Aeromechanical evaluation of large HAWT’s blades

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This paper presents aeromechanical evaluation of a blade (length, 50 m) of horizontal axis wind turbines (HAWT). Aerodynamic module combines three-dimensional non-linear lifting surface theory approach and a two-dimensional panel method for steady axisymmetric flow. It provides effective incident velocity and angle of attack at each blade section and 3D pressure distribution on blade as an input data for finite element analysis (FEA) package. FEA provides deformations, strains and stress distributions along blade and material induced fatigue. Degradation linear accumulation model was used in fatigue study under one million cycles of loading. Calculated accumulated damage was found below critical value.

Keywords: Aerodynamics, Numerical simulation, Structural behaviour, Wind turbine

Introduction

In normal running, blades of a wind turbine must withstand centrifugal forces, bending moments caused by pressure aerodynamic forces and gyroscopic effects. In order to improve design of horizontal axis wind turbine (HAWT) blades, optimisation of design requires more accurate estimations of loads and therefore more elaborate models incorporating coupling of aerodynamics, structural dynamics and wind turbulence. Modern HAWT blades are composite thin structures with a rather sophisticated distribution of laminated resins spanwise and chordwise. Mechanical optimisation of such devices should be made by modelling blade as a set of thin layer elements rather than using beam elements approach. Accurate evaluation of interlaminar strengths require a detailed evaluation of the external force field, namely pressure field, which is supposed to supply a better estimate of rotor performance than simplified momentum theories, using global lift and drag forces at each section.

This paper presents a combination of aerodynamic module, based on Lifting Surface method (LSM) and 2D panel method, and structural module, based on ANSYS finite element package, which is applied to analyse a large HAWT¹ (blade length, 50 m; and rated power, 3 MW).

Aerodynamic Analysis

Proposed configuration wind turbine modeled by LSM is a steady, uniform wind that flows over a HAWT with K blades of radius R, rotating at constant angular velocity ω aligned with incoming free stream velocity, V∞. A Cartesian system of coordinates (X, Y, Z) is defined relative to first blade (Fig. 1). Y direction coincides with turbine rotation axis, oriented towards incoming wind stream. Z axis goes along blade span, oriented from root to tip and starting at hub pitching centre. X direction is third orthogonal right-handed axis lying on rotation plane. Absolute non-stationary irrotational velocity field is computed in terms of upstream velocity, V∞, plus a perturbation due to velocities induced by vorticity field. It is assumed that vorticity is concentrated at thin blade boundary layers and wakes, modelled as vorticity sheets (Fig. 1). Vorticity associated to boundary layers can be merged into a single vortex surface, the lifting surface. LSM geometry is a cambered twisted continuous surface build up by the sequence of profile cambered middle lines going from leading edge to trailing edge². LSM allows obtaining an effective velocity and angle of attack at each section of blade³.
Pressure distribution along blade for non-stalled conditions is extracted from effective relative velocity and angle of attack by means of a plane flow analysis for each section using a conventional 2D vortex panel method. This pressure field constitutes input data for finite element analysis (FEA) module. Basic design is presented in Table 1. Several modifications were made to this basic configuration in order to evaluate its aerodynamic performance (Table 2). Firstly, performance of Lifting Surface approach is compared versus results of Glauert theory. Secondly, angular speed is increased according to reported data. Finally, chord and pitch angle distributions and references therein were considered. Points under power – incident velocity (top) and power coefficient – tip speed ratio (bottom) curves (Fig. 2) correspond to reported computations with so-called PROP code, which is based on Glauert theory combined with blade element theory. In such calculations it was assumed that the rotor diameter was 102 m, a rated power of 3 Mw and active power regulation. This is the reason why the power is kept constant after an incident velocity of 12 m/s. On the contrary, in the present computations the power regulation is due to aerodynamic stall leading to an absolute maximum in the power – velocity curve.

Basic Glauert case provides very similar results (Fig. 2) to those obtained with PROP code in spite of different geometric parameters, because in Glauert theory, influence of profile geometry is very reduced. On the other hand, LSM in basic case provides nominal power (3 MW) for an incident velocity slightly higher than 12 m/s and also maximum power coefficient is somewhat lower than that provided by Glauert theory. If angular speed is increased (Case 1, Fig. 2), available power is increased but also risk of turbine run away is substantially increased. Finally, Case 2 (Fig. 2) considers reduction of chord along the span, which implies a reduction of blade area and, therefore, also a reduction of torque that wind transfer to blade. Final result is a significative decrement in both, power and power coefficient of turbine.

### Structural Analysis

In normal running, blades of a wind turbine must withstand centrifugal forces, bending moments caused by pressure aerodynamic forces and gyroscopic effects, which appear during orientation changes that can accompany gusts, for example. Aerodynamic module has been coupled with a structural module, ANSYS, where pressure distribution along blade and its geometry constitute input data for ANSYS to perform structural
calculation. According to reported structure\(^1\), blade construction was assumed to be a stressed shell (composite material: polycarbonate, 65%; and fibreglass 35%), which was composed of four primary components (a low pressure shell on downwind side, a high-pressure shell on upwind side and two shear webs bonded between two shells).

Structural analysis for W15S blade (Fig. 3) was performed for basic case of Table 2. In static analysis, blade deflection and von Misses stresses were analysed. Nominal loads (pressure loads acting on blade at maximum efficiency) have been considered. In these conditions, maximum deflection obtained was 3.7 m, an acceptable value because tower clearance is around 10 m. Consistently, maximum stresses are located near blade root and decrease towards tip. Also, safety factor, calculated in this case, provides values along the blade well above 1, which is critical value. Dynamic analysis considered blade natural modes of vibration. Those must be uncoupled with natural frequencies of other components of wind turbine in order to avoid mechanical resonance. First four modes and sixth were flexural modes whilst fifth was a torsion mode (Fig. 4). First natural frequency (0.4 Hz) is a very similar to reported value\(^1\).

In fatigue analysis, blade is put under the action of cyclic loads during a total time of 10 min in order to evaluate its accumulated damage (Fig. 5). Model
employed to evaluate fatigue of a composite material has been Degradation Lineal Accumulation model\textsuperscript{5,6}, which evaluates accumulated damage at certain number of cycles. Although accumulated damage after one million of cycles of periodic loading is below critical value of one. Undergone stress by blade was around 0.4 times the ultimate stress.

Conclusions

Structural study of HAWT blade showed that safety factors under static, dynamic and fatigue loading were found below critical value, indicating safe structural performance of blade.

References