J. Wind Eng. Ind. Aerodyn. 146 (2015) 163–171

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Dynamic stall in vertical axis wind turbines: Comparing experiments and computations

A-J. Buchner [a,b,*], M.W. Lohry [a], L. Martinelli [a], J. Soria [b,c], A.J. Smits [a,b]

[a] Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ, United States
[b] Laboratory for Turbulence Research in Aerospace and Combustion (LTRAC), Department of Mechanical and Aerospace Engineering, Monash University Melbourne, Australia
[c] Department of Aeronautical Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

ARTICLE INFO

Article history:
Received 4 March 2015
Received in revised form
1 September 2015
Accepted 2 September 2015
Available online 26 September 2015

Keywords:
Vertical axis wind turbine
Dynamic stall
URANS
PIV
Turbulence modelling

ABSTRACT

Dynamic stall is often found in unsteady aerodynamic flows where the angle of attack can vary over a large range. It is of particular interest in the context of vertical axis wind turbines, where dynamic stall is the principal impediment to achieving improved aerodynamic efficiency. Here, we report computations using the unsteady Reynolds-averaged Navier–Stokes (URANS) equations with the Menter-SST turbulence model on a two-dimensional domain, over a range of tip speed ratios typical of the operation of vertical axis wind turbines. Comparisons are made against high resolution experimental data from particle image velocimetry (PIV), with special attention to the ability of the turbulence model to emulate the turbulence properties of the flow. It is shown that the computations approximate the experimental results well in most respects.

1. Introduction

Previous studies (Sutherland et al., 2012; Ferreira et al., 2009; Buchner et al., 2014, 2015) suggest that vertical axis wind turbines can operate at power coefficients comparable to that of horizontal axis wind turbines, while reducing the unsteady interaction with the atmospheric boundary layer, providing efficient structural scaling and non-directionality with respect to the freestream wind vector, and potentially offering an increase in wind turbine array efficiency (Whittlesey et al., 2010; Dabiri, 2011; Kinzel et al., 2012). One of the principal impediments to achieving higher efficiencies is dynamic stall arising from the large and rapid changes in angle of attack that occur on each blade during the rotation cycle. Dynamic stall consists of a separation of the boundary layer from the suction-side surface of the blade and subsequent roll-up into a leading edge vortex, which can introduce excessive structural vibrations, reduce efficiency, and produce unwanted noise. Although dynamic stall is a dominating feature of vertical axis wind turbine flows, it has been studied extensively in many other contexts (McCroskey, 1976; Leishman and Beddoes, 1986; Carr, 1988; Geissler and Haselmeyer, 2006; Buchner et al., 2012; Buchner and Soria, 2014). On horizontal axis wind turbines, for example, even mild stall decreases performance and increases noise production significantly (Hibbs, 1986; Loratro et al., 2014), and similar effects are experienced to a greater magnitude by vertical axis turbines (Allet and Paraschivoiu, 1995; Scheurich and Brown, 2011).

To predict unsteady, highly turbulent flows such as wind turbine dynamic stall requires accurate and efficient computational solvers. In many cases, especially for design purposes, unsteady Reynolds-averaged Navier–Stokes (URANS) methods are used, but turbulence models are often unreliable in predicting complex flow phenomena such as flow separation (Wilcox, 1998), and validation with experiment is crucial. In this respect, Srinivasan et al. (1995) evaluated several turbulence models for unsteady flows over an oscillating airfoil with similar dynamics to a periodically retreating helicopter rotor or a vertical axis wind turbine blade. The accuracy of force prediction in the stalled flow regime was shown to depend strongly on the turbulence model used; each of the models tested matched some aspects of the experimental force and pitching motion measurements, but none provided an accurate solution over the entire pitching cycle. Hysteresis and downstroke forces in particular were found to be poorly predicted. It was found that, of the models tested, one-equation models performed better than algebraic models such as Baldwin–Lomax (Baldwin and Lomax, 1978) or the renormalisation group theory method (Yakhot and Orzag, 1986). Similarly, McLaren (2011) and McLaren et al. (2012) performed URANS on a high solidity vertical axis wind turbine but only validated blade forces against the experimental data of Sheldahl and Klimas (1981) for a stationary airfoil. Their

---

* Corresponding author at: Department of Mechanical and Aerospace Engineering, Monash University, Clayton VIC 3166, Australia
E-mail address: abel-john.buchner@monash.edu (A-J. Buchner).

http://dx.doi.org/10.1016/j.jweia.2015.09.001
0167-6105/© 2015 Elsevier Ltd. All rights reserved.

Nomenclature

A	cross-sectional area of turbine
c	chord length of turbine blades
C_f	coefficient of friction
C_p	coefficient of power
C_p	specific heat capacity
C_s	Smagorinsky constant
E	energy
i	iteration number
i,j	tensor subscripts
k	turbulent kinetic energy
L	integral length scale
n	number of blades
Pr	Prandtl number
Pr_t	turbulent Prandtl number
R	radius of vertical axis turbine
$\mathbf{R}$	residual vector
Re_b	blade Reynolds number
Re_t	turbine Reynolds number
$\overline{S}$	resolved scale rate of strain tensor
t	time
$\tilde{t}$	pseudo-time
U_∞	freestream velocity
$\overline{U}$	resolved scale velocity
$\hat{u}$	subgrid scale velocity
$u, v, w, u_{i,j}$	velocity components
$x, y, z, x_{i,j}$	coordinate variables
$\mathbf{w}$	vector of flow variables, $[\rho, \rho u, \rho v, \rho E]$
α_{s0}	laminar separation bubble formation angle
α_{s1}	dynamic stall vortex formation angle
γ	ratio of specific heats
Γ	circulation
δ	uncertainty
Δ_{IW}	PIV vector spacing, or resolution
ϵ	turbulent dissipation rate
θ	azimuthal blade angle
λ	tip speed ratio
ν	kinematic viscosity
ν_t	kinematic eddy viscosity
ρ	density
ρ_{xx}	cross correlation coefficient
σ	solidity ratio
$\overline{\tau}$	azimuthally averaged rotor torque
τ	subgrid scale stress
ω	specific turbulent dissipation rate
ω_z	spanwise vorticity component
Ω	rotation speed of vertical axis turbine

results suggested that beyond stall the force predictions provided by the standard Wilcox k–ω (Wilcox, 1988, 1998) and Menter shear stress transport (SST) (Menter, 1993, 1994) models are superior to the k–ϵ model (Jones and Launder, 1972).

A more complete validation was given by Ferreira et al. (2010), who compared several different turbulence models against two-dimensional experimental velocity data, but only at a single tip speed ratio ($\lambda = 2$). They found that both Spalart–Allmaras (Spalart and Allmaras, 1992, 1994) and k–ϵ turbulence models under-predicted leading edge circulation production and were unable to match the trailing edge wake roll-up behaviour observed in the experiments. Better agreement was only achieved by resorting to more computationally intensive Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) methods. In none of these prior publications has there been discussion of the distribution and quantitative accuracy of the modelled turbulent flow properties and their effect on the mean behaviour of the velocity field. To fill this need, we present new comparisons of URANS with experiment in the context of dynamic stall on vertical axis wind turbines, and we provide direct comparisons between unsteady flow fields, as well examining the unsteady vortex shedding behaviour.

2. Numerical method

The time dependent flow around the vertical axis wind turbine configuration is modelled by the unsteady, compressible Reynolds-averaged Navier–Stokes equations. A two-equation Menter shear stress transport (SST) model (Menter, 1993, 1994, 2009) is used for closure, with equations for the turbulent kinetic energy and specific dissipation rate. The strain rate is used as the turbulence production term and no wall functions are used. The Menter-SST model has previously been shown (Bardina et al., 1997; McLaren, 2011; McLaren et al., 2012) to produce results in separated or adverse pressure gradient flows of superior accuracy to simulations using a standard Wilcox k–ω or Launder and Sharma k–ϵ model.

The flow equations are solved in integral form by second order accurate finite volume discretisation in space on hexahedral cells. A fully implicit dual-time stepping scheme based on a second order A-stable backward differentiation formula (BDF) is used where the inner iteration is converged by an efficient multigrid time-stepping scheme (Jameson, 1991). Methods of this class combine the stability and time-step advantages of fully implicit schemes while allowing an efficient implementation on parallel machines (Alonso et al., 1995; Jameson and Martinelli, 1998). This approach also allows for time-accurate extension for low Mach number flow using a preconditioner (Belov et al., 1997).

A multi-block structured mesh approach has been selected for this work, which allows for accurate representation of the boundary layers near the blades. The original implementation was developed by Martinelli et al. (1997) and Reuther et al. (1997) as *FLO107MB* and has been widely used and validated for a wide range of flow regimes. For this study, we used the multi-block *SUmb* solver appropriately modified to include the low Mach number preconditioner of Weiss and Smith (1995). *SUmb* was developed at Stanford University by van der Weide et al. (2006), and evolved from *FLO107MB*.

The computations were performed on a structured multi-domain grid with a circular boundary, centred on the turbine axis and extending radially to 10 turbine diameters, or 75 blade chord lengths (Fig. 1). The two-dimensional mesh allows for a relatively small number of cells $\sim \mathcal{O}(10^5)$, which is shown here to be sufficient to capture the main features of the unsteady separating flow. The first wall-normal grid point location at the turbine blades is at $y^+ = 1$ for a Reynolds number based on the freestream velocity and chord length, and the grid is expanded at a rate away from the wall of 1.09 using the hyperbolic tangent stretching function of Vinokur (1983). The simulation is run with a time-step size equal to 2.5 degrees of rotation of the turbine, equivalent to 0.15 blade convection times $c/\lambda U_\infty$, and the solution is judged converged after four periods of rotation, when the period to period root mean square error of the force and moment histories drops below 2.5% of the maximum value. A freestream turbulence intensity of 1%, typical of wind tunnels, is applied to the numerical