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Near wake flow analysis of a vertical axis wind turbine by stereoscopic particle image velocimetry

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ABSTRACT

The development of the near wake of a vertical axis wind turbine is investigated by stereoscopic particle image velocimetry. The experiments are conducted in an open-jet wind tunnel on an H-shaped rotor, operated at a tip speed ratio of 4.5 and at an average chord-based Reynolds number of 1.7×10^5. Phase-locked measurements are acquired at the turbine mid span in order to study the horizontal wake dynamics at the symmetry plane. Results show the evolution of the vorticity shed by the blade, how it organizes in large scale vortical structures at the edges of the wake and the resulting asymmetric induction field in the wake. The evolution of the blade tip vortices and the 3D wake geometry are detailed by a second set of measurements acquired at several vertical planes aligned with the free stream. The dynamics of the system of tip vortices, their vertical motion and interactions are discussed and related to the geometry and the recovery of the wind turbine wake. The experimental data are made publicly available for research purposes.

1. Introduction

Recent developments in wind energy identify in Vertical Axis Wind Turbines (VAWT) a cost reduction potential for offshore applications. Compared to Horizontal Axis Wind Turbines (HAWT), VAWT possess higher potentials for scalability [16,12], a simpler design and maintenance with no yaw or pitch mechanisms and a lower center of mass, with the generator not constrained on top of the tower. The reduced maintenance costs and the possibility to displace the electric generator under water are of major interest in floating offshore applications [27]. Moreover some previous studies on VAWT [3,9] hypothesized a faster wake recovery, leading to a reduction of the turbine spacing and more clustered arrays in a wind farm scenario. The study of VAWT wakes constitutes a severe challenge, due to the complexity of the unsteady 3D aerodynamic flow field. As the turbine converts the energy of the wind by variation over the rotation of the blades bound circulation, unsteadiness is an inherent characteristic of VAWT's wake and different aerodynamic scales can be observed. Previous literature studies, both computational and experimental, tried to isolate different aerodynamic aspects with the intent of simplifying the analysis of the turbine wake. Early studies concentrated on the 2D characteristics of VAWTs [23,26] experimentally and numerically investigating the evolution of the 2D wake generated from a shed vorticity field balancing the variation in time of the blade bound circulation. In the last decade Paraschivoiu [15] compared experimental measurements of the average 2D induction field with prediction models, which poorly estimated the wake energy recovery. On the computational side, most of the numerical models are based upon actuator disk and streamtube models, which have been adapted from the HAWT field, not entirely addressing the underlying physics. Although the role of the airfoil design has been found more relevant for the blade loading rather than for the energy conversion [2,5,8], the effects of the unsteady vorticity field generated by the blade cannot be neglected in the study of the evolution from the blade to the rotor wake. From the 3D point of view the wake of a VAWT has been characterized mainly by numerical analysis [4,5,19], with models based on potential flow and vortex methods, while a continuous and extensive experimental activity is still missing. In the present paper a detailed experimental investigation of the near wake of an H-rotor VAWTs by the use of planar and stereoscopic Particle Image Velocimetry (PIV) is presented. The planar PIV analysis focuses on the vorticity dynamics in the 2D horizontal mid span plane of the turbine, from its generation at the blade level to the formation and diffusion of large scale structures, and on the wake expansion and induction field. Moreover, the main characteristics of the wake 3D geometry are detailed by the stereoscopic PIV measurements. The analysis focuses on the

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generation and mutual interaction of the upwind and downwind tip vortices, the cross-flow variation of their vertical motion and the 3D induction field.

2. Methodology

2.1. System of reference and conventions

To make the presentation and the following discussion on the results easier to follow, some common terminology has to be defined. Typically traditional momentum based streamtube models used to divide the rotor area in an upwind and a downwind half, so that a double multiple streamtube concept could be adapted [1,14]. In the present experimental study, a more complete subdivision is adopted. Following the work of Simão Ferreira [5], the blade orbit is divided in 4 regions:

- upwind: $45^\circ < \theta < 135^\circ$;
- leeward: $135^\circ < \theta < 225^\circ$;
- downwind: $225^\circ < \theta < 315^\circ$;
- windward: $315^\circ < \theta < 45^\circ$;

with θ being the blade azimuthal position and $\theta = 0^\circ$, 90°, 180° and 270° being respectively the most windward, upwind, leeward and downwind positions (see Fig. 1). The adopted division refers to the blade orbit but will be extended to the rotor and wake area.

The coordinate system is a Cartesian frame with origin at the turbine center; *x*-axis directed positively downwind the turbine, positive *y*-axis pointing to the windward side and *z*-axis positive upwards. A positive rotation of the turbine is counter clockwise seen from top.

2.2. Wind tunnel and VAWT model

The experimental activity has been performed in the Open Jet Facility (OJF) which is the closed-circuit, open-jet wind tunnel of the Delft University of Technology. The OJF produces an octagonal jet with a cross-section of 2.85 $D \times 2.85\ D$, following a contraction ratio of 3:1 and free to expand in a 13.7 $D \times 6.6\ D \times 8.2\ D$ test section. The wind tunnel is powered by a 500 kW electric fan allowing for a free stream velocity range from 3 m/s to 34 m/s with a maximum 0.5% of turbulent intensity. A 350 kW heat exchanger maintains a constant temperature (20 °C, in the present experiment) in the test section. Previous studies [10] showed a uniform free stream flow (uniformity of ±0.5% in area) up to 6 *D* from the jet exit. Fig. 2 shows a schematics of the facility.

The model is a two-bladed H-rotor VAWT, shown in Fig. 3. The rotor blades are generated by straight extrusion of a NACA0018 aluminum section with two inner spars and a chord of 0.06 *D*, resulting in an untwisted, untapered blade of 1 *D* span (*H*). The turbine has a diameter (*D*) of 1 m, an aspect ratio (AR) of 1.0 and a blade solidity (σ) of 0.11. The wind tunnel blockage ratio is 0.14. Considering the chord-based Reynolds number range of the tests, the airfoil has been tripped, to avoid the occurrence of laminar separation bubbles [6,13,24], and to limit the level of unsteadiness of the blade flow. A 3D-turbulator tape developed by Glasfaser Flugzeug (6 mm point distance, 0.20 mm thick, 12 mm width, 60° zig-zag tape) at 8% of the chord on both sides has been applied, following the recommendations of Selle [21]. The blade-tower connection is obtained with two aerodynamically profiled struts (NACA0030, chord 0.023 *D*) per blade, installed at 0.2 *D* from the blade tips. The location of the connections minimizes the maximum deformation at blade mid-span and blade tips due to centrifugal effects. The strut-blade connection has been shaped to minimize the flow interference. Both blades and struts, as well as the central part of the tower, have been painted in black to minimize laser reflections. The tower is a 3 *D* steel shaft of 0.04 *D* diameter, connected to a Faulhaber© brushless DC Motor 4490 BS providing with 202 W maximum output power, driving the turbine at low wind speeds and maintaining constant the rotational speed. A Faulhaber© gearbox with 5:1 gear ratio is coupled to the electrical engine to obtain sufficient torque at the operating regimes. The motor operates within a measured accuracy of ±0.02 Hz. A photo diode is installed on the shaft to obtain a 1 pulse per revolution trigger signal to synchronize the PIV system in phase locked acquisition. The turbine model is operated at a tip speed ratio (λ) of 4.5 (predicted $C_P = 0.4$, $C_T = 0.8$), under a free stream velocity (V_∞) of 9.3 m/s and at a rotational speed (Ω) of 800 rpm, in a range of chord-based Reynolds numbers from 1.3×10^5 to 2.1×10^5. The high λ has been chosen after 2D numerical simulations to limit the angles of attack experienced by the blade below the static stall, in order to avoid dynamic stall.

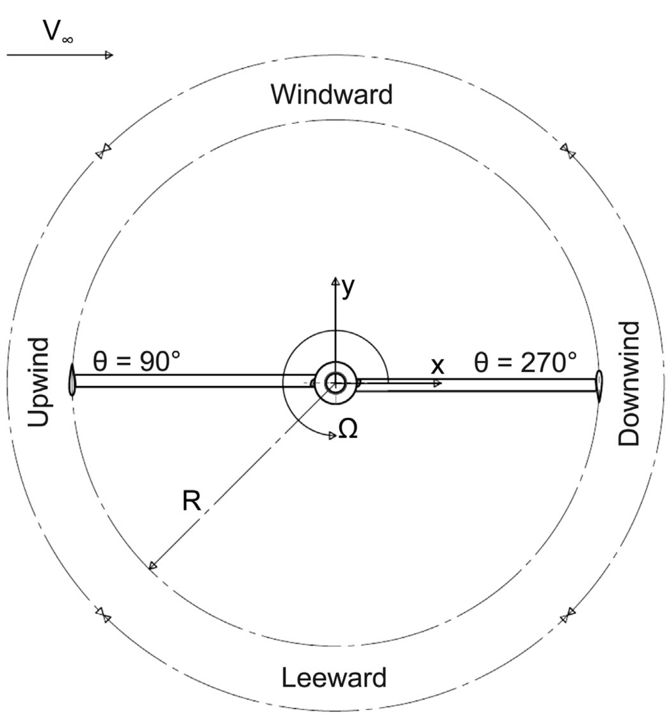

Fig. 1. Schematic of the blade motion on a vertical axis wind turbine.

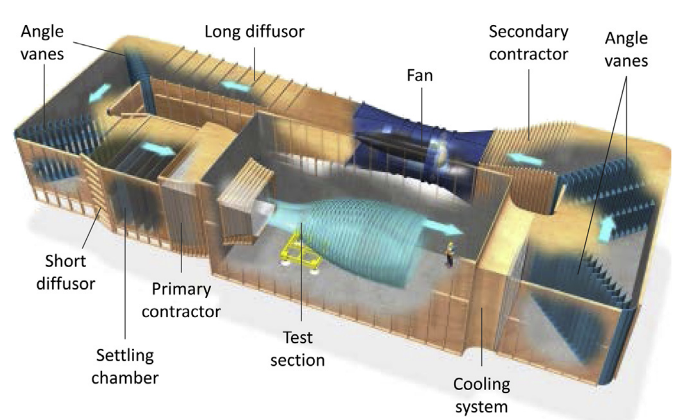

Fig. 2. Schematic of the TUDelft Open Jet Facility.