Composite Structures 159 (2017) 144–156

Contents lists available at ScienceDirect

Composite Structures

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

Proposal for a coupled aerodynamic–structural wind turbine blade optimization

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ARTICLE INFO

Article history:
Received 31 May 2016
Revised 15 September 2016
Accepted 15 September 2016
Available online 17 September 2016

Keywords:
HAWT
FEM analysis
BEM theory
Evolutionary algorithm
S.O.C.R.A.T.E. algorithm

ABSTRACT

An advanced design algorithm for the AOC 15/50 wind turbine is hereby presented: both aerodynamic and structural parameters are considered as the design variables for a coupled BEM–FEM optimization.

In order to obtain an improvement in rotor blade design, a modified version of the S.O.C.R.A.T.E. algorithm combines a BEM evaluation of its aerodynamic performance, a FEM structural analysis and a genetic algorithm. Both the aerodynamic power (resulting from the BEM analysis) and the tip displacement (produced by the aerodynamic forces and the inertial loads) are considered as the fitness functions for the optimization problem.

An improved distribution of both chord values and twist angles is determined, as well as an optimal layout of the blade composite skin. A slight increase in the aerodynamic power generation is obtained, as well as a marked improvement in overall blade deformation characteristics.

1. Introduction and background

The horizontal-axis wind turbine (HAWT) represents the most common architecture among existing wind energy conversion systems, with thousands of MWs of new capacity worldwide installed each year. Its design process, largely accepted by manufacturers as well as by academic institutions, is generally separated in two consecutive stages [1]:

- the external geometry of the blade (in terms of both chord and twist angle distribution along the blade span, rotor size and other factors, often empirical, related to the cost of energy) is first determined using a Blade Element Momentum (BEM) based algorithm
- a proper layout of both blade skin and reinforcements is determined by means of a structural analysis based on the finite element method (FEM), considering both the aerodynamic and inertial loads acting on the blade.

Both stages have been widely investigated by several authors. Liu and Janajreh [2] proposed an improved BEM model for the analysis of HAWT performance, considering both the tip loss effect and the rotational one, with the aim of extending its application to the turbulent wake regime. Refan and Hangan [3] investigated the aerodynamic performance of a 2.2 m diameter three-bladed HAWT in order to assess the applicability of the BEM Theory for the modelling of small scale rotors. ElQuatary and Elhadidi [4] compared BEM and Computational Fluid Dynamics (CFD) simulations for two HAWTs characterized by different blade thickness, registering a marked agreement especially for the thicker blade configuration. Kong et al. [5] proposed a structural design of a medium scale composite HAWT blade made of E-glass/epoxy. Several design load cases (such as aerodynamic forces, those due to ice accumulation, hygro-thermal and mechanical loads) were considered and the most dominant design parameters were included in a FEM analysis, also estimating the fatigue life of the blade.

Among numerical optimization methods, particular relevance is nowadays assumed by evolutionary algorithms, whose solutions are generated on the basis of techniques inspired by natural evolution. As observed by Mendez and Greiner [6], genetic algorithms are global optimizers that have a wide trade-off between exploration and exploitation of the space problem: among their advantages, a global search capability is to be recognized, due to the management of a population of candidate solutions instead of only one. Moreover, their only requirement is the knowledge of the fitness function, without any other consideration such as its derivability or continuity. A great number of engineering problems can be dealt with genetic algorithms [7]: Benini and Toffolo [8] performed a multi-objective optimization for the design of stall-regulated HAWTs, coupling the BEM Theory and a multi-objective evolutionary algorithm, with the scope of achieving the

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http://dx.doi.org/10.1016/j.compstruct.2016.09.042
0263-8223/

Nomenclature

A [m^2]	blade surface
A_0 [m^2]	original AOC 15/50 blade surface
c [m]	section chord length
d [mm]	total displacement at the tip
d_0 [mm]	total displacement at the tip of the original AOC 15/50 blade
EI [MN · m^2]	blade flexural rigidity
E_L [MPa]	longitudinal elastic modulus
E_T [MPa]	transversal elastic modulus
E_Z [MPa]	out-of-plane elastic modulus
F [N]	aerodynamic force acting on the blade section
f_A [−]	ratio between blade surface area and that of the original AOC 15/50 blade
f_P [−]	objective function of power
f_d [−]	objective function of deformation
f_m [−]	ratio between blade mass and that of the original AOC 15/50 blade
G_{LT} [MPa]	in-plane shear modulus
G_{TZ} [MPa]	out-of-plane shear modulus
G_{LZ} [MPa]	out-of-plane shear modulus
i_A [−]	penalty function for the area
i_m [−]	penalty function for the mass
i_P [−]	penalty function for the power
m [m]	blade mass
m_0 [m]	mass of the original AOC 15/50 blade
M [Nm]	bending moment acting on each blade cross section
p [−]	generation number
p_{max} [−]	maximum generation number
P [kW]	aerodynamic power generated from the rotor
P_0 [kW]	aerodynamic power generated from the original AOC 15/50 rotor
r [m]	sectional distance from the axis of rotation
R [m]	blade radius
t [mm]	thickness of the layer
V [m/s]	unperturbed wind velocity
α [°]	section angle of attack
θ [°]	section twist angle
$\frac{d\Theta}{dz}$ [−]	rate of rotation of the blade section
ν_{LT} [−]	in plane Poisson's ratio
ν_{TZ} [−]	out-of-plane Poisson's ratio
ν_{LZ} [−]	out-of-plane Poisson's ratio
ρ [kg/m^3]	material density
ρ_A [kg/m^3]	blade surface density

best trade-off between annual energy production per square metre and cost of energy. Cai et al. [9] developed a structural optimization of an HAWT blade using a particle swarm optimization algorithm based on FEM calculations, proving a great potential improvement on overall structural blade performance. Dal Monte et al. [10] improved the structural response of the AOC 15/50 Sandia blade using the S.O.C.R.A.T.E. (Structural Optimization for Composite Rotor Air TurbinE) algorithm: both the choice of the employed materials and their placement in the layout of the blade skin were considered as design variables for the optimization, obtaining a marked reduction in the mass of the blade and a corresponding increment of its flapwise rigidity. An optimization procedure for a HAWT blade based upon an ultimate limit state analysis was proposed by Hu et al. [11]: in order to minimize the blade cost and its total mass, two different composite materials, such as glass fibre reinforced plastic (GFRP) and carbon fibre reinforced plastic (CFRP) were considered, being the design variables of the blade skin the input parameters for a combined FEM and evolutionary algorithm analyses.

Several tools for the multi-disciplinary wind turbine optimization have been proposed in the open literature in the last years; Pourrajabian et al. [12] proposed a procedure for the aero-structural design of a small wind turbine blade based on a BEM code and on a simple structural model. Bottaso et al. [13] described a procedure for the multidisciplinary optimization of wind turbines with a parametric high fidelity aero-servo-elastic model, considering the Annual Energy Production and the Weight of the blade as cost functions. Ashuri et al. [14] also developed a multidisciplinary optimization for the design of offshore wind turbines; the considered objective functions is represented by the levelized cost of energy and it included design constraints as stresses, deflections modal frequencies and fatigue limits. Grujicic et al. [15] proposed a multidisciplinary design optimization procedure for the development of the cost effective composite layout of an HAWT using the Cost of Energy (COE) as single fitness function. In the cited tools the multi-objective design is not formulated as a Pareto optimal problem but using a combined cost (AEP divided by total weight), a levelized cost of energy or the Cost Of Energy only.

Even though aerodynamic and structural optimizations of HAWT blades have been widely proposed by several authors, in reviewing the literature, the potential of an evolutionary algorithm based on the coupling of an aerodynamic model (based upon the BEM Theory) and a structural one (based on a FEM analysis) have been not often investigated; Zhu et al. [16] proposes an aerodynamic and structural integrated optimization for the HAWT Blades design, Wang et al. [17] developed an aerodynamic and structural integrated design optimization method for a composite wind turbine blade based on multidisciplinary design optimization (MDO).

Gradient-based optimizers have also proved their capabilities in aerospace optimization. They have played and continue to play a key role during the aero-structural design of the aircraft. Ghommem et al. [18] implemented a shape optimization of flapping wings in forward flight, combining a gradient-based optimizer (GCMMA) with the unsteady vortex lattice method (UVLM). Gillebart et al. [19] presented a two-dimensional low-fidelity aeroelastic analysis of an airfoil and a gradient based optimization (GCMMA) consisting of a coupled potential flow model and curved Timoshenko beam model combined with a boundary layer model. A great advantage of the gradient-based optimizer is to handle a large number of design variables and coinstrants; furthermore they result faster and less computational expensive compared to genetic algorithms, however a potential weakness is the relative intolerant of difficulties such as noisy objective function spaces and topology optimization; additionally they find a local rather then a global minimum [20]. The characteristics of the analysed problem potentially involve several local minimum, furthermore the evaluation of both aerodynamic and structural function is not expensive in terms of time. For such reason the genetic algorithm formulation has been chosen as optimization method over the gradient based formulation. The hereby proposed genetic algorithm considers at the same time both BEM and FEM genes, in order to determine an aerodynamic fitness function and a structural one. The purpose of the present optimization is therefore to increase both the power