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Effect of the shaft on the aerodynamic performance of urban vertical axis wind turbines

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ABSTRACT

The central shaft is an inseparable part of a vertical axis wind turbine (VAWT). For small turbines such as those typically used in urban environments, the shaft could operate in the subcritical regime, resulting in large drag and considerable aerodynamic power loss. The current study aims to (i) quantify the turbine power loss due to the presence of the shaft for different shaft-to-turbine diameter ratios δ from 0 to 16%, (ii) investigate the impact of different operational and geometrical parameters on the quantified power loss and (iii) evaluate the impact of the addition of surface roughness on turbine performance improvement. Unsteady Reynolds-averaged Navier-Stokes (URANS) calculations are performed on a high-resolution computational grid. The evaluation is based on validation with wind-tunnel measurements. The results show that the power loss increases asymptotically with increasing δ due to the higher width and length of the shaft wake as the blades pass through a larger region with lower velocity in the downwind area. A maximum power loss of 5.5% compared to the hypothetical case without shaft is observed for $\delta = 16\%$. The addition of surface roughness is shown to be an effective approach to shift the flow over the shaft into the critical regime, reducing the shaft drag and wake width as a result of a delay in separation. For an optimal dimensionless equivalent sand-grain roughness height of 0.08, the turbine power coefficient at $\delta = 4\%$ improves by 1.7%, which is equivalent to a 69% recovery of the corresponding turbine power loss. The results are found to be virtually independent of the shaft-to-turbine rotational speed ratio.

1. Introduction

Vertical axis wind turbines (VAWTs) have regained interest during the last decade for application as large-scale multi-MW turbines in off-shore areas [1–3] and as small-scale turbines in urban environments [4,5]. The large-scale turbines are interesting for off-shore application due to their low manufacturing, installation and maintenance costs, scalability, robustness, reliability, and installation of the generator on the ground, while their omni-directional capabilities make them highly desirable for urban environments where the wind direction is frequently changing [6]. However, a significantly lower amount of research in the past three decades has resulted in VAWT performance falling behind that of their horizontal axis counterparts. Several research activities have recently focused on further understanding the complex unsteady aerodynamics of VAWTs [7–15] and characterizing their performance via parameters such as the number of blades [16], blade (airfoil) shape [17–20], turbine solidity [16,18,21] and blade pitch angle [22,23]. Employment of ducts [11], guide vanes [24–26] and utilization of flow control on turbine blades [27–31] also have recently received attention.

The tower is an inseparable component of horizontal and vertical axis wind turbines, which greatly affects the flow on the blades in its neighborhood. For an upwind horizontal axis wind turbine (HAWT) the effect is due to the blades passing through the stagnation region in front of the tower, while for a VAWT or a downwind HAWT this is due to the blades passing through the wake of the tower. A significant amount of research has been performed to characterize the effect of the tower shadow on the aerodynamic and structural performance of HAWTs [32–36]. In contrast, early research on VAWT focused on large turbines with a very small ratio of the tower diameter to turbine diameter. This results in a large relative distance between the tower (which can also be referred to as the shaft) and the blades, in which the effect of the shaft wake on the turbine aerodynamic performance was assumed to be negligible and was therefore not quantified in existing research [4]. However, this is not the case for smaller urban-scale VAWTs with comparatively large shaft-to-turbine diameter ratios, as the turbine power loss due to the blades passing through the wake of the shaft could be substantial. However, to the best of our knowledge, a detailed

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Nomenclature

A	turbine swept area, $h{\cdot}d$ [m^2]
c	blade chord length [m]
C_d	sectional drag coefficient [–]
C_f	skin friction 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	turbine diameter [m]
D	cylinder diameter [m]
d_s	turbine shaft diameter [m]
f	frequency of vortex shedding [Hz]
F_s	safety factor [–]
h	turbine height [m]
k	turbulence kinetic energy [m^2/s^2]
k_s	equivalent sand-grain roughness height [m]
M	turbine moment [Nm]
n	number of blades [–]
P	turbine power [W]
q	dynamic pressure [Pa]
R	turbine radius [m]
Re_c	airfoil chord-based Reynolds number [–]
Re_{crit}	critical Reynolds number [–]
Re_D	cylinder diameter-based Reynolds number, DU_∞/ν [–]
Re_s	turbine shaft diameter-based Reynolds number, d_sU_∞/ν [–]
Re_θ	momentum-thickness Reynolds number [–]
St	Strouhal number
t	time [s]
T	turbine thrust force [N]
TI	turbulence intensity [%]
U_∞	freestream velocity [m/s]
δ	shaft-to-turbine diameter ratio [–]
γ	intermittency [–]
η	shaft-to-turbine rotational speed ratio [–]
θ	azimuth angle [°]
λ	tip speed ratio [–]
ν	kinematic viscosity of air [m^2/s]
σ	solidity [–]
φ	circumferential angle on the cylinder (shaft) [°]
ω	specific dissipation rate [1/s]
Ω	turbine rotational speed [rad/s]
Ω_s	shaft rotational speed [rad/s]

study on the effect of the shaft on the aerodynamic power loss of urban-scale VAWTs has not yet been performed. Moreover, due to strong Reynolds number effects on flow over cylinders [37], the down-scaling of the turbine shaft in urban-scale VAWTs would most probably result in the shaft operating in the subcritical regime. Note that for a smooth cylinder the critical diameter-based Reynolds number corresponds to $Re_s < 2.5 \times 10^5$ [38]. This leads to a relatively large drag and massive flow separation [39], which can subsequently magnify the corresponding turbine power loss. This further emphasizes the importance of such a study.

The extensive literature on the loading and flow field of cylinders, either smooth [38,39] or rough [40–43], stationary or rotating [44–47], can be very useful to identify the flow regime over the turbine shaft and minimize the turbine power loss associated with the presence of its shaft. Previous studies have shown [39–41] that adding roughness to the surface can promote the laminar-to-turbulent transition in the boundary layer, consequently delaying flow separation over the cylinder and eventually significantly decreasing the cylinder drag coefficient C_d by shifting the flow to the critical regime. A reduction in drag, a delay in flow separation and a consequent reduction in wake width together with a jump in the shaft Strouhal number St can signal this shift in flow regime [40,41]. The thinner shaft wake can, in turn, result in turbine blades passing through a region containing more energy on the downwind side that could potentially lead to less power loss due to the presence of the shaft.

The current study is performed in three steps:

1. The turbine power loss associated with the turbine shaft for different shaft-to-turbine diameter ratios δ from 2% to 16%, relevant for small- to medium-scale VAWTs, is quantified. The results are then compared with those for a hypothetical turbine with no shaft.
2. The impact of different operating conditions (including inlet turbulence intensity, chord-based Reynolds number and tip speed ratio) and geometrical characteristics (including solidity and number of blades) on the quantified power loss is investigated.
3. The flow regime over the turbine shaft is identified. Then the effect of the shaft surface roughness is investigated in order to find the optimal roughness height corresponding to the critical Reynolds number Re_{crit}, where a minimum shaft drag is achieved. The corresponding effect on the turbine aerodynamic performance is then investigated in detail. The dependence of the performance of the turbine with optimal roughness height on the shaft-to-turbine rotational speed ratio η is then studied in the range from 0 to 1, where 0 corresponds to a stationary shaft and 1 to a shaft rotating at the same rotational speed and direction as the turbine.

Unsteady Reynolds-averaged Navier-Stokes (URANS) simulations are performed on a high-resolution computational grid. The evaluation is based on validation with wind-tunnel measurements of flow over smooth and rough cylinders by [40,41,48], and for a VAWT by [49,50].

The outline of the paper is as follows: Section 2 presents a description of the computational settings and parameters where the geometrical and operational characteristics, computational domain, grid and other numerical settings and validation studies for both (smooth and rough) cylinders and the turbine are presented. The results of the study on the quantification of the turbine power loss due to the presence of the shaft for different shaft-to-turbine diameter ratios δ are discussed in Section 3.1. Section 3.2 presents a sensitivity analysis to investigate the effect of different operational and geometrical parameters on the turbine power loss due to the presence of the shaft. The possibility of turbine power improvement by addition of surface roughness to the shaft is discussed in Section 4.1. Section 4.2 explains the effect of the shaft-to-turbine rotational speed ratio η on the findings. The limitations of the work, recommendations for future work and the conclusions are provided in Section 5.

2. Computational settings and parameters

Given the main objectives of this study, it is important first to make sure that the flow around the shaft of the turbine, which is basically a cylinder (either smooth or rough), as well as the flow around the whole turbine is accurately simulated. Therefore, three sets of validation studies are performed where the geometrical and operational characteristics are selected to be the same or similar to those in the main study. The studied cases are (1) a stationary smooth cylinder at subcritical Re_D $(=DU_\infty/\nu)$; (2) a stationary rough cylinder at subcritical and critical Re_D; and (3) a VAWT. CFD results of the VAWT have been extensively validated against experimental data of Tescione et al. [50] and the results, together with a comprehensive discussion of the possible explanations for observed deviations, have been published in [51].