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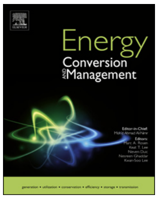

Characterization of aerodynamic performance of vertical axis wind turbines: Impact of operational parameters

Abdolrahim Rezaeiha[a,*], Hamid Montazeri[a,b], Bert Blocken[a,b]

[a] Building Physics and Services, Department of the Built Environment, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
[b] Building Physics Section, Department of Civil Engineering, KU Leuven, Kasteelpark Arenberg 40 – Bus 2447, 3001 Leuven, Belgium

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ABSTRACT

Vertical axis wind turbines (VAWTs) have received growing interest for off-shore application and in the urban environments mainly due to their omni-directional capability, scalability, robustness, low noise and costs. However, their aerodynamic performance is still not comparable with their horizontal axis counterparts. To enhance their performance, the impact of operational parameters such as tip speed ratio (λ), Reynolds number (Re_c) and turbulence intensity (TI) on their power performance and aerodynamics needs to be deeply understood. The current study, therefore, intends to systematically investigate the effect of these parameters in order to provide a deeper insight into their impact on the aerodynamic performance of VAWTs. For this investigation, a Darrieus H-type VAWT has been employed. A wide range of the parameters is considered: $\lambda = 1.2$–6.0, $Re_c = 0.3 \times 10^5$–4.2×10^5 and $TI = 0\%$–30% to analyze the turbine performance, turbine wake and dynamic loads on blades. High-fidelity computational fluid dynamics (CFD), extensively validated with experimental data, are employed. The results show that (i) variable-speed operation maintaining the optimal λ at different wind speeds improves the turbine power coefficient, e.g. up to 168% at 4 m/s, while keeping an almost constant thrust coefficient, (ii) the turbine performance and wake are Re-dependent up to the highest Re_c studied, (iii) large TI ($> 5\%$) improves the turbine performance in dynamic stall by promoting the laminar-to-turbulent transition and delaying stall on blades, however it deteriorates the optimal performance by introducing extra skin friction drag. The findings of the current study can support more accurate performance prediction of VAWTs for various operating conditions and can help the improvement of the aerodynamic performance of VAWTs.

1. Introduction

Vertical axis wind turbines (VAWTs) have received growing interest [1–7] for off-shore applications [8–10] as well as the built environment where they have the potential to be installed on the roof [11], included in the façade [12–15] or between buildings [16]. The installation can also be integrated in the ventilation ducts [17,18] and wind catchers [19–22]. The growing interest in the use of VAWTs could be attributed to several advantages such as [19,23–28]:

- Omni-directional capability: no yaw system is needed.
- Very low noise: due to operating at relatively low tip speed ratios and small diameters, the blade tip speed is very low.
- Low manufacturing cost: due to simple blade profiles with no taper and twist as well as simplicity in the control system, i.e. no pitch and yaw control system.
- Low installation and maintenance costs: due to having the generator on the ground.
- Scalability: the turbine height can scale up with minimal effect on performance.
- Robustness and reliability.
- Very small shadow flickering.
- Birds safety: due to their shape and typically low installation height
- Visually attractive.
- Multifaceted installation tower, e.g. telecom towers
- High space efficiency: VAWTs have smaller plan area compared to HAWT of the same swept area.

However, the aerodynamic performance of VAWTs is currently lower than HAWTs [29–32]. Research on VAWTs, despite their complex aerodynamics, has been situated in the shadow of the studies on HAWTs and hence received comparatively little attention during the last decades [33]. The underlying physics behind the power generation of VAWTs is much more complex compared to HAWTs [34–40]. The complexity could be mainly attributed to the VAWT's inherent unsteady power conversion due to the large variations of angle of attack and the

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[*] Corresponding author.
E-mail address: a.rezaeiha@tue.nl (A. Rezaeiha).

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Nomenclature

A	turbine swept area, $h{\cdot}d\,[\mathrm{m}^2]$
c	blade chord length [m]
C_d	sectional drag coefficient, $D/(0.5\rho c V_{rel}^2)$ [–]
C_{Fn}	instantaneous normal force coefficient [–]
C_{Ft}	instantaneous tangential force coefficient [–]
C_l	sectional lift coefficient, [–]
C_m	instantaneous moment coefficient [–]
C_P	power coefficient, $P/(qAU_\infty)$ [–]
C_T	thrust coefficient, $T/(qA)$ [–]
CoP	pressure coefficient [–]
D	sectional drag force [N/m]
d	turbine diameter [m]
h	turbine height [m]
k	turbulence kinetic energy $[\mathrm{m}^2/\mathrm{s}^2]$
K	reduced frequency, $\Omega c/(2V_{rel})$ [–]
L	sectional lift force [N/m]
L_w	turbine wake length [m]
M	turbine moment [Nm]
n	Number of blades [–]
P	turbine power [W]
q	dynamic pressure [Pa]
R	turbine radius [m]
Re_c	airfoil (blade) chord-based Reynolds number [–]
Re_θ	Momentum-thickness Reynolds number [–]
T	turbine thrust force [N]
TI	approach-flow total turbulence intensity [%]
TI_i	incident-flow total turbulence intensity [%]
$\overline{u}$	time-averaged streamwise velocity [m/s]
V	velocity magnitude [m/s]
V_n	normal velocity [m/s]
V_t	tangential velocity [m/s]
U_i	induced velocity [m/s]
U_∞	freestream velocity [m/s]
$\overline{v}$	time-averaged lateral velocity [m/s]
V_{rel}	relative velocity [m/s]
$V_{rel,geo}$	geometrical relative velocity [m/s]
W	domain width [m]
X/c	dimensionless chordwise position along the blade [–]
α	angle of attack [°]
α_{geo}	geometrical angle of attack [°]
α_i	induced angle of attack due to induced velocity [°]
α_{ss}	static stall angle [°]
γ	intermittency [–]
θ	azimuth angle [°]
λ	tip speed ratio [–]
ν	kinematic viscosity of air $[\mathrm{m}^2/\mathrm{s}]$
σ	solidity [–]
ω	specific dissipation rate [1/s]
Γ	circulation $[\mathrm{m}^2/\mathrm{s}]$
Ω	turbine rotational speed [rad/s]
Ω_{opt}	optimal turbine rotational speed [rad/s]
LSB	laminar separation bubble

relative velocity during each turbine revolution [23]. In addition, this can be accompanied by several complex flow phenomena such as dynamic stall [41,42], blade-wake interaction [43], flow curvature effects [44], Coriolis and centrifugal forces on the boundary layer of the rotating blades and the shed vortices [45]. In order to improve the aerodynamic performance of VAWTs, therefore, these flow complexities need to be well understood. In addition, the impact of various geometrical parameters and operational parameters on the aerodynamic performance of VAWTs needs to be comprehensively characterized. The geometrical parameters include number of blades [46–48], solidity [49–51], airfoil shape [52–54], blade pitch angle [23] and turbine shaft [55]. The operational parameters consist of tip speed ratio [56–61], Reynolds number [61–65] and turbulence intensity [58,66–68]. The focus of the present study is on the impact of the aforementioned operational parameters.

Tip speed ratio λ is one of the most important operational

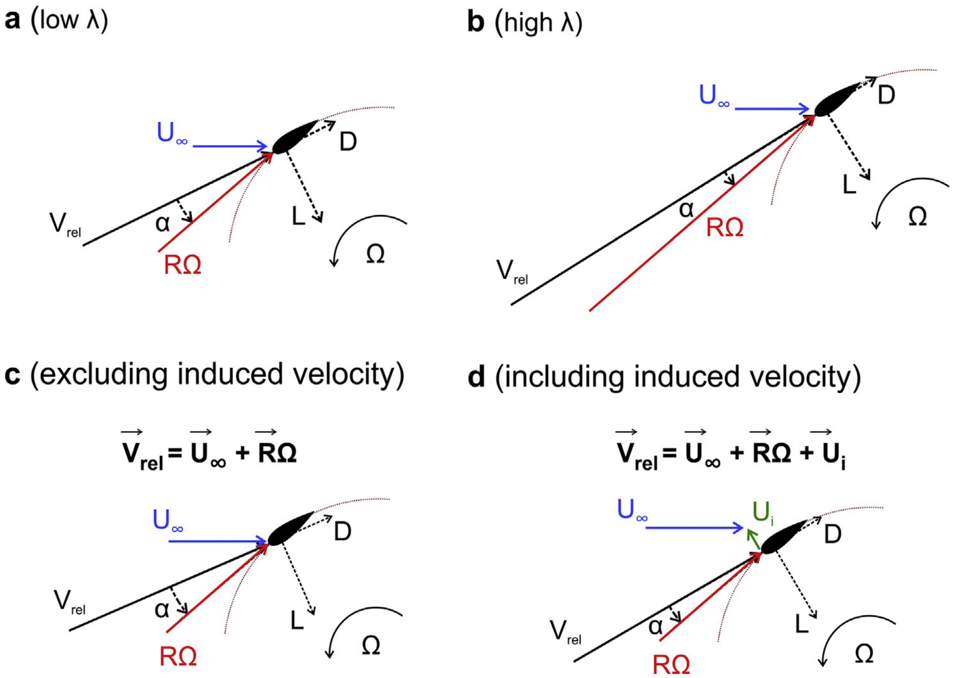

Fig. 1. Schematic of velocity triangle on a VAWT blade showing the difference between: (a and b) low versus high tip speed ratio, (c and d) considering versus ignoring the induced velocity (not to scale).