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Experimental Tests of a Vertical-Axis Wind Turbine with Twisted Blades

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Abstract—An experimental campaign of measurements for a Darrieus vertical-axis wind turbine (VAWT) is presented for open field conditions. The turbine is characterized by a twisted bladed design, each blade being placed at a fixed distance from the rotational shaft. The experimental setup to perform the acquisitions is described. The results are lower than expected, due to the high influence of the wind shear.

Keywords—Vertical-axis wind turbine, Darrieus wind turbine, twisted blades, experimental measurements, wind shear.

I. Introduction

WIND Energy has gained an increasing importance in the last decades, due to the awareness for the urgent need of a transition from fossil fuel generation to renewable energy. Vertical-axis wind turbines (VAWTs) are designed considering advanced computational tools such as Blade-Element Momentum, Vortex and CFD codes, but experimental tests are still to be considered mandatory for full turbine characterization: for this purpose, wind turbines are generally tested by means of wind tunnel or open-field measurements. Different examples of both testing procedures are available in literature. Howell et al. [1] tested a straight-bladed rotor with an aspect ratio of 4:1 in the Sheffeld University wind tunnel (1.2 m x 1.2 m test section), highlighting the dependence of rotor performance from blade surface finish (a rough surface determined an increase of rotor performance for low Reynolds numbers). Bravo et al. [2] tested a small wind turbine with a diameter of 2.5 m and a height of 3 m in the NRC Low Speed Wind Tunnel, Ottawa (9 m x 9 m test section). Battisti et al. [3] presented a wide experimental investigation on the aerodynamics and performances of a Darrieus wind turbine in the Milan Bovisa large scale wind tunnel (4 m x 3.8 m test section), also analyzing rotor wake for different tip speed ratios.

The present analysis considers open field measurements. Sandia National Laboratories presented a wide series of reports about experimental tests of VAWTs sizing 2-meters [4], 5-meters [5], 17-meters [6], [7] and 34-meters [8]. All the tests were conducted in the Sandia test site and at fixed rotational speeds. The results of such tests are particularly useful to validate the numerical codes for the prediction of rotor performance.

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The present work describes the results of an experimental campaign of measurements conducted on a VAWT having a radius of 1 m and an aspect ratio of 1.6, shown in Figure 1, tested in an open field facility located in Longarone, BL (Italy). The measurement setup was arranged by considering the dictates from the International Standard 61400-12 [9], [10], as will be explained in the next sections.

Fig. 1: VAWT tested in Longarone open wind facility, BL (Italy)

II. Test Site

The tested rotor is characterized by three twisted blades, placed at a fixed distance from the rotational shaft. The airfoil section is a NACA 0018 with a chord length of 200 mm. The equatorial plane of the rotor is placed at 3 m from the ground and the shaft is equipped with a torque-meter and a variable speed motor, capable of spinning the wind turbine at several fixed angular velocities, defined by the motor driver. The torque-meter is adopted to measure the torque between the motor and the turbine, in order to estimate how much power is produced (or absorbed) due to the rotation of the turbine. An installation scheme is reported in Figure 2.

The test site includes a measurement tower, equipped with two anemometers placed at different heights: at 3 m (the same height of the center of the wind turbine) and at 6 m. The difference between wind data registered at such heights would allow the investigation of the wind shear. Additionally, a wind vane is placed at the lower level, in order to check the wind

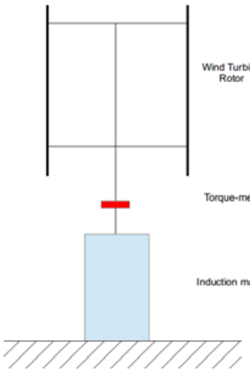

Fig. 2: Installation scheme of the torque measurement device

direction. The wind is mainly coming from North and secondly from South, due to the orography of the test site, as can be drawn from Figure 3, where the probability rose for the wind direction is represented.

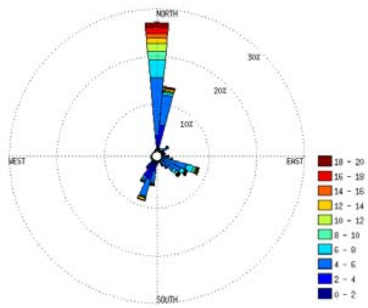

Fig. 3: Probability rose for the wind direction at the test site

In order to avoid any possible interference between the measurement mast and the wind turbine, the former is placed 315° North with respect to the latter, at a distance of 8.6 m, as prescribed by the International Standard IEC 61400-12: the equivalent radius of the tested rotor is calculated to be 1.4 m and the met mast must be placed at $(2.5+0.5)\cdot D_{eq}$. The mast installation scheme is reported in Figure 4.

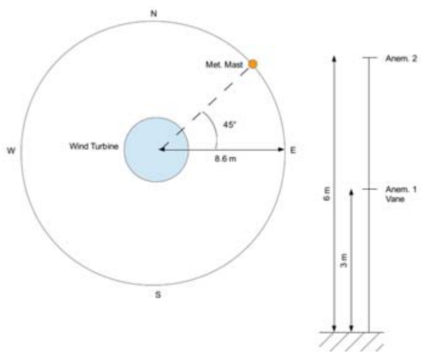

Fig. 4: Meteorological mast installation scheme

The signal from the anemometers are processed by a Gantner D101 receiver, whereas the vane and the torque-meter are connected to a Gantner A101. Both the measurement modules are connected to a Gantner Q.Gate IP that performs the data logging. The sampling rate is set to 100 Hz.

The air density is computed on the basis of both the air temperature and the site altitude. Having registered an almost constant temperature of 5° C during the whole measurement campaign, the air density is computed by means of the formula:

$$\rho = \rho_0 \cdot \left(1 - \frac{0.00651}{288} \cdot q\right)^{4.255} = 1.212\ \frac{kg}{m^3} \qquad (1)$$

being ρ_0 the air density at the sea level, $1.269\ \frac{kg}{m^3}$ at $5\ °C$, and q the altitude of the test site (473 m) over the sea level.

III. Results and Discussion

The results of the measurement campaign are analysed with the method of bins, considering periods of 10 minutes of contiguous data. The rotational speed is set at the fixed rate of 100 rpm and, successively, at the fixed rate of 150 rpm. The power produced for the two rotational speeds is plotted with respect to the wind speed in Figures 5 and 6.

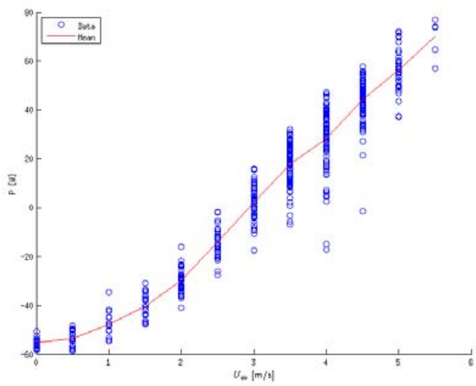

Fig. 5: Power production with respect to the wind speed for a fixed rotor angular velocity of 100 rpm

A comparison between the average power production with respect to the wind speed for the two tested angular velocities is reported in Figure 7.

The power coefficients needs to be computed considering the wind shear. As a matter of fact, the turbine is placed at a height of 3 m and therefore the wind shear linked to the ground presence is considerable. In order to compute the wind shear, the logarithmic law is considered, linking the unhindered wind speed U_∞ at the reference height (3 m) with the local wind speed U_z:

$$U_z = U_\infty \cdot \frac{ln(\frac{z}{z_0})}{ln(\frac{z_{ref}}{z_0})} \qquad (2)$$

Considering the data registered from the two anemometers placed at 3 and 6 m, the value of z_0 can be estimated, resulting

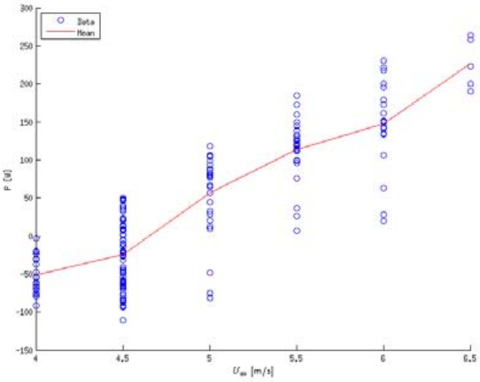

Fig. 6: Power production with respect to the wind speed for a fixed rotor angular velocity of 150 rpm

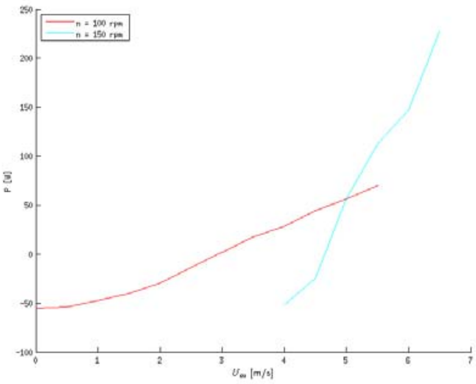

Fig. 7: Mean power production with respect to the wind speed for angular velocities of 100 and 150 rpm

around 0.40 m. Considering this value, the wind speed at every wind turbine section can be evaluated, as shown in Figure 8.

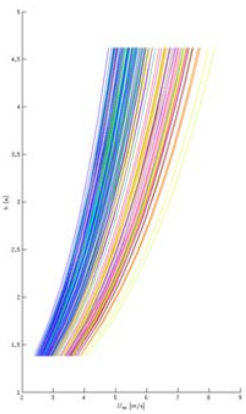

Fig. 8: Wind shear: each line is representing the wind speed distribution at the different heights for different nominal wind speed conditions

For a nominal wind speed of $U_\infty = 5.5$ m/s, the local wind speed is ranging from approximately $U_z = 3.5$ m/s to $U_z = 6.5$ m/s over the rotor height. This needs to be carefully taken into consideration for the estimation of the power coefficient, since the adoption of a uniform wind speed will provide misleading results. The rotor height is therefore divided in 10 sections and for each of them the free-stream wind power is computed. All these values are then summed up and adopted for estimating the power coefficient C_P, shown in Figures 9 (for a rotational speed of 100 rpm) and 10 (for a rotational speed of 150 rpm), in formulas:

$$C_P = \frac{P}{\sum_{N=1}^{10} 0.5 \cdot \rho \cdot (A/10) \cdot U_z^3} \tag{3}$$

being P the power production, A the swept area and U_z the local wind speed, with respect to the tip speed ratio λ, defined as:

$$\lambda = \frac{\omega R}{U_\infty} \tag{4}$$

where ω is the rotational speed, R is the rotor radius and U_∞ is the free-stream velocity.

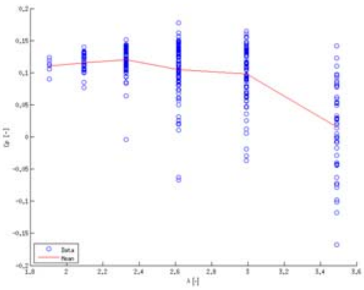

Fig. 9: Power coefficient with respect to the tip speed ratio for a rotational speed of 100 rpm

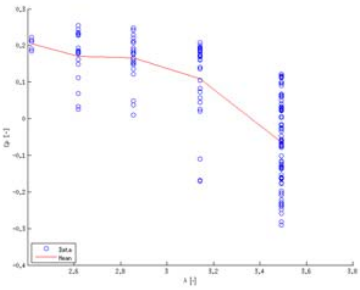

Fig. 10: Power coefficient with respect to the tip speed ratio for a rotational speed of 150 rpm

A comparison between the average power coefficient with respect to the tip speed ratio at the different rotational speeds is reported in Figure 11.

Due to the great range of wind speeds experienced by the turbine rotor along its height, some sections of the rotor are always operating for non-optimal tip speed ratio conditions. As

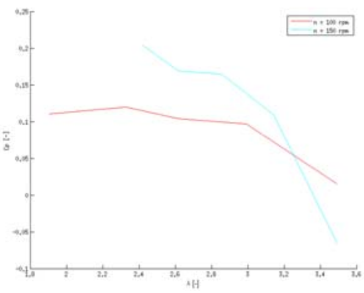

Fig. 11: Power coefficient with respect to the tip speed ratio for rotational speeds of 100 and 150 rpm

expected, the wind shear is highly affecting the performances and a maximum power coefficient approximately equal to 0.2 is achieved.

IV. Conclusions

A wind turbine characterized by twisted blades has been tested in an open field facility. The adopted measurement technique for the aerodynamic characterization of the rotor has been derived from the prescrictions contained in the International Standard IEC 61400-12. Due to the low altitude over the ground of the tested rotor, a strong wind shear has been registered, heavily affecting the overall aerodynamic performance.

Nomenclature

A $[m^2]$	Rotor swept area
C_P $[-]$	Rotor power coefficient
D_{eq} $[m]$	Rotor equivalent diameter
P $[W]$	Power produced by the rotor
q $[m]$	Site altitude over the sea level
R $[m]$	Wind turbine radius
U_∞ $[m/s]$	Unhindered wind speed at the reference height (3 m)
U_z $[m/s]$	Local wind speed
z $[m]$	Height over the ground for wind shear calculations
z_0 $[m]$	Base height for wind shear calculations
z_{ref} $[m]$	Reference height for wind shear calculations
λ $[-]$	Rotor tip speed ratio
ρ $[kg/m^3]$	Air density at desired altitude
ρ_0 $[kg/m^3]$	Air density at sea level altitude
ω $[rad/s]$	Rotor angular velocity

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