Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: Luis Santamaría *et al* 2022 *J. Phys.: Conf. Ser.* **2217** 012039

Journal of Physics: Conference Series **2217** (2022) 012039 doi:10.1088/1742-6596/2217/1/012039

Preliminary flow measurements of a small-scale, vertical axis wind turbine for the analysis of blockage influence in wind tunnels

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Abstract. The development of competitive lift vertical axis wind turbines (VAWTs) is yet a challenge in wind power research. New designs typically require wind tunnel testing before in site implementation. One of the major problems at the laboratory stage is the appearance of a significant flow blockage for small scale models, which affects the performance of the tested wind turbines and prevents the direct extrapolation of results to open field conditions without previous correction. Unfortunately, a suitable blockage correction for lift VAWTs has not been achieved yet, so more studies are needed in this research field to fill the gap. As part of preliminary work with this aim, a small scale VAWT prototype has been designed, constructed, and tested in a 1.15x1 m^2 test section wind tunnel with a semi-closed chamber, featuring a blockage ratio of 0.37. Preliminary aerodynamic measurements were performed for different tip speed ratios on the downstream near wake using a special 3-hole pressure probe. Results show that the wake velocity profiles present a velocity increase around the prototype with a low velocity region in the windward quadrant of the turbine, indicating an important influence of the tunnel boundaries. These preliminary measurements have given an initial insight on the aerodynamic relationships between turbine performance and flow patterns. Additionally, they will help to devise an appropriate strategy for the following experiments, with the final objective of developing a blockage correction for small scaled VAWTs.

1. Introduction

Nowadays, renewable energy projects are experimenting an exponential growth, with wind energy and solar photovoltaic in the lead. As wind energy projects increase worldwide, interest is rising in challenging fields, such as urban environments and deep-water, offshore sites. After receiving an important research effort in the last two decades, especially by the academic community, lift-type, vertical axis wind turbines (VAWT) are presented as good candidates for this kind of applications [1,2]. However, these turbines are still in a developing phase, and there is still a great research gap to fill and technical barriers to study and overcome.

Wind tunnel testing provides a necessary starting point in the experimental research of this kind of turbines. However, one of the main problems in wind tunnel testing is the prototype-tunnel interaction, which affects the characteristic turbine performance and flow, and is usually addressed as blockage. To avoid this kind of interactions, prototypes are usually forced to be scaled down, hindering reliable torque measurements, and enhancing mechanical losses and self-starting issues. Furthermore, with the down-scaling, test conditions get harder, as small prototypes must withstand high rotational velocities. Consequently, most of the wind tunnel campaigns conducted on VAWTs feature a relevant level of blockage [3]. Hence, understanding turbine-tunnel flow relations is crucial to perform an objective analysis of experimental results, especially if their aim is to predict real-scale prototype behaviors.

2. Previous works in VAWT blockage

A first approach for wind tunnel testing of bluff objects, airfoils, propellers and airscrews was developed by Glauert [4] and later by Maskell [5] and Pope and Harper [6], laying the basis of blockage research. Savonius turbines blockage correction was addressed by Alexander and Holownia [7] first, and later by Ross and Altman [8]. Mikkelsen and Sørensen [9] developed a wall correction model for HAWT wind tunnel testing, based on the work by Glauert. Battisti et al. Dossena et al., studied Darrieus turbine blockage, basing their corrections on experimental thrust measurements [10,11]. Finally, the most recent contributions to Darrieus VAWT blockage was provided by Jeong et al. [12] and [13].

Nevertheless, despite the works mentioned, there is still limited knowledge about the fluid behavior and its effects in tests with relevant blockage levels.

With the aim of obtaining more information about wind tunnel-turbine interactions and improving the existing correction methods, the authors have started an experimental research campaign in this topic. As part of this campaign preliminary aerodynamic measurements have been performed and are presented in this work.

3. Experimental Set-up

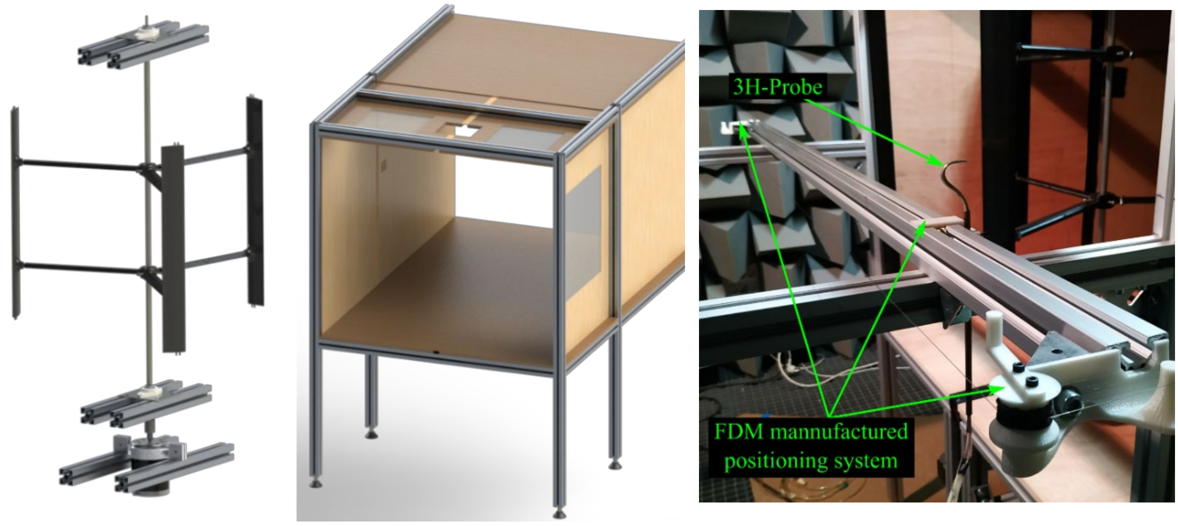
3.1. Turbine.

The turbine used in this research is small-scale prototype of a straight bladed or H-Type VAWT, with 3 fixed blades with no pitch, featuring the airfoil "DU06-W-200" developed by Delft University [14]. It has a diameter (D) of 0.8 m, an effective blade span (H) of 0.52 m and a blade chord (c) of 0.065 m. These dimensions provide a solidity (σ) of 0.5 and an aspect ratio (H/D) of 0.65. The turbine was manufactured combining conventional materials such as: aluminum profiles, bearings, a steel shaft; with Fused Deposition Modeling (FDM) PLA parts where complex geometries were needed, as in the blades and the struts. The assembly of the turbine includes a 1kW DC motor, which allows great rotational speed control and a digital optical tachometer to measure axis rotational speed. A realistic sketch of the turbine assembly is shown in figure 1 a.).

3.2. Wind-Tunnel.

The turbine was tested in the Xixón Aero-acoustic Wind Tunnel (XAWT) which is a closed-circuit wind tunnel. This wind tunnel can achieve velocities up to 22 m/s featuring a mean turbulence intensity around 0.7%; additional data can be found in [15]. The original test chamber is 4.2 m long and has a cross-section of 4.45x2.80 m^2, while the test section is 1.15x1 m^2. This combination of turbine and test section dimensions gives a blockage ratio (projected turbine area over test section area) of 37%, which is a high-blockage condition, chosen so that blockage effects are noticeable. Usually, to avoid blockage effects in measurements, blockage ratio is kept under 10%.

To research blockage effects in a confined environment, a special modular test chamber was built with the same dimensions of the test section, formed by an empty duct module of 1 m (1.25D) and a module of 0.77 m (0.96D) in which the turbine is placed. The first module is devised to avoid disturbances in the inlet velocity, which is a known effect of solid blockage. As it is shown in [12] as the blockage ratio increases, the perturbation of inlet velocity is also greater, but occurs closer to the turbine. Thus, it is expected that the chosen duct length will be suitable, given the test wind velocity, blockage ratio, turbine dimensions and solidity. A characterization of the velocity distribution in the outlet of modular test chamber without the turbine was carried out to verify its suitability and make sure that the boundary layer thickness was not relevant to the overall dimensions. The outlet of the modular test chamber is open to the original chamber, so the wake can expand freely and only wall and inlet section blockage is studied. In figure 1 b.) a realistic sketch of the modular test chamber is shown.



a) b) c)

Figure 1. a) VAWT model assembly, b) special test chamber, c) 3-hole probe and positioning system.

3.3. Instrumentation.

Regarding the instrumentation, inlet velocity is measured with a differential pressure sensor (CP210-R) with pressure tabs at the inlet and outlet of the nozzle. Additional pressure sensors were used to evaluate the pressure at several positions along the test chamber, but these are not relevant to the aerodynamic measurements presented in this work. At the outlet, the velocity profiles were measured using a special 3-Hole pressure probe called “Cobra-probe” designed and manufactured in earlier works by some of the authors. This type of probe is used to measure mean wind velocity and mean incidence angle, since its frequency response is too low to perform instantaneous measurements. More information can be found in [16,17]. The new calibration method devised and presented in [16] extends the angular range of this probe up to ± 80 ° which makes it suitable for its use in the vicinity of the turbine. Each probe tube is connected to a Validyne DP15-26 pressure transducer, each transducer to a voltage amplifier and finally each amplifier to a data acquisition card. The data acquisition card also receives the signals from the other pressure sensors and the tachometer. Equipment uncertainties are detailed in table 1.

Differential pressure sensor	Pressure transducers & amplifiers	Cobra probe	Positioning system	Tachometer
Inlet pressure difference: $\frac{u\Delta P_{0-1}}{\Delta P_{0-1}} = \pm 5.98\%$	Hole pressure measurement: $\frac{uP_i}{P_i} = \pm 0.25\%$	Angle: $\frac{u\alpha}{uP_i/P_i} \cdot 100 = 0.6[°]*$	Probe displacement step $\frac{u\Delta x}{\Delta x} = \pm 6.6\%**$	Rotational speed: $\frac{un}{n} = \pm[0.09 - 0.16]\%$
Temperature for density correction: $\frac{uT}{T} = \pm 3.18\%$		Dynamic pressure: $\frac{uP_d}{uP_i} = \pm 0.95[\%]*$		

*(relative to the sensor uncertainty)
**(increased to account for possible random wire slip)

Table 1. Equipment uncertainties.

In order to measure several velocity profiles with precision and optimizing test times, a positioning system was designed and manufactured using FDM (figure 1 c.)). The system transforms the circular motion of a manual crank joined to a pulley, to linear displacement of a slider which carries the probe, by means of a non-elastic wire. The pulley has been designed so the that its perimeter is multiple of the test section width. In this way, different steps-sizes can be chosen as a function of the pulley's rotation. A general view of the wind tunnel and a diagram of the experimental set-up is shown in figure 2.

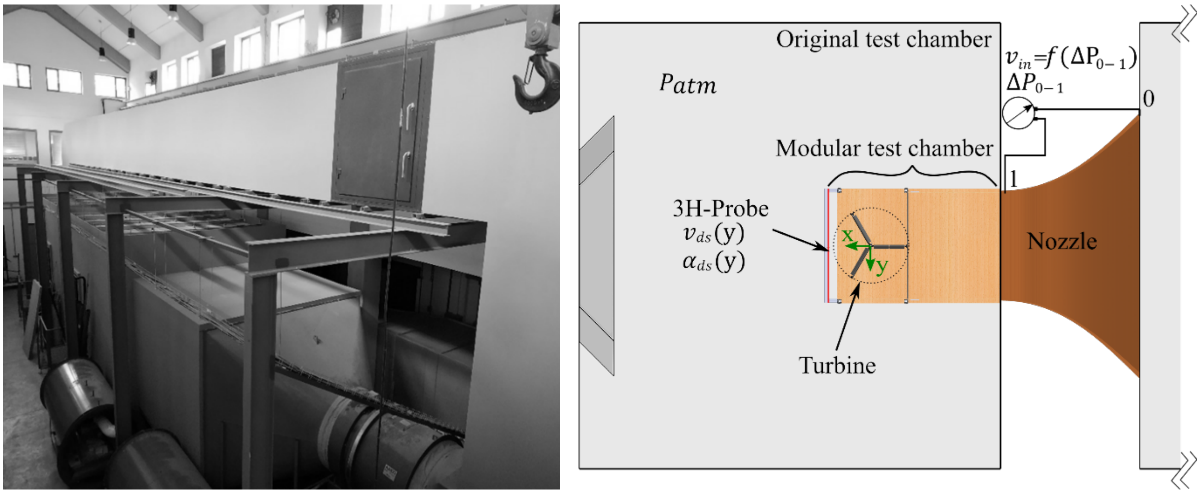


Figure 2. XAWT wind tunnel general view and experimental set-up diagram.

4. Measurements

Using the 3-hole cobra probe, downstream velocity profiles in a near wake position (0.59D) have been measured for 9 different tip-speed ratios (blade velocity over reference wind velocity) ranging from $\lambda = 0.87$ to $\lambda = 3.55$. The reference wind velocity was kept constant at approximately 7.5 m/s which is the velocity at the nozzle outlet. The different tip-speed ratios are achieved by spinning the turbine at different rotational speeds. The turbine is continuously driven by the DC motor which is controlled through voltage regulation. This procedure allows great rotational speed control. A lateral displacement step of approximately 3 cm (half crank turn) was chosen for the cobra probe, producing a total of 39 measurement positions. For each measurement, the chosen acquisition frequency and time were 1000 Hz and 5 s respectively, which was found to be sufficient to produce accurate averages. Figure 3, shows a picture taken during a measurement.

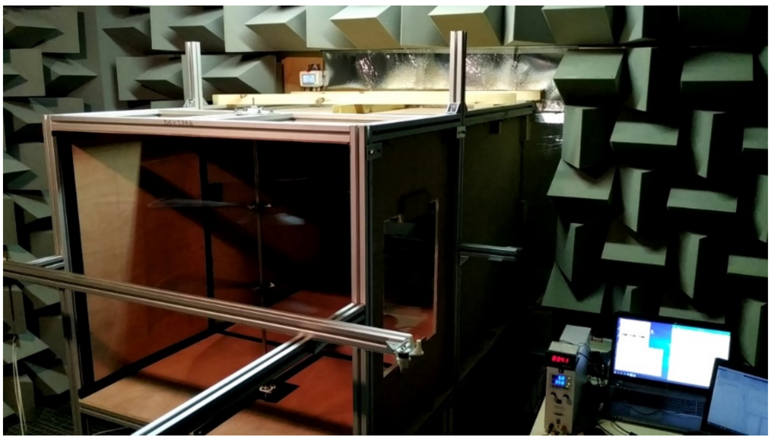


Figure 3. Picture taken during a measurement.

5. Results and discussion

A selection of 4 velocity profiles corresponding to tip-speed ratios: $\lambda = (0.87, 2.06, 2.76, 3.55)$ is presented in figure 4. The selected tip-speed ratios correspond to: a negative performance coefficient (C_P), a low positive C_P in the high slope zone, a high C_P where the slope is decreasing to approach the maximum and a C_P past the maximum with increasing slope, respectively. Vector representation was chosen for downstream velocity, normalized with the velocity at the inlet, to enhance visual interpretation of the data and downstream velocity angle is also shown independently in each sub-figure. The dotted blue lines indicate the position of the turbine; it rotates in the counterclockwise direction, so in the graphs, the leeward half corresponds to the negative normalized positions and the windward half to the positive ones.

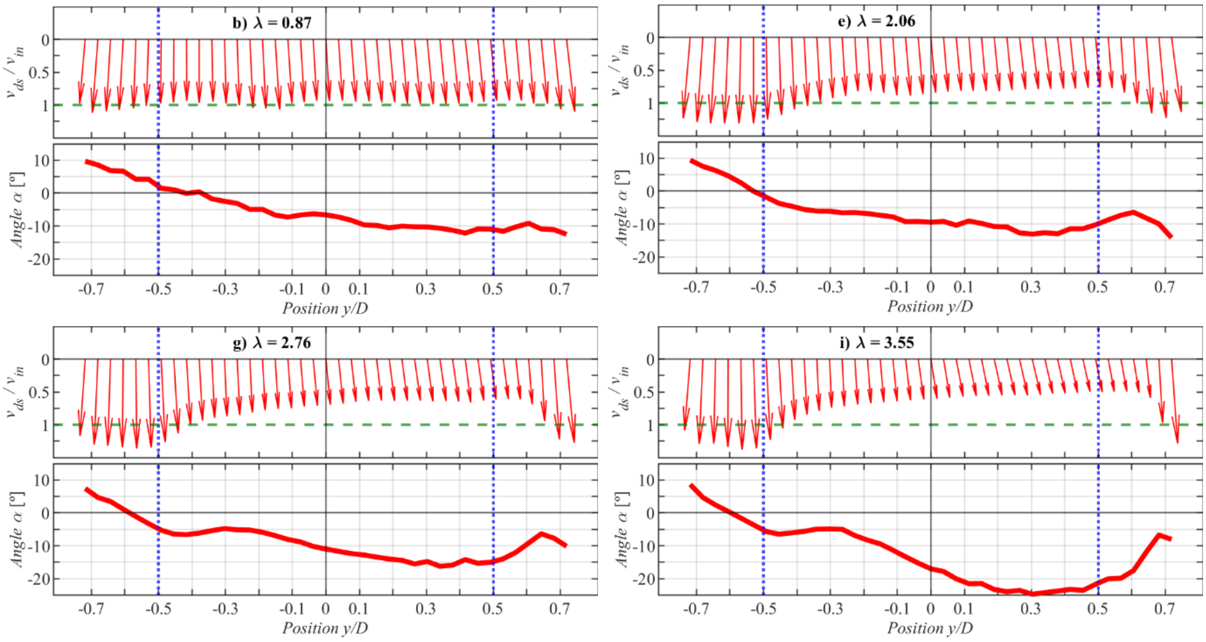


Figure 4. Selection of 4 downstream velocity profiles, showing the normalized downstream velocity in vector form and the velocity angle, over the normalized position.

- The velocity profile at $\lambda = 0.87$ shows a very light influence of the turbine rotation, with mean downstream velocities very close to the reference velocity. Incidence angles have the typical shape of an opening jet with a slight offset to the negative due to the effect of the turbine rotation.
- In the velocity profile at $\lambda = 2.06$ a marked increase in the velocity around the turbine can be appreciated, especially in the leeward zone, while the wake shadow starts to be noticeable. Incidence angle is not very different from the previous velocity profile, except from the zone corresponding to the gap between the turbine and wall in the windward side. There, the important increase in streamwise velocity, possibly because of the strong solid blockage in the area, produces a strong decrease in the absolute magnitude of the incidence angle.
- The velocity profile at $\lambda = 2.76$ exhibits the same trend as the previous ones, with minimum and maximum velocities greater than ±0.25 times the reference velocity. Regarding the incidence angle, there is an overall increase in the absolute value towards the negative direction.
- Finally, the velocity profile at $\lambda = 3.55$ shows a clear wake shadow region, revealing an important increase in the absolute value of the incidence angle towards the negative direction. This noticeable increase is the result from the combination of strong solid blockage with its consequent decrease in streamwise velocity, and the increase in turbine rotational speed.

Journal of Physics: Conference Series **2217** (2022) 012039 doi:10.1088/1742-6596/2217/1/012039

For a more general approach, downstream streamwise velocity and incidence angle measurements from every tip-speed ratio are shown in a contour plot in figure 5. Turbine position is indicated with black dashed lines.

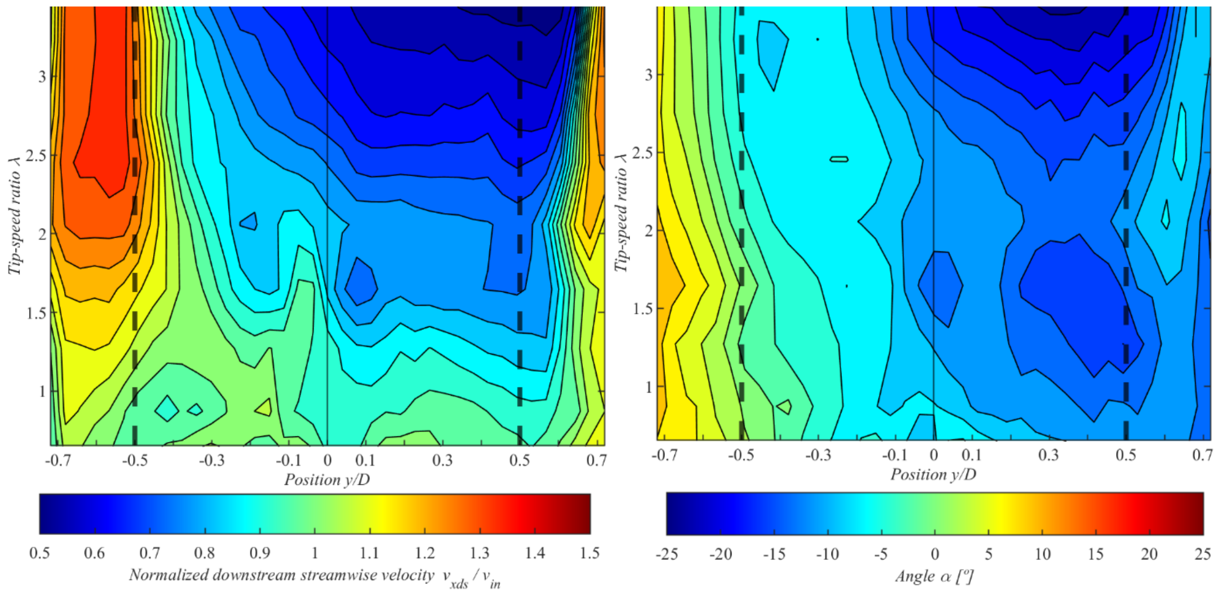


Figure 5. Contour plot of the downstream streamwise normalized velocity and the incidence angle.

A general common trend can be observed among all the measurements. There is a progressive increase of the streamwise component of the downstream velocity, around the turbine, in the leeward half, as tip speed ratio increases. On the other hand, in the same zone of the windward half, the opposite effect is appreciated, with a strong decrease in the streamwise component of the downstream velocity. A clear shadow of the wake can be observed as a decrease of the streamwise component of the downstream velocity, both in the leeward and windward halves, though stronger in this last one.

The incidence angle of the leeward side experiences a slight decrease in the absolute value, responding to a greater increase in streamwise velocity than that of the spanwise component, throughout the tip-speed ratio range. However, in the windward side, there is a strong increase in the incidence angle towards the negative direction, due to both the stronger relevance of the spanwise component induced by the turbine rotation, and the high blockage zone and its consequential decrease in streamwise velocity component.

Although the observed behavior matches the expected, the difference between the streamwise velocity from the reference velocity, and the magnitude of the incidence angle are really notable, indicating a strong influence of the wind tunnel-prototype interaction in the flow field.

6. Conclusions

Preliminary aerodynamic measurements were performed on a small-scale H-VAWT prototype in a confined environment featuring high solid blockage level, but free wake expansion, for a wide range of tip-speed ratios.

These preliminary measurements have given an initial insight on the aerodynamic relationships between turbine performance and flow patterns. Those measurements will be a starting point to complement ongoing investigations on blockage correction.

The 3-hole pressure probe developed in earlier works turned out to be a great tool to measure mean velocity profiles close to the turbine, due to its wide range, its simplicity, and the relatively low uncertainties of the measurements.

Likewise, the modular test chamber devised offers and interesting approach, permitting the study of solid blockage detached from wake blockage.

In future works, downstream velocity profiles will be measured with the same methodology and equipment at different heights, focusing specially on the lower and upper gaps. Additionally, the combination of these measurements and those from the other pressure sensors in the test chamber will allow an estimation of the turbine performance through the control volume theory. Moreover, the modular test chamber allows easy wall removal, which will be useful to perform future measurements in an unconfined environment and obtain and interesting comparison.

Further tests for different blockage conditions will shed more light on how the wind tunnel conditions are affecting turbine performance and, therefore, allow a deeper understanding of the obtained results.

Acknowledgments
The authors wish to thank the support of: MINECO, Spain [ENE 2017-89965], Principality of Asturias [GRUPIN-IDI/2018/000205], University Institute of Industrial Technology of Asturias (IUTA) and Ayto. Gijón [SV-18-GIJON-1-05, SV-19-GIJON-1-15, SV-20-GIJON-1-17].

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