3 the different steps of the developed methodology are described. The assumptions and statements that have been made are described in order to focus the application frame of this methodology. Section 4 describes the influence of the deformation of the blade on the load calculation, analysing thus the coupling between blade loads and deformation. Section 5 deals with the validity of the methodology, comparing it with results obtained from FAST and Bladed codes. Finally, Section 6 presents the global and local stress/strain results for one of the most critical zones of the wind turbine blades, this is, the connection between the spar cap and the shear web. Different wind load cases, starting from below rated conditions to extreme ones, are studied in this section.

2. Wind turbine blade model

The wind turbine blade which is chosen as reference to illustrate methodology development is a combined design between UpWind (The Upwind Project, 2017) and NREL blades (Jonkman et al., 2009). This was essential because it turned out to be impossible to collect all the necessary information to build a complete blade with the finite element method. Both of them describe a 3 bladed 5 MW wind turbine. In summary, the material lay-up is taken from the UpWind project, while the aero-elastic model is taken from the NREL blade.

UpWind was Europe's largest European R&D wind energy project. It was a five year project that aimed to develop and verify substantially improved models of the principal wind turbine components, which the industry needs for the design and manufacturing of wind turbines for very large-scale future applications, e.g. offshore wind farms of several hundred MW.

NREL (National Renewable Energy Laboratory) is part of the U.S. Department of Energy. They designed a 5 MW wind turbine for off-shore applications gathering publicly available information from other projects, such as Multibrid 5000 and REpower 5 MW prototypes. Detailed specifications were not accessible, so NREL exploited also publicly available properties of conceptual models from DOWEC, RECOFF and WindPACT projects.

The general properties of the selected wind turbine are listed in Table 1. To complete the definition of a wind turbine blade (WTB), geometrical properties, material definition and lay-up description are required. As commented previously, the geometrical properties are taken from the NREL blade, while the material lay-up definition is taken from the UpWind project.

A wind turbine blade is composed of various airfoils. Commonly, airfoils with circular shape are used at the blade root. The shape of the airfoils changes smoothly into typical airfoil profile, having the largest

Table 1
Wind turbine general properties.

Wind turbine characteristics	Value
Rated Power [MW]	5
Number of Blades	3
Rotor Orientation	Upwind
Rotor Diameter [m]	126
Hub Diameter [m]	3
Hub Height [m]	90
Cut-In, Rated, Cut-Out Wind Speed [m/s]	3, 11.4, 25
Cut-In, Rated Rotor Speed [rpm]	6.9, 12.1
Rated Tip Speed [m/s]	80
Shaft Tilt, Precone and Blade Pitch Angle [°]	5, 2.5, 0