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Evaluation of the different aerodynamic databases for vertical axis wind turbine simulations

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ABSTRACT

A review on a wide number of different aerodynamic coefficient databases to be used for vertical axis wind turbine simulations is conducted in this work. The databases are adopted in conjunction with a Blade Element-Momentum algorithm, a commonly used tool to design and verify the aerodynamic behaviour of these machines. Experimental data derived from field test available in the literature for a wide range of rotor sizes are considered and compared to the simulation results. The aerodynamic databases provide strongly different estimations due to the different working conditions: in each case suggestions on their use are provided based on their reliability. Finally, resuming all the conducted validations, practical general considerations are proposed to the wind turbine designer to conduct reliable simulations.

Contents

1. Introduction

Vertical axis wind turbines are recently gaining a considerable interest due to their inherent qualities that make their use with respect to the horizontal axis systems. The design simplicity linked to the bottom position of the generator and combined with the easiest control policy, which does not require any pitch or yaw mechanism, allows their use in both urban and extremely isolated areas, where the maintenance work needs to be minimized. On the other hand, these machines are characterized by a complex aerodynamics due to the peculiar unsteady working conditions. A flexible and reliable design tool is thereby needed, which should be preventively validated against experimental data.

In the past years, a considerable amount of papers has been developed on experimental activities for Darrieus rotor of different sizes and characteristics. Sandia National Laboratories provided experimental data from both wind tunnel and open field tests for rotors with a height of 2 m [1], 5 m [2] and 17 m [3,4]. Turbines with even greater size have been tested in open field environment: the most important examples are the 37 m height Darrieus installed on Magdalen Islands [5,6], for a maximum power production of 230 kW, and the biggest Darrieus ever realized, the Éole project with a height of 96 m and a power production of 4 MW [7]. These turbines operate at different Reynolds numbers, due to their different sizes, and are characterized by different solidities and aerodynamic profiles, mainly NACA 0012, NACA 0015 and NACA 0018. All these experimental data provide a good background for the validation of numerical models, which are needed in order to conduct a successful design activity.

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Nomenclature

a (−)	axial induction factor
a_u (−)	upwind axial induction factor
ΔA (m^2)	streamtube cross-sectional area
A_S (m^2)	rotor swept area
c (m)	airfoil chord
C_D (−)	airfoil drag coefficient
C_L (−)	airfoil lift coefficient
C_N (−)	blade element normal coefficient
C_P (−)	rotor power coefficient
C_T (−)	blade element tangential coefficient
ΔF_N (N)	normal force exerted by the blade element as it passes through the streamtube
ΔF_T (N)	tangential force exerted by the blade element as it passes through the streamtube
ΔF_x (N)	instantaneous streamwise force exerted by the blade element as it passes through the streamtube
$\Delta F_{x,u}$ (N)	instantaneous streamwise force exerted by the blade element as it passes through the upwind streamtube
$\Delta \overline{F}_{x,u}$ (N)	average streamwise force exerted by the blade element as it passes through the upwind streamtube
G_u (−)	auxiliary function for induction factor iterative algorithm
H (m)	rotor total height
N (−)	number of blades
N_θ (−)	number of horizontal mesh subdivisions
N_v(−)	number of vertical mesh subdivisions
P(W)	power produced by the turbine
p_u^+ (Pa)	pressures on the upstream face of the upwind actuator disc
p_u^- (Pa)	pressures on the downstream face of the upwind actuator disc
r (m)	rotor radius relative to a blade element
R (m)	wind turbine maximum radius
T (N m)	rotor torque
V (m/s)	freestream wind speed
V_e (m/s)	downstream equilibrium wind speed
V_i (m/s)	flow velocity at a blade section, i can be up or down
V_u (m/s)	flow velocity at the downwind blade section
W_i (m/s)	relative velocity at a blade element cross-sectional plane, i can be up or down
W_u (m/s)	relative velocity at the upwind blade element cross-sectional plane
Δz (m)	streamtube height
α (rad)	blade relative angle of attack (between airfoil chord line and relative wind velocity)
δ (rad)	blade element inclination with respect to the vertical plane
λ (−)	tip speed ratio
ρ (kg/m^3)	air density
θ (rad)	blade azimuthal coordinate
$\Delta\theta$ (rad)	azimuthal mesh size
ω (rad/s)	rotor angular velocity

Different numerical models for the simulation of the complex aerodynamics of these machines have been developed. Three main approaches have been followed, subsequentially developed with the advent of more powerful computational resources. The first model is the Blade Element-Momentum (BE-M) Multiple Streamtube developed by Strickland [8], successively improved by Paraschivoiu [9,10] considering the Double Disc approach. This model has the advantage of being extremely light and fast to provide an estimation of the whole power curve and off-design production, but on the other hand the result reliability is strongly dependent on the quality and the extension of the aerodynamic database adopted. An improved description for the Darrieus wake was possible by the Vortex Wake model developed by Strickland [11], which is able to provide an additional insight of the aerodynamic behaviour. On the other hand, the computational time required for the simulation is sensibly increased with respect to the previously mentioned method. Finally, Computational Fluid Dynamics (CFD) codes provide the most accurate description for turbine aerodynamics [12,13] but, on the other hand, require more computational time, limiting their use for final testing simulations more than design activities.

The BE-M code is considered by the authors to be the most suitable code for design purposes. The choice is linked to the simplicity of the algorithm formulation along with the small computational time required. These peculiarities allow its adoption even coupled with optimization algorithms for the automatic design improvement, which may require a considerable number of rotor performance evaluations. As stated before, the reliability of this method is strongly dependent on the accuracy of the aerodynamic database adopted. The simulation of vertical axis rotors requires aerodynamic coefficients extended from angles of attack between -180° and $+180^\circ$ covering a large span of Reynolds number. Unfortunately, the literature review provides mainly experimental databases developed for aeronautic applications, which are very limited in angles of attack and Reynolds numbers. In this work, the main databases available in the literature are considered and the results obtained were compared, in order to provide the vertical axis turbine researchers with a practical indication on the methodology to apply for their studies. The databases considered are the one from Sheldahl et al. [14] and their derivatives from Paraschivoiu [15] and Lazauskas et al. [16]. In addition to these, databases from Jacobs et al. [17,18], Bullivant [19] and Gregorek at al. [20], obtained for aeronautic applications, have been extended beyond stall and included in the comparison. A complete description of these databases is reported in the technical report from Bedon et al. [21].

2. Simulation model

The simulation model hereby adopted is based on the Double Multiple Streamtube approach developed by Strickland [8] and Paraschivoiu [9,10]. Two actuator discs describe the upwind and downwind rotor sections, where the induction factors are calculated. The induction factor represents the decrease of air velocity from the freestream due to the interaction with the blade and is defined as

$$a = 1 - \frac{V_i}{V} \quad (1)$$

where V_i is the velocity at the blade (upwind or downwind section) and V is the freestream air speed. The induction factor is estimated equating the streamwise forces on the airfoil blades to the change in fluid momentum. The first forces can be estimated considering that the actuator disc extracts energy from the fluid and therefore generates a pressure jump which, for the upwind section, can be calculated as

$$\Delta \overline{F}_{x,u} = (p_u^+ - p_u^-)\Delta A \quad (2)$$