Characterization of a wind turbine model for wake aerodynamics studies.

Francesco Cuzzola, Sandrine Aubrun, Bernd Leitl
Meteorological Institute - University of Hamburg, Bundesstrasse 55, 20146 Hamburg
E-mail: francesco.cuzzola@zmaw.de

Abstract. A model wind turbine has been designed at the University of Hamburg within the scope of the FP7 funded project WAUDIT. The purpose of the experiment described in this paper is to characterize the performances of two rotors by means of measuring the thrust coefficient $C_t$. $C_t$ is a similarity parameter for the wake and is thought to be the most effective one. Its value has been directly measured using a force balance and indirectly calculated from the velocity profiles measured three diameters downstream of the rotor with hot wire anemometry. Results show that, in order to reproduce the wake behaviour, the matching of the $C_t$, which is a quantitative achievement, has to be integrated with measurements such as velocity profiles in the wake. In fact the velocity deficit illustrates the mechanism of transforming the axial momentum into torque assuring qualitatively the proper reproduction of the wake. This latter information assures that the achievement of a certain thrust force acting on the rotor is due to its performances in transforming the axial momentum into torque and not an effect of other phenomena such as a stall at the blades.

1. Introduction
A dimensional analysis of the wake of a wind turbine leads to the definition of four dimensionless similarity parameters that have to be matched when an experimental simulation of the wake of a wind turbine is intended to be carried out in conditions of similitude. These four parameters are the Reynolds number $Re$, the tip speed ratio $\lambda$, the power coefficient $C_p$ and the thrust coefficient $C_t$. The latter is thought to be the most effective one [1].

At the geometric scale at which the next experiment will be carried out it is not possible to match $Re$ and achieve conditions of full similarity. Thus, conditions of partial similarity have to be investigated in order to assess how to operate the wind turbine model appropriately.

The systematic variation of parameters such as $\lambda$, the tunnel wind speed $U_\infty$ and the pitch angle $\theta$ allows the researchers to describe the dependencies of the $C_t$ with respect to the operating conditions. Once $U_\infty$ and $\theta$ were set then $\lambda$ was adjusted to the desired value and data have been collected.

In this paper we present the results for the three configurations described in Tab.1:

2. Experimental set-up
The experiment was carried out in the “Malavard” wind tunnel at the PRISME Laboratory of the University of Orléans. In this study, the main test section (2m high, 2m wide and 5m long) of the wind tunnel is used to perform measurements in Homogeneous Isotropic turbulent flow by placing a turbulence grid at the entrance of the test section. The turbulence grid is made
Table 1. Wind turbine configurations investigated

| $U_\infty$ (m s$^{-1}$) | $\lambda$ | Wind turbine status |
|-------------------------|--------|------------------|
| 10                      | [0.2-2]| active           |
| 2.5                     | 7      | active           |
| 10                      | 2.5    | passive          |

of metallic square section bars of diameter 25mm and mesh size 100mm. The upstream mean velocity is $U_0 = 10$ m s$^{-1}$ and the turbulence intensity is $Iu_0 = 3\%$ (ratio between the standard deviation of streamwise velocity and its time average) at the rotor location.

Aerodynamic loads are measured with a 6-axis balance located below the test section. The mast of the model, 34mm of diameter is used to link the balance to the model. The precision of the balance is estimated to be 0.16N for the drag component and 0.48N for the lift component. The sampling frequency is fixed to 500Hz, and 25000 samples are acquired for each configuration. The measurement of the three components of velocity was carried out using a Dantec triple hot-fiber probe, connected to the Dantec StreamLine system. The probe was fixed on an automated traverse system.

The architecture of the model also allows rotors and/or blades to be exchanged. Therefore two different blades were designed and manufactured, which are object of this investigation. The first blade, from now on called **Optimal Blade** was designed and optimized for highest power coefficient $C_p$. The second blade, from now on called **Linear Chord blade**, was designed in order to have a comparison element in assessing the importance of the chord distribution for models of such small scale.

The blades share the same Jedelsky **EJ85** airfoil, the length of 210mm, the wet surface of 0.303m$^2$ and the twist angle distribution which is a linear approximation of the optimum distribution. The only geometric parameter which changes is indeed the chord distribution.

The geometry of the blade is defined by means of a self implemented BEM code which does not take into account the tip-root losses [2]. This design procedure was previously used for designing a first blade which was tested in an experiment carried out in the open section wind tunnel at the University of Hamburg [3]. The choice of using the Jedelsky **EJ85** airfoil was taken because of its performances at low Reynolds number and its geometry which can be easily manufactured.

Fig.1 and Fig.2 the model wind turbine with the two rotors and the experimental set-up.

The model wind turbine is equipped with a Faulhaber DC motor 3268 G024 BX4 which allows the rotational velocity to be controlled using a power supply (active status). Disconnected from the power supply the motor can also be used as a generator if the turbine is driven by the wind only (passive status).
3. Force balance measurements

3.1. Results at 10 m s\(^{-1}\) - active status

Fig.3 and Fig.4 show the variation of the thrust coefficient for LC and OB.

The OB keeps rotating up to \(\theta = 70^\circ\) while the LC rotor is unable to perform at pitch angles \(\theta > 60^\circ\). This is due to the outer part of the optimum blade which does not block the flow as much as the linear chord blade.

The LC configuration shows a \(C_t\) which is remarkably higher than that of the OB one (30\% to 50\%) for a given value of \(\lambda\). Also, depending on the value of \(\theta\), the trend of the variation can be very different.

From these measurements it is clear that the chord distribution has a very important influence on the \(C_t\) and on its dependency from the tip speed ratio. The graphs show furthermore that the maximum value of the thrust coefficient is found at higher tip speed ratios when the pitch angle increases. At higher \(\theta\), the trends suggest that the maximal value of \(C_t\) might be found in a range of \(\lambda\) higher than has been achieved with the present DC motor-power supply system.

3.2. Results at 10 m s\(^{-1}\) - passive status

The disconnection of the power supply means that the rotational speed of the model depends on the wind speed and on the electrical load applied to the DC motor/generator. In fact, while in case of a short circuit the internal torque of the motor blocks the shaft and the turbine stops, the
application of a resistance to the output lowers the internal torque until, if an infinite resistance is applied, it tends to zero. In this case an infinite resistance case was simulated by keeping unplugged the output connections.

Fig.5 shows the $C_t$ vs $\theta$ curves in this latter configuration. Both curves exhibit a change at $\theta = 40^\circ$ where the thrust coefficient starts increasing with a steeper trend.

![Figure 5. $C_t - \theta$ curves, $U_\infty = 10\text{ m s}^{-1}$, passive status](image)

4. Velocity measurements

Horizontal velocity profiles have been measured at a distance of 708mm downstream of the rotor plane, which corresponds to three rotor diameters as can be seen in Fig.6.

![Figure 6. $V$ and $W$ Non dimensional velocity components three diameters downstream of the LC rotor. $U_\infty = 10\text{ m s}^{-1}$, passive status](image)

4.1. Results at $10\text{ m s}^{-1}$ - passive status

The graphs of Fig.7 and Fig.8 show the velocity deficit along the blades for the two rotors. The abscissa is $r = x/R$ where $R$ is the radius of the rotor and $x$ the radial distance. The velocity deficit increases with increasing pitch angle.

The wind speed recovers smoothly in the OB configuration showing a trend which is consistent with previous experiment such as [4], [5] and field experiment [6]. The LC configuration, which at $\theta = 50^\circ$ delivers a remarkably high $C_t$, shows a different wake behaviour, with the maximum of the velocity deficit occurring in the outer part of the blade.

Fig.9 and Fig.10 present the root mean square curves of the $U$ component of the velocity. From these graphs it is possible to interpret how the velocity deficit is created. The OB configuration has a fairly low turbulence intensity, although it shows a spike at about the 60% of the blade span. This location corresponds to the elbow of the blade where, from previous experiments [3], it is known that the vortex is shed.

The LC configuration instead shows an increase of the turbulence intensity in the outer part ($r = [0.6 - 1]$) of the blade. At $\theta = 50$ this increase is much higher than in the case of OB.
4.2. Results at 2.5 m s\(^{-1}\) - active status

In order to investigate the wake with \(\lambda = 7\), a value of the tip speed ratio in use also for commercial wind turbines, the wind speed was set to \(U_\infty = 2.5\) m s\(^{-1}\) and the rotational speed to \(\Omega = 708\) rpm. The result, see Fig. 11, shows that the turbine does not extract energy from the flow field but it is accelerating the flow, the axial force acts in the opposite direction of the stream and the model is not behaving as a turbine but as a propeller. Thus, for this model wind turbine, the matching of the similarity parameter \(\lambda\) is inappropriate when conditions of similitude in the wake are intended to be achieved.

**Figure 11.** Velocity deficit for LC at \(\theta = 30^\circ\) and \(\lambda = 7\). \(U_\infty = 2.5\) m s\(^{-1}\), active status
4.3. Calculation of the thrust coefficient

At the distance of three rotor diameters downstream of the wind turbine model, the \(V\) and \(W\) components of the velocity are less than 5% of \(U\) (see Fig.6) and can be neglected in the calculation of the thrust coefficient that, according to the blade element momentum theory [7], can be calculated using the relation:

\[
T = 2\pi \int_{0}^{\infty} \rho U_{\text{mean}}(r)(U_{\infty} - U_{\text{mean}}(r))r \, dr
\]  

(1)

Tab.2 shows a comparison between the values of the thrust coefficient evaluated respectively from the force measurements and from the velocity ones.

| rotor | LC | OB |
|-------|----|----|
| measurement type | Force | Velocity | Force | Velocity |
| Tip speed ratio | 1.60 | 1.53 | 1.81 | 1.98 |
| \(\theta = 30^\circ\) | 0.19 | 0.047 | 0.07 | 0.054 |
| \(\theta = 50^\circ\) | 0.75 | 0.62 | 0.25 | 0.22 |

Summarizing, when the OB rotor is mounted the wind turbine model has a noticeably smaller thrust coefficient but the velocity measurements show a behaviour consistent with previous literature and with expectations. The opposite happens for the LC rotor. This suggests that the OB rotor is a better choice when the wake of a wind turbine is intended to be reproduced in a wind tunnel.

5. Conclusions

A study of the aerodynamics and of the performances of a model wind turbine model has been carried out. In particular we tested two blade designs which differ with respect to the chord distribution only. The similarity parameter \(C_t\) has been calculated both directly using force measurements and indirectly using velocity profiles. This latter evaluation is carried out using the blade element momentum theory and overestimates the thrust force, but the trends are consistent with the direct calculation. Also, the velocity measurements allow the researchers to have a deeper insight in the understanding of how and where the thrust force is created.

As expected, the chord distribution has a big influence in the performances and in the wake of the model. In particular the LC blade delivers a higher thrust coefficient than the OB one whereas this latter configuration only shows velocity profiles consistent with previous literature. Thus the main result of this investigation is that, for a rotor model wind turbine, the matching of the thrust coefficient needs to be integrated with velocity measurements that can assure the transformation of the axial momentum of the flow field into torque, thus harvesting energy. Also, operating actively the turbine in order to match a certain \(\lambda\) will obviously result in a change in the overall behaviour of the turbine which will add energy to the flow.

Further developments of this experiment focus on an experimental campaign which aims to map the wake of the model in the atmospheric boundary layer wind tunnel "WOTAN" at the University of Hamburg, in addition measurements of the power coefficient \(C_p\) applying different resistors to the electric output of the model wind turbine are going to be taken.
References
[1] Neff D, Meroney R, McCarthy E and Davis E 1990 *Journal of Wind Engineering and Industrial Aerodynamics* **36** 1405–1414
[2] Cuzzola F, Doerenkaemper M, Leitl B and Schatzmann M 2011 *Physmod2011* International Workshop on Physical Modeling of Flow and Dispersion Phenomena
[3] Doerenkaemper M, Cuzzola F, Leitl B and Schatzmann M 2011 *Physmod2011* International Workshop on Physical Modeling of Flow and Dispersion Phenomena
[4] Chamorro L P and Porté-Agel F 2009 *Boundary Layer Meteorology* 129–149
[5] Sanderse B 2009 *ECN-e–09-016*
[6] Mann J 2010 *Wind Energy* 51–61
[7] Aubrun S, Devinant P and España G 2007 *European Wind Energy Conference* 1–8