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A consistent vortex model for the aerodynamic analysis of vertical axis wind turbines

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ABSTRACT

A consistent two dimensional vortex type aerodynamic model for VAWTs is presented alongside with its validation against measured data. The flow solver assumes incompressible and inviscid conditions. It combines a source-vorticity panel formulation for the blades and a vortex blob representation of their wakes. By construction the model accounts for the effects of curvature of the relative to the blade inflow while blade vortex interactions are modelled by locally correcting the position of the wake vortices when they impinge on the blade. In order to get realistic loading estimations, lift and drag are corrected using a modified version of the ONERA model in which only the contribution of the separated generalised circulation is considered. Comparisons against wind tunnel tests on model rotors as well as full scale, field measurements on a 12 kW VAWT indicate that the model predicts well the aerodynamic loads on the blades and the power output of the rotor.

1. Introduction

In the early years of wind energy technology, the Vertical Axis Wind Turbine (VAWT) concept underwent considerable engineering development. Significant research effort was directed to the development of new methods for the analysis and optimisation of their aerodynamic performance. Initially, VAWTs were investigated in parallel with Horizontal Axis Wind Turbines (HAWTs) and some medium size turbines in the scale of 100–600 kW were installed in the 80s especially in the US and Canada. Typical examples of such turbines are the 34 m diameter Sandia prototype DOE 625 kW (Sutherland et al., 2012) and the commercial FloWind turbines (Paraschivoiu, 2002). In the early 90s VAWTs were totally abandoned in favour of HAWTs which ever since prevailed and finally dominated the market of large scale energy production using wind energy until today. Recently, the increasing interest in offshore wind farms targeting to installations in deep water and the continuous research on floating wind turbine concepts has placed VAWTs again into the frame. Important drivers are the lower cost of VAWTs, their simple design architecture and the light weight structure that renders them ideal for offshore floating applications. Also, the fact that the drive train system and the generator can be situated on the base of the turbine (or even underwater) could considerably reduce maintenance costs and improve the logistics in case of remote installations.

Despite their very simple design philosophy, there are several challenges with respect to their aerodynamics. The main feature of VAWTS is that the effective angle of attack “seen” by the blades undergoes a very big variation which in moderate to low tip speed conditions drives the blades into stall both in the negative and the positive angles of attack regime. The variation of the angles of attack within the post stall region gives rise to significant flow unsteadiness and dynamic stall phenomena. The unsteadiness of the flow and therefore dynamic stall hysteresis effects strongly depend on the reduced frequency k that scales the blade motion which in turn depends on the solidity of the rotor.

Moreover, the blades of VAWTs are subjected to strong Blade Vortex Interactions (BVIs). The retreating VAWT blade impinges on its own wake but also on the wakes of preceding blades that are formed in earlier times. The number over one revolution and the strength of BVI encountered by each blade depends on the operating conditions. At high tip speed ratios where wake convection velocity is low, the retreating blades experience multiple wake crossings. Thereby, BVI gets stronger at high tip speed ratios while it is considerably weakened at low tip speed ratios where dynamic stall phenomena dominate.

Another important effect that must be taken into account concerns the curvature of the flow lines in the relative frame. As a result of the circumferential motion of the blades, the streamlines of the relative flow are highly curved and therefore the flow characteristics

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Nomenclature

$\boldsymbol{u}$	flow velocity in the fixed coordinate system
$\boldsymbol{w}$	flow velocity in the relative coordinate system
$\boldsymbol{u}_{\omega}$	vortical part of velocity field
$\mathbf{U}_{\infty}$	free stream velocity
$\mathbf{U}_b$	body velocity
φ	scalar potential
$\boldsymbol{\psi} = \psi \mathbf{k}$	stream function
$\boldsymbol{\omega} = \omega \mathbf{k}$	vorticity field
p	pressure field
TE	trailing edge point
σ	source distribution over the airfoil
γ	bound vorticity distribution on the airfoil
Γ	circulation around a circuit C
γ_w	vorticity distribution on the wake
$\mathbf{x}_w$	arbitrary point on the wake
$\mathbf{x}_{cp}$	collocation point on the airfoil
S	airfoil length
Γ_w	intensities of vortex particles on wakes
$\mathbf{Z}_{\mathbf{w}}$	position vectors of vortex particles on wakes
$f(\varepsilon)$	cut off function
ε	cut off length of vortex particles
γ_w^{Δ}	surface vorticity of TE wake panel
ΔS_w^{Δ}	lengths of TE and SP near wake panels
θ_w^{Δ}	angles of TE and SP near wake panels
Δt	time step of numerical simulation
G	Green's function $G(r) = 1/2\pi \ln r$
$\Gamma_{1L}, \Gamma_{2L}, \Gamma_{2D}$	circulation components of the ONERA model
C_{D0}	friction drag (minimum of drag coefficient polar)
ΔC_L	difference of the real viscous steady state lift coefficient from the corresponding inviscid
ΔC_D	difference of friction drag coefficient $C_{D0}$from the real viscous steady state drag coefficient.
Ω	rotor rotational speed
c	local blade chord length
R	rotor radius
B	number of rotor blades
$\lambda = \Omega R / U_{\infty}$	tip speed ratio (TSR)
W_{eff}	local effective flow velocity including wake induced effects
w_0	component of W_{eff} normal to the blade chord
W	local geometric flow velocity $W = \sqrt{U_{\infty}^2 + (\omega R)^2}$
α_{eff}	local effective angle of attack of the airfoil section
$\tau = \frac{c}{2 \cdot W_{eff}}$	time constant of the ONERA model
$a^{\ell}, r^{\ell}, E^{\ell}$	empirical parameters of the ONERA model
C_L	lift coefficient
C_D	drag coefficient
F_n	local blade normal force
F_t	local blade tangential/driving force
$C_n = F_n / \left(\frac{\varrho}{2} W^2 c \right)$	normal force coefficient
$C_t = F_t / \left(\frac{\varrho}{2} W_2 c \right)$	tangential force coefficient
$k = \frac{\Omega}{2 W_{eff}} \frac{c}{} \approx \frac{c}{2R}$	reduced frequency of the airfoil
$s = \frac{Bc}{2R}$	solidity of the rotor

are significantly altered as compared to those of the rectilinear flow. A symmetric airfoil moving in a curved path will have the aerodynamic characteristics of a cambered airfoil (non-zero, zero lift angle of attack). The strength of the virtual cambering effect is related to the curvature of the path undergone by the blade in relation to the blade chord. This is directly linked to the parameter c/R.

Finally, the local Reynolds number will also vary significantly over the revolution. Maximum Reynolds number occurs at the beginning of the advancing side where the relative inflow velocity takes its maximum value (sum of wind speed and rotation velocity) and attains its minimum at the beginning of the retreating side where the wind velocity is subtracted from the rotation velocity. Clearly the variation is bigger at higher wind speeds and it is expected to significantly affect the aerodynamic loads, especially for smaller size wind turbines that operate at low average Reynolds numbers, in the order of 10^5.

In the 80s and 90s the aerodynamic modelling of VAWTs was primarily based on multiple stream tubes, actuator cylinder models coupled with the blade element method (Strickland, 1975; Paraschivoiu, 1988) and vortex type free or prescribed wake models (Strickland et al., 1979; Ponta and Jacovkis, 2001;Coton et al., 1994). Recently, in response to the renewed interest on VAWT, new models that belong to both categories have been developed with the aim to provide answers to the deficiencies of earlier methods. For example Madsen et al. (2012) and Larsen and Madsen (2013) developed an updated non-linear actuator cylinder model in which the assumption that the flow pressure fully recovers at the centre of the rotor before the flow crosses the downstream cylinder is no longer made. Also, new 2D and 3D vortex type free wake models have been developed with main focus on better representing wake dynamics and modelling of dynamic stall (Zanon et al., 2013; Simão Ferreira, 2009; Scheurich et al., 2011). Moreover, as a result of the continuous increase in computer capabilities, a number of aerodynamic analyses of VAWT employing CFD methods have been published (Hansen and Sørensen, 2001; Simão Ferreira et al., 2007).

In the context of wind turbine design verification, the aerodynamic tool should be of low to moderate computational cost so as to perform the long list of time domain aeroelastic simulations with turbulent wind contained in the IEC standard. With regard to HAWTs, actuator disk models combined with blade element (BEM models) have been widely used over the years. Through the application of appropriate engineering corrections that account for dynamic inflow, unsteady aerodynamics and yaw misalignment effects, BEM models constitute a very powerful design tool of HAWTs (Hansen et al., 2006). The equivalent in the VAWT case corresponds to the actuator cylinder model which however cannot properly model phenomena like blade vortex interaction or virtual/apparent cambering that play here a decisive role. So the predictions of actuator type models for VAWTs are compromised and at present no consistent engineering corrections have been proposed or tuned in order to improve their prediction capabilities. An efficient modelling alternative, also suitable for the purposes of aeroelastic analysis, lies in vortex type models. They stand in between actuator and CFD models. The main advantage of vortex models is that wake dynamics and all the effects induced by the wake are build in. Aiming at the lowest possible cost, vortex models are to be formulated as inviscid flow models in which case viscous effects, such as flow separation, are added as corrections either a posteriori directly on the loads (Riziotis and Voutsinas, 1997) or by introducing additional vorticity emission from the point of separation (Voutsinas and Riziotis, 1996; Zanon et al., 2013) (usually referred to as the "double wake" concept; see Vezza and McD Galbraith, 1985 and Voutsinas and Riziotis, 1996). In order to become fully predictive, the double wake model is strongly coupled with a viscous boundary layer which provides the separation location (Riziotis and Voutsinas, 2008).

In the present paper, a 2D vortex type free wake aerodynamic model with consistent corrections on loads is presented. A standard panel method is used in the modelling of the flow around the blades (Basu and Hancock, 1978) while the wake is represented by freely moving vortex blobs. In the calculation of the unsteady pressure the contribution of the wake vorticity is considered separately by solving a