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Comparative assessment of the harmonic balance Navier–Stokes technology for horizontal and vertical axis wind turbine aerodynamics

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ABSTRACT

Several important wind turbine unsteady flow regimes, such as those associated with the yawed wind condition of horizontal axis machines, and most operating conditions of all vertical axis machines, are predominantly periodic. The harmonic balance Reynolds-averaged Navier–Stokes technology for the rapid calculation of nonlinear periodic flow fields has been successfully used to greatly reduce runtimes of turbomachinery periodic flow analyses in the past fifteen years. This paper presents an objective comparative study of the performance and solution accuracy of this technology for aerodynamic analysis and design applications of horizontal and vertical axis wind turbines. The considered use cases are the periodic flow past the blade section of a utility-scale horizontal axis wind turbine rotor in yawed wind, and the periodic flow of a H-Darrieus rotor section working at a tip-speed ratio close to that of maximum power. The aforementioned comparative assessment is based on thorough parametric time-domain and harmonic balance analyses of both use cases. The paper also reports the main mathematical and numerical features of a new turbulent harmonic balance Navier–Stokes solver using Menter's shear stress transport model for the turbulence closure. Presented results indicate that (*a*) typical multimegawatt horizontal axis wind turbine periodic flows can be computed by the harmonic balance solver about ten times more rapidly than by the conventional time-domain analysis, achieving the same temporal accuracy of the latter method, and (*b*) the harmonic balance acceleration for Darrieus rotor unsteady flow analysis is lower than for horizontal axis machines, and the harmonic balance solutions feature undesired oscillations caused by the wide harmonic content and the high-level of stall predisposition of this flow field type.

1. Introduction

The aeromechanical design of wind turbines is a complex multidisciplinary task that requires consideration of a very large number of operating regimes due to the extreme variability of the environmental conditions on time scales ranging from seconds (*e.g.*wind gusts) to months (*e.g.*seasonal wind variations). Several fatigue-inducing unsteady regimes, however, are predominantly periodic. In the case of utility-scale horizontal axis wind turbines (HAWTs), periodic fluid-induced excitations of the rotor blades and drivetrain may result from the blades rotating (*a*) through wind stratifications associated with the atmospheric boundary layer, (*b*) through the variable pressure field due to the presence of the tower (multimegawatt turbines typically feature upwind rotors), (*c*) through portions of the wake shed by an upstream turbine in the wind farm environment, (*d*) in yawed wind, a condition occurring when the freestream wind velocity is not orthogonal to the turbine rotor [1], and (*e*) in a region of nonuniform wind resulting from the combination of two or more of the kind of phenomena mentioned above. With regard to yaw misalignments, utility-scale HAWTs typically feature yaw control systems that monitor the direction of the wind and rotate the entire nacelle towards the wind [2]. However, yaw actuators adjust the nacelle position only after a yaw error has been detected for a relatively long time-interval, usually 10 min. Therefore, at sites with frequent variations of the wind direction, blade and drivetrain fatigue due to yawed wind can be significant. HAWT rotors experience constant periodic excitations when the turbines are placed at inclined sites, such as mountainous terrains. Here wind speeds are often higher than on flat terrain due to the acceleration induced by the surface geometry, however the

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entire wind stream is inclined on the ground, and this yields periodic rotor flows similar to those induced by yaw errors [3]. In all these cases, the fundamental frequency of the periodic excitation is a multiple of the rotor speed.

The flow field past vertical axis wind turbines (VAWTs) [2], such as the popular Darrieus turbine, is inherently unsteady and predominantly periodic in the vast majority of operating conditions. At present these machines are used predominantly for distributed power generation in the built environment. For this application, they are often preferred to HAWTs due their simpler build, simpler and cheaper maintenance requirements, and for their insensitivity to the wind direction. This feature is particularly important in the urban environment, as the variability of wind speed and direction is higher that on open terrains. The Darrieus VAWT is a lift-driven machine in which the blade airfoils are contained and rotate in planes orthogonal to the rotor axis. The periodic nature of the flow past the blades is due to the cyclic variation (every rotor revolution) of modulus and direction of the relative velocity perceived by their airfoils [4], and also the interactions between the blades traveling in the downwind region of the rotor and the vorticity shed by the blades in the upwind rotor region [5]. These complex unsteady flow patterns are further complicated by the occurrence of dynamic stall [6] over a significant portion of the entire turbine operating range [5].

The comments above highlight the necessity of accurately predicting periodic flows when designing wind turbines. This is of crucial importance for reliably predicting the actual amount of harvested energy and the fatigue-inducing loads which may reduce turbine life and/or increase its operation and maintenance costs. In many cases, however, wind turbine design methods still rely on low-fidelity and/or semi-empirical models such as blade element momentum theory (BEMT) and dynamic stall models [7–9]. The main advantage of these techniques is their extremely high computational speed. Their main drawback is that they heavily rely on the existence and availability of high-quality airfoil data, and this hinders their applicability to the design of radically new turbine configurations. Moreover these low-fidelity methods model strongly unsteady three-dimensional (3D) flow features, such as HAWT yawed flows and the radial pumping effect occurring in the presence of stalled flow [10] with a high degree of uncertainty even when detailed airfoil data are available. A wider discussion on the predictive reliability of low-fidelity tools for the wind turbine design can be found in [11].

The use of high-fidelity computational aerodynamics tools such as Navier–Stokes (NS) Computational Fluid Dynamics (CFD) codes has the potential of greatly reducing the uncertainty associated with the flow predictions of low-fidelity models. Several remarkable examples of the predictive capabilities of NS CFD for HAWT yawed flows have been published, including the articles [12–15]. The article [12] also includes comparisons of CFD NS results, experimental data and results obtained with low-fidelity codes, including a BEMT code. The report shows that the agreement between NS CFD analysis and measured data is substantially better than that between low-fidelity analyses and measured data, as expected. Early assessments of the NS CFD technology for Darrieus rotor aerodynamics, aiming primarily at thoroughly investigating the complex fluid mechanics of these machines, include the articles [5,6,16]. The computational and experimental study reported in [17] provides detailed evidence of the predictive capabilities of 3D NS CFD for Darrieus rotors. An exhaustive comparative assessment of NS CFD and BEMT results, highlighting the difficulties of the BEMT technology of accurately predicting complex flow features, particularly in the absence of reliable airfoil force data, is reported in [18]. The article [19] also highlights that NS codes can predict fairly accurately measured Darrieus turbine aerodynamics provided that best practice in defining the physical domain, con-

Nomenclature

Acronyms

AoA	Angle of attack
BEMT	Blade element momentum theory
FERK	Fully explicit Runge–Kutta
HAWT	Horizontal axis wind turbine
HB	Harmonic balance
IRS	Implicit residual smoothing
MG	Multigrid
NS	Navier–Stokes
PDE	Partial differential equation
PIRK	Point-implicit RK
RK	Runge–Kutta
TD	Time-domain
VAWT	Vertical axis wind turbine

Greek symbols

$\Delta\tau$	Pseudo-time-step (s)
Δl_r	Logarithm in base 10 of normalized residual RMS of RANS equations
Ω	Rotor angular speed (RPM)
Ω_f	Flow vorticity (s^{-1})
$\underline{\mathbf{\Phi}}_c$	Generalized steady and *TD* convective flux vector
$\underline{\mathbf{\Phi}}_{cH}$	Generalized *HB* convective flux vector
$\underline{\mathbf{\Phi}}_d$	Generalized steady and *TD* diffusive flux vector
$\underline{\mathbf{\Phi}}_{dH}$	Generalized *HB* diffusive flux vector
α_∞	Angle of attack associated with velocity vector $\underline{W}_\infty$ (°)
α_m	m^{th} RK coefficient
δ	Yaw angle (°)
γ_p	Twist angle (°)
λ	Reduced frequency
λ_D	Tip-speed ratio
μ_T	Turbulent viscosity (kg/ms)
ν	Molecular kinematic viscosity (m^2/s)
ω	Specific turbulence dissipation rate (s^{-1})
ϕ^r_∞	Angle of attack associated with velocity vector $\underline{W}^r_\infty$ (°)
ρ	Density (kg/m^3)
τ_w	Wall viscous stress (Pa)
θ	VAWT rotor azimuthal position (°)

Latin symbols

A	Matrix for implicit update of k and ω
CD_ω	Cross-diffusion term of ω equation (kg/m^3s^2)
C_l, C_d	Lift and drag force coefficients
C'_m	Constant-head pitching moment coefficient
C_m	Variable-head pitching moment coefficient
C_{MG}	Overhead of *HB* MG cycle
C_T	Torque coefficient
C_x, C_y	Horizontal and vertical force coefficients
D	*HB* antisymmetric matrix
D_ω	Destruction term of ω rate (kg/m^3s^2)
D_k	Destruction term of k (kg/ms^3)
M^r_∞	Mach number associated with velocity $\underline{W}^r_\infty$
N_H	Number of complex harmonics
N_{pde}	Number of PDEs
P_d	Turbulent production term (s^{-2})
$\mathbf{Q}$	Array of steady and *TD* conservative variables at cell center
$\mathbf{Q}_H$	Array of *HB* conservative variables at cell center
R	HAWT rotor radius (m)
$\mathbf{R}_\Phi$	Array of steady and *TD* cell residuals