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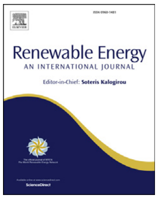

On the determination of the mechanical properties of wind turbine blades: Geometrical aspects of line based algorithms

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ABSTRACT

This paper discusses the aspects relating the geometric discretization of anisotropic wind turbine blade cross sections via line elements and the calculation of its mechanical properties. The geometrical reconstruction of the blade is done through an algorithm that reads a table that contains the representation of the aerodynamic profile of the blade as a set of connected line segments. The composite material theoretical background is based on a vector variant of the classical lamination theory embedded into a geometrically exact large deformation-small strain thin-walled beam formulation; transverse shear and out of plane warping effects are considered. The impact of the geometric reconstruction in the accuracy of the mechanical properties is studied using both rectangular and trapezoidal elements. It is found that a proper geometrical reconstruction of the cross section must be ensured to obtain small errors in the mechanical properties. It is shown that line based algorithms can give very accurate results provided the cross section geometry is adequately represented.

1. Introduction

Renewable energy is increasingly contributing to the global energy generation; biomass, wind, solar and geothermal energies, thermoelectricity, etc., are just a few of the many clean sources that are being used nowadays to obtain energy without affecting the environment [1–5]. Among them, wind energy is clearly one the most exploited sources.

Wind turbines are almost exclusively used to extract energy from the wind; its study is of paramount importance for increasing the current global energy production. The performance of a wind turbine is governed mainly by the rotor; its design involves the study of a wide variety of subjects; among them, the blade design is the most important.

Computational modeling of composite wind turbine blades is a hot research subject [3,6–10]; both 3D, 2D and 1D modeling techniques have been investigated extensively. Most modern approaches make use of finite elements, so the response of the blade is typically computed after some kind of discretization.

In the most general case, the full blade can be discretized into solid finite elements; however, this three dimensional modeling technique is rarely used since the time and computation resources required to generate such a complex geometry are huge. Besides, the aeroelastic nature of the blade dynamics makes a full fluid-structure 3D simulation using solid elements very difficult to execute. This opens the possibility for a wide variety of the so-called "reduced theories", which make use of various hypotheses to model the structural behavior of the blade; they simplify the geometrical representation blade and also the description of its mechanical behavior.

Currently, three approaches are predominantly used to simulate the mechanics of composite wind turbine blades:

i) 3D shell approaches, where the outer surface of the blade is discretized into tridimensional surface elements of composite material that deform arbitrarily in space [11]. This approach is often used in serial with a method to extract the cross sectional properties of the blade at a certain span location via static loading [10–13]. The geometrical errors arising from the definition of the cross section as a set of shell

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elements cannot be avoided; although, the accuracy of the method is generally good [12].

ii) Coupled surface-line algorithms (SLAs), where the blade is conceived as a set of cross sections modeled as 2D continuum elements; the group of cross sections move solidary to a reference 3D curve that deforms in space following the kinematic laws imposed by certain beam theory [14–16]. This is probably the most accurate approach to describe the mechanic behavior of the blade since the cross sectional modeling with 2D elements permits a fine description of the blade geometric constructive details; also, the cross sectional algorithm can be coupled with almost any beam theory.

iii) Coupled line-line algorithms (LLAs), where the blade is conceived as a set of cross sections modeled as 2D line elements; the group of cross sections move solidary to a reference 3D curve that deforms in space following the kinematic laws imposed by certain beam theory [14–16]. The accuracy of the LLAs is dependent on the geometrical reconstruction algorithm and the composite material formulation. The accuracy of modern LLAs is very good; for certain cross sections LLA can give more accurate results than 3D shell approaches [12].

Although SLAs are more accurate than LLAs, the survival of LLAs is favored by the following important factors: i) the high time consumption for the creation and execution of a SLA model, ii) the difficulty of SLAs to handle very small thickness layers of paint and coating and iii) the impossibility to use LLAs coupled with geometrical optimization software without implying the generation of a new mesh and the interaction with a user.

Both LLs and SLAs are structured such that a beam theory is fed with a matrix of cross sectional stiffness coefficients, which are individually obtained a priori. However, in SLAs the coefficients are obtained through finite element modeling of the cross sectional shape with 2D continuum elements.

In LLAs, thin-walled beam theory is used in linear and nonlinear variants [10,15–18]. Researchers have dedicated thirty years of efforts to formulate thin-walled beam theories; almost every work found in the literature concludes that refinements in the constitutive and kinematic aspects of the formulations lead to significant improvements in the theory. Static displacements, stresses, natural frequencies and frequency response of the beam have been used to test the effects of the proposed theoretical improvements. The impact of the geometric description of the cross section in the accuracy of the thin-walled theory has been addressed very rarely; in this paper this will be shown to be of paramount importance for obtaining accurate results.

Nowadays LLAs are widely used in rotor design to determine the cross sectional stiffness of blades. Chen et al. [15] presented a detailed assessment of computational tools for calculating wind turbine blade cross sectional stiffness. This study includes numerical comparisons between: thin walled beam theory, the SLA VABS (the most renowned algorithm for the determination of cross sectional properties, developed by Prof. Hodges and coworkers [14,16,19]) and the LLAs: FAROB [20] (developed at the Dutch Knowledge Center of Wind Energy Materials and Construction), PreComp [21] (developed at National Renewable Energy Laboratory in USA) and CROSTAB [22] (Cross Sectional Stability of Anisotropic Blades, developed at the Energy Research Center of the Netherlands). The study concludes that the LLAs are inconsistent and therefore its applicability to modeling realistic blades is questionable; the present paper will show that this conclusion is misleading.

Resor et al. [23] compared results obtained with PreComp and BPE (Blade Property Extraction, a 3D shell approach developed by Global Energy Concepts and Sandia National Laboratories [24]), to those obtained in experimental testing of the BSDS blade; according to this paper the overall difference between PreComp and BPE is in the range of 15–25% and the difference between the experimental results and BPE are in the range of 5–20%. In a later study, Resor and Paquette also included VABS in the assessment of cross sectional stiffness calculations [25]. The paper reproduced the same results of [15] for a particular wind turbine cross section, only the diagonal terms of the stiffness matrix were presented. For the CX-100 blade, discrepancies were found between VABS and BPE, especially in sections near the blade's root. These discrepancies were attributed to local straining.

In a previous work, the authors have presented LL formulation to obtain the cross sectional properties of composite cross sections; the work showed that a LLA can be very accurate provided it is correctly implemented [12]. In the present paper, an improved version of the previously presented LLA is used to analyze the impact of the discretization aspects on the accuracy of the results. The composite material theoretical background is based on a vector variant of the classical lamination theory embedded into a geometrically exact large deformation-small strain thin-walled beam formulation; transverse shear and out of plane warping effects are considered. The geometrical reconstruction of the cross section is performed with two types of segments: classical thin-walled beam theory rectangular segments and a variable layer length trapezoidal segments. The influence of the number of layers in the laminate also studied. It is shown that the choice of the reconstruction technique greatly affects the prediction of the cross sectional parameters. The 1D nature of the approach permits its use in optimization studies, when variation of parameters must be executed without requiring user interaction. The approach gives excellent results with minimal modeling time; results are often better than 3D approaches.

2. Theoretical aspects

2.1. Beam formulation

The cross sectional parameters are dependent on the beam formulation; they are uniquely defined for a particular strain energy function. As a consequence, a particular cross sectional stiffness measure is strictly consistent only with the kinematic formulation from which it was derived. A detailed derivation of the composite beam formulation used in this paper can be found in Refs. [12,26]; hereafter, only relevant details are reproduced.

It is assumed that the blade is moderately slender; so its mechanic behavior can be reasonably approximated by beam theory.

The position vectors of a point in the blade in the undeformed and deformed configuration can respectively be expressed as [12]:

$$\begin{aligned} \boldsymbol{X}(x,\xi_2,\xi_3) &= \boldsymbol{X}_0(x) + \sum_{i=2}^{3} \xi_i \boldsymbol{E}_i, \\ \boldsymbol{x}(x,\xi_2,\xi_3,t) &= \boldsymbol{x}_0(x,t) + \sum_{i=2}^{3} \xi_i \boldsymbol{e}_i + \omega \boldsymbol{e}_1. \end{aligned} \tag{1}$$

In both above equations $\boldsymbol{X}_0$ is the position of the pole in the reference configuration, $\boldsymbol{x}_0$ is the position of the pole in the deformed configuration and the coordinates ξ_2 and ξ_3 are the components of the position vector of a point in the cross section in $\boldsymbol{E}_i$, see Fig. 1. The variable ω accounts for the displacements in the cross section due to torsional warping.

Three frames of reference attached to the cross section are introduced: a) a reference material frame $\{\boldsymbol{E}_1, \boldsymbol{E}_2, \boldsymbol{E}_3\}$, b) a sectional frame $\{\boldsymbol{E}_1, \widehat{\boldsymbol{n}}, \widehat{\boldsymbol{s}}\}$ and c) a layer individual frame $\{\widehat{1}, \widehat{2}, \widehat{3}\}$, see Fig. 2.