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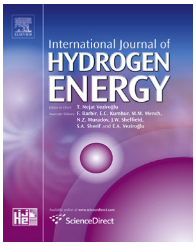

Unsteady and non-linear aeroelastic analysis of large horizontal-axis wind turbines

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ABSTRACT

Analysis results, obtained from numerical simulation, for non-linear and unsteady aeroelastic behavior of large horizontal-axis wind turbines are presented in this paper. Simulations are carried out using a partitioned scheme of weak interaction that allows dealing with the fluid–structure interaction problem by using one method to solve the structural-dynamic problem and another method for the aerodynamic problem.

The aerodynamic model used is the non-linear, unsteady vortex lattice method (NLUVLM). The structural model used is a system of beam finite elements and rigid bodies with finite rotation. This provides a very general tool with relatively low computational cost.

The proposed method allows predicting from the operating conditions (wind speed and direction, pitch angle of blades, etc.) the aeroelastic response of wind turbines, characterized by variables such as rotation speed of the rotor, loads on the structural components and the extracted power, among others.

1. Introduction

The size of the horizontal axis wind turbines has dramatically increased in the last quarter century. They have evolved from 15 m-diameter-rotor turbines with 0.05 MW rated power to large horizontal axis wind turbines (LHAWT), commercially available today, with rotor diameters of more than 120 m and power ratios of approximately 7.5 MW [1]. This trend is expected to continue to reach turbines with rated power of about 10 MW–20 MW, which would allow, for example, to cover 20% of Europe's energy demand by 2020 and 33% by 2030 [2].

Betz's *Elementary Momentum Theory*, developed between 1922 and 1925, indicates that the maximum power extractable from an air stream by a LHAWT increases with the square of the length of the blades [3]. For this reason, the worldwide trend is to develop wind turbines with longer blades. Designs of turbines with blades of large aspect ratio and slenderness, highly flexible and constructed with composite materials, have forced to substantially change the analysis techniques. It is necessary the use of methods that are able to capture the unsteady characteristics and the nonlinearities typical of these phenomena. They must be able to represent complex constitutive relations, adequate structural damping models, coupled problems (multiphysics), etc.

The accuracy in predicting loads and the design optimization to maximize energy extraction are crucial points to

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improve in order to achieve a wind turbine industry economically competitive with respect to other energy sources. The set of branches of engineering necessary to carry out an analysis of this type includes the structural dynamics and fluid mechanics, leading to the study of aeroelastic phenomena (fluid–structure interaction, FSI). The next step is the inclusion of control strategies.

The main difficulty in the field of computational aeroelasticity (CAE) is that the aerodynamic actions upon a body depend on its shape, speed, and acceleration, while these three variables depend on the aerodynamic loads of the fluid on it. To overcome this difficulty, many authors propose a partitioned scheme [4–7]. The partitioned scheme considers a phenomenon divided into sub-problems of different nature. Each sub-problem is addressed with the method that best suits it. An interaction scheme allows coupling the submodels, thus reconstructing the original phenomenon.

This work was carried out by the same research group that led two other studies published previously. The first of these works [8] describes in detail the aerodynamic model used in the second and even the present works. The second one [9] presents an aeroelastic study, where the structure is described as a multibody system, treating the flexible bodies (tower and blades) as beams. The method of assumed-modes is used for the tower. The blades are modeled as non-straight, linearly elastic, undamped beams. Large displacements and rotations due to the motion of the blade as a rigid body are considered separately from small displacements and small rotations due to elastic deformation. In order to account for the small elastic deformation, the blades are discretized using two-noded beam finite elements along the elastic axis.

Following this line of research, the present paper incorporates the aerodynamic model presented in Ref. [8], replacing the structural model used in Ref. [9], using in this particular case nonlinear beam elements able to undergo large displacements and rotations. These elements are part of an extensive library of elements incorporated into a code of general purpose [10] that also allows modeling the nonlinear behavior of viscoelastic and anisotropic materials (essential characteristics to simulate structures built in composite materials). The existence, within that library, of shell elements would enable to improve the structural model effortlessly.

Sections 2, 3 and 4 describe the model for determining loads on the structure, the model that allows predicting the response of the structure and the scheme that interrelates both, respectively. Section 5 presents the simulation strategy and Section 6 evaluates the results. Finally, some conclusions are drawn.

2. Aerodynamic model

The aerodynamic model allows determining the load of air on the blades, which causes their rotational movement and constitutes the mechanism by which the wind energy is transferred to the turbine. In this paper, we use the non-linear unsteady vortex lattice method (NLUVLM) [11]. This method shows an excellent balance between generality and computational cost. The implementation by Cristian Gebhardt for horizontal axis wind turbines LHAWT/AC [12] is used in the present effort. This method considers incompressible flow at very high Reynolds number. This allows confining vorticity to a small area of the domain within the boundary layers and the wakes, while the remainder fluid is assumed irrotational.

As a simplification, we model the boundary layer and the wake as vortex sheets. The boundary layer is represented by a vortex sheet attached to the surface of the body at all times, moving with it. Its position is determined by the displacements and deformations of the structure, and thus it represents an input for the aerodynamic problem. The wakes are represented by free vortex sheets whose positions are not specified a priori. They are convected from the sharp edges of the bodies at the local velocity of the fluid particles, taking positions so that no resultant forces act on them. These vortex sheets join at the edges where the wake is convected. Fig. 1 shows the representation of a blade and the wake associated to it.

The vortex sheets are discretized becoming aerodynamic grids (AG) composed of straight vortex segments of constant circulation Γ along its length. Fig. 2 shows the AGs resulting from the discretization of the vortex sheets of Fig. 1. Each vortex has an associated field of perturbation velocity obtained applying the Biot–Savart Law. Two are the boundary conditions of NLUVLM: the condition of no penetration and the condition of regularity at infinity. The first one allows determining vorticity at each segment. The second is implicitly fulfilled by the Biot–Savart law.

LHAWT/AC can handle different wind directions and speed values and it can simulate the effect of the boundary layer using a pre-established velocity profile.

3. Structural model

The structural model is responsible for predicting the dynamic response of the turbine to the aerodynamic loads. That is, the position, velocity and acceleration of the different parts of the machine over time. The model consists of a set of beam finite elements, rigid bodies and kinematic constraints. Simpact [10], a general purpose code with explicit integration of equations of motion, is used.

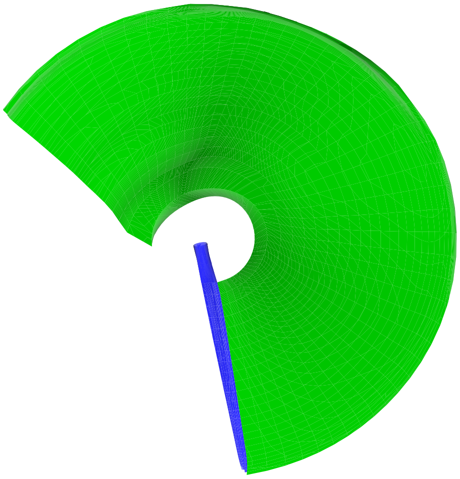

Fig. 1 – Vortex sheet representing a blade and its wake.