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Wind Tunnel testing of small Vertical-Axis Wind Turbines in Turbulent Flows

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Abstract

This study presents an innovative wind tunnel approach to evaluate the efficiency of Vertical-Axis Wind Turbines (VAWT) in turbulent flows, to study their integration in urban environments.

The first part of the research is devoted to obtaining highly-turbulent wind profiles in the wind tunnel, with the use of different configurations of square grids. A careful study and validation of this technique is done, in order to obtain uniform wind conditions with the adequate values of turbulence intensity and length scales to model the urban flows.

The set-up is used to test a H-Darrieus VAWT under values of turbulence over 5%, in comparison with the operation of the turbine under free stream. The preliminary results show that high levels of turbulence do have a significant effect in turbine performance, causing a drop of power for high rotational speeds, increased vibrations in the structure and more difficult control of the rotor. More tests are advised to validate these observations, as well as to expand the study over higher values of turbulence intensity, in order to present a more detailed study with empirical conclusions.

Keywords: Wind energy; VAWT; urban wind turbines; urban flows; wind tunnel; turbulent flows.

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Nomenclature

b	Bar width (m)
c	Turbine blade chord (m)
C_P	Power Coefficient (-)
D	Diameter of the rotor (m)
H	Height of the rotor (m)
I_u	Intensity of Turbulence (-)
L_{ux}	Integral Length Scale of turbulence in the wind direction (m)
M	Mesh size (m)
Q	Torque (Nm)
R	Turbine Radius (m)
V	Wind speed (m/s)
x	Distance from grid (m)
λ, TSR	Tip Speed Ratio (-)
ρ	Density of air (kg/m^3)
ω, RPM	Angular speed (min^{-1})
HAWT	Horizontal-Axis Wind Turbines
VAWT	Vertical-Axis Wind Turbines

1. Introduction

Vertical-Axis Wind Turbines (VAWT) vary from the conventional horizontal ones (HAWT) in the orientation of their axis, which leads to differences in their operation. The 3-bladed HAWT, the so called "Danish concept", presents the highest efficiency and has become the most established technology [1]. However, for urban flows, where the wind is typically slow and complex, HAWTs show poor results. VAWTs, on the other hand, are omni-directional, adapting quicker and better to changing wind direction, and operate at lower Tip-Speed Ratios (TSR), which makes them less noisy [2]. Thanks to these features, VAWTs have found their market in small urban wind energy during the last decade [3]. Detailed literature is available on large VAWTs from research programs in the 80s [4, 5], and several small VAWT models are under operation and testing. However, there is still little research available about their performance under urban flow conditions.

In built environments, the rotor experiences high levels of turbulence, inclined, reverse and stratified flows. The challenge of finding a desirable location is considerable, and has led to multiple cases of bad practice. The lack of a detailed wind study of the location leads to turbines with poor energy production, giving bad press for VAWTs and renewable energy in general. To avoid this, literature and on-site measurements can be used to determine the best locations for wind turbines in an urban environment: top of buildings, large avenues, canyon effects, etc. [6]. From literature, it can be seen that these sites provide an acceleration of wind speed, but high levels of turbulence (I_u >20%) are reached [7]. This turbulence level is rarely considered when evaluating the performance of the wind turbine prototypes, and wind tunnel studies are normally done at I_u levels of less than 1%.

From those few studies in the subject it is difficult to extract definitive conclusions. For medium-sized VAWTs Siddiqui [8] predicted a decrease in performance using CFD, while Mollestrom [9] recorded an increase in field measurements. An experiment in wind tunnel using a turbulence grid was carried on by Ahmadi-Baloutaki [10] also predicting a boost of power, but restricted to low values of TSR, far from the optimal operation point. The generation of turbulence by passive grids is also a complicated issue. The experience in the CRIACIV wind tunnel at the University of Florence [11], shows the complexity of achieving high values of turbulence (I_u>10%) while maintaining uniform windspeed and turbulence profiles inside the wind tunnel. This should be also addressed in the current study, as obtaining uniform profiles is a necessary condition to have reliable results.

2. Methodology

2.1. Wind Tunnel and equipment

The objective of this work is to experimentally evaluate the behaviour of VAWTs in turbulent flows. The research is performed at the Vrije Universiteit Brussel, in Belgium. The wind tunnel of the Department of Mechanical Engineering is of the Boundary Layer type, with a cross section of 2 m x 1 m in the test area, that allows to develop stable turbulence intensity and length scale levels (Figure 1).

Fig. 1. Wind tunnel of the Department of Mechanical Engineering of the Vrije Universiteit Brussel, Belgium.

The wind flow characteristics are measured with a Constant Temperature Hot-Wire Anemometer, model Dantec mini-CTA 54T42. Its calibration is done using a Pitot tube. The time histories obtained from the hot-wire are acquired by a National Instruments Card and processed using Labview software to obtain mean speed U and Turbulence intensity I_u. The values of the Integral Length scale L_{ux} are calculated according to Taylor's frozen-eddy hypothesis and the results were confirmed by fitting the expression proposed by von Kármán to the measured spectrum [12].

2.2. The generation of turbulence

To generate high levels of turbulence inside the wind tunnel, several kinds of grids can be used. These grids modify the free stream present in the wind tunnel, stopping the flow and creating vortexes. From the conclusions of Roach [13] it can be drawn that a square-mesh of square bars is the simplest way to obtain isotropic turbulence, with low dependency of Reynolds number as the flow separation occurs always in the trailing edge. The design of the grid is made following the thesis of Laneville [14], that presented an empirical relation of the I_u that would be obtained at a distance x from a grid with bar size b (Eq. 1).

$$I_u = 2.58\left(\frac{x}{b}\right)^{-\frac{8}{9}} \tag{1}$$

The literature results considered during this study [12, 14, 15] seem to fit adequately this equation, and show that values of $I_u>10\%$ can be easily reached within the fully developed turbulent profiles zone ($x>10M$ according to [13]).

When operating with turbulent flows, not only the intensity but also the integral length scale L_{ux} of these eddies should be considered. In urban environments $L_{ux}>1$m [16], while from literature results it can be seen that the anisotropic turbulence obtained by grids inside the wind tunnel has values of $L_{ux}\sim0.1$m. Therefore, it would be impossible to recreate the conditions in urban environments, but at least it should be ensured that that $L_{ux}>c$ [15], where $c=0.05$m, is the turbine blade chord. Roach [13] presents an empirical relation to calculate L_{ux} from the grid dimensions (Eq. 2):

$$\frac{L_{ux}}{b} = 0.2\left(\frac{x}{b}\right)^{\frac{1}{2}} \tag{2}$$

Using Eq. 1 and 2, the values chosen for the grid are M=0.33m and b=0.072m, that would allow to achieve the desired values of I_u and L_{ux}. However, when the grid was built, it was clear that it was very complicated to obtain a uniform profile, which was predicted by Roach [13] for mesh sizes M larger than 10% of the wind tunnel dimension. Different grid configurations have been built (Fig.2) always conserving the M/b relation. Differences of centimetres in the grid geometry cause radical changes in the flow, as it was already announced by Roach, and can be observed by the huge variation between the profiles b and c (Fig. 3).

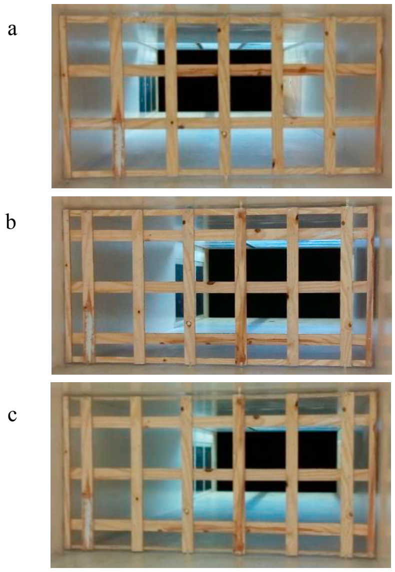

Fig. 2 (a, b and c). Different grids used to generate turbulent profiles inside the wind tunnel.

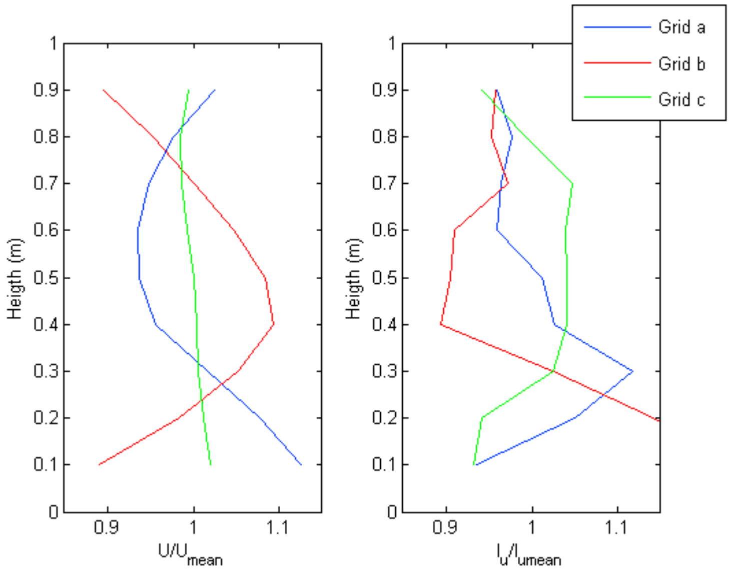

Fig. 3. Non-dimensionalized wind speed and turbulence intensity vertical profiles obtained with the different grids.

The most uniform profile is obtained with grid c, and would be the one used for the first experimental campaign. This was performed at a distance of 3.9 m from the grid at 9 m/s. The average values obtained over the height of the turbine are summarized in Table 1, and present good agreement with the empirical equations (1) and (2).

Table 1. Average values obtained over the vertical profile in the center of the wind tunnel.

	I_u (%)	L_{ux} (m)
Measured	6.94	0.099
Predicted by literature [14, 13]	7.44	0.106

Although these values are acceptable, the profile deteriorated when moving the grid to other positions along the wind tunnel. Therefore, a more detailed study of grid turbulence generation must be performed in the following months to be able to choose freely the values of I_u and L_{ux} for the experiments.

2.3. The wind turbine

The VAWT is a 2-bladed H-Darrieus design with D=50 cm and H=80 cm, and it was built in lightweight carbon fibre at VUB (Figure 4). The blades' profile is a NACA0018 with c=5cm chord. The turbine is supported by an aluminium modular frame already tested in other VAWT measurements. The torque is measured by Lorenz Messtechnik DR-3000 torque meter (max 5 Nm, precision 1% of 2 Nm), and the rpm are measured using variable resistors [17]. The axis of the turbine is coupled to a brushed DC motor/generator, that allows the start-up of the turbine.

The parameter to calculate the performance of the turbine will be the Power Coefficient (C_P):

$$C_P = \frac{P_{turbine}}{P_{wind}} = \frac{Q\omega}{\frac{1}{2}\rho D H V^3} \tag{3}$$

The conventional way of representing C_P in wind turbine studies is plotting it against the Tip-Speed Ratio of the turbine, a non-dimensional number that relates the speed of the blade tip with the incident wind:

$$\lambda = \frac{\omega R}{V} \tag{4}$$

3. Results

The values of C_P of the turbine are measured fixing V at 9m/s and changing ω within the operational limits (900-1200 rpm), and plotted to obtain the $C_P - \lambda$ curves that represent the wind turbine performance. First, the turbine efficiency is evaluated conventionally, with no obstacles in the wind tunnel and therefore very low turbulence (I_u =0.5%). Then, the tests are repeated at medium turbulence (I_u =6.94%). The first power curves obtained are plotted in Figure 5. The values are divided by the optimal values of C_P and λ in the low turbulence case. As it can be seen, the two curves present a similar behaviour until C_{Pmax}. After that, the turbine under high turbulence exhibits significantly lower performance.

Fig. 4. VAWT model built by the VUB team.

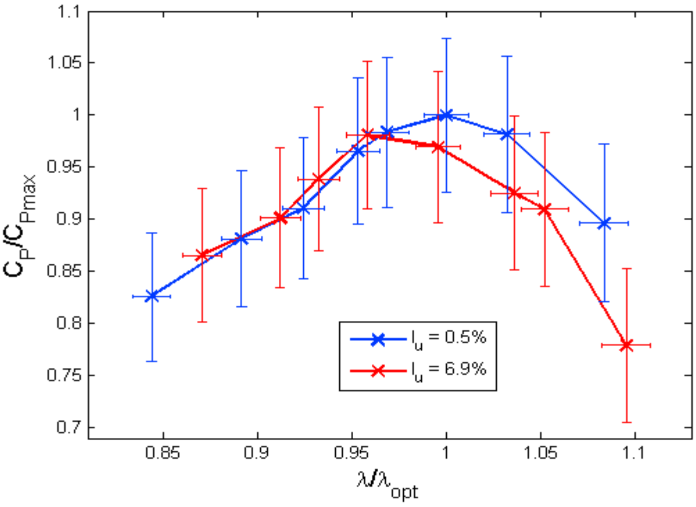

Fig. 5. $C_P - \lambda$ curves obtained with different I_u levels of at V=9 m/s.

However, as it can be seen from the error bars, the uncertainties are substantial due to the low resolution of the torque meter and the accuracy of the wind speed measurement. More experiments should be done in the future to validate these results. There was not enough time to measure at different turbulence levels, but in the following months, when grid turbulence generation techniques are improved, measurements will be done at different I_u and L_{ux}, to understand the effect that turbulence has on the performance of VAWT.

The first tests also arose another question, as during the testing at I_u =6.94% it was observed that the vibrations in the turbine and support structure increased significantly. In future campaigns a quantitative value of this parameter must be recorded, which will prove of key importance in the structural design on VAWT for built environment. The control of the turbine, which was done manually, proved to be more challenging also for the increased turbulence case, which would be an important issue for turbine manufacturers.

4. Conclusions

The present work highlighted the difficulty, but also the interest, of creating a benchmark for testing experimentally the performance of H-Darrieus VAWT under turbulent flows. The first preliminary results show that high levels of turbulence do have a significant effect on turbine performance, causing a drop of power for high TSR, increased vibrations in the structure, and more difficult control. Those three are key aspects in the operation of these machines, and their further study will be of high significance for manufacturers and researchers, especially for the operation of VAWT in urban environments. With a larger range of turbulent values than the present work, and quantitative measurements of vibrations and control, the results obtained would permit to present some empirical rules about this phenomenon.

The first part of the research, moreover, will become an interesting contribution to the wind tunnel testing knowledge. As every wind tunnel presents particular characteristics, applying the same procedures in two of them (CRIACIV after VUB) will provide valuable experience in grid-generated turbulence and its appropriate application.

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