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Wind tunnel testing of a horizontal axis wind turbine rotor and comparison with simulations from two Blade Element Momentum codes

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ABSTRACT

The results of wind tunnel tests performed on a full scale horizontal axis wind turbine with a rotor diameter of 1.2 m are presented, analyzed and compared with those predicted by WT_Perf and Qblade Blade Element Momentum (BEM) codes. The studied rotor, carved in wood, belongs to a family of wind turbines suitable for production by unskilled persons with hand tools, with more than one thousand turbines already produced. The experiments were conducted in a 2×2 m open test chamber closed circuit wind tunnel at wind speeds of 3.0; 3.7; 4.4; 5.5; 7.2; 7.7 m/s and shaft power with varying tip speed ratios (λ) was measured. The maximum experimentally obtained power coefficient (C_p) was found to vary significantly with the wind speed, between $C_p=0.32$ for 3.0 m/s and $C_p=0.40$ for 7.7 m/s. The tip speed ratio corresponding to peak power coefficient was found to vary inversely with the wind speed, from $\lambda=6.5$ at 3.0 m/s to $\lambda=4.8$ at 7.7 m/s. Comparison of the obtained wind tunnel data with the results provided by the two BEM codes was found to be good.

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1. Introduction

Small wind turbines are increasingly contributing to the energy needs of both isolated and grid connected consumers, Bishop and Amaratunga (2008), Simic et al. (2013). In the present work the rotor of a particular type of wind turbine is being studied, one designed to be constructed locally by the end users, Watson et al. (1999), Leary et al. (2012a).

The studied rotor, with a 1200 mm diameter, belongs to the family of open source wind turbine designs by Piggott (2010). The rotor is carved in wood and designed for production by unskilled persons with hand tools. This line of turbines, ranging in diameter from 1200 to 4200 mm, has become established worldwide, with over 1000 turbines locally constructed by the end users. Also notably, Hugh Piggott's design has been adopted by a large number of non-profit aid organizations, whose aim is to help local populations gain autonomy in the capacity to obtain basic electric energy supply. Examples of such organizations are Wind Empowerment, Engineers Without Borders UK, Wind Aid Peru. The main design goals of these wind turbines are economical viability, ruggedness, ease of construction and good performance at low to medium wind speeds (3 to 10 m/s) with the capacity to survive extreme weather conditions. The general layout follows the norm in this class of turbines, Clausen and Wood (1999), Gipe (1999), and consists of a three bladed fixed pitch rotor directly connected to an axial flux permanent magnet coreless generator, Bumby and Martin (2005), thus dispensing the need for a gearbox. The orientation to the wind is provided by a tail vane. To protect the turbine against extreme winds, again as common practice in this class of turbines, a furling mechanism is built in the rotor-tail assembly, so that in very strong winds the rotor's plane of rotation becomes skewed relative to the wind direction thus reducing the swept area of the rotor exposed to the wind. The wind turbine is supported by a guyed tower that can be lowered for inspection and repair. An example of a typical Piggott wind turbine is presented in Fig. 1.

Wood is employed in the rotor and tail vane areas due to its resistance to cyclic loads, availability, low price and workability, Mishnaevsky et al. (2011), while the other parts of the turbine are mostly made of welded steel tubes and plates. New or second hand automobile wheel hubs are employed to support the rotor/alternator assembly and car brake disks are typically used as the plates where the generator's magnets are placed. Currently the main use given to these turbines is in battery charging stand alone systems, although several are already grid connected. The turbine's generator can be wired for 12, 24 or 48 V operation.

The present study has several goals. The first is to obtain wind tunnel data on the performance of the 1200 mm diameter rotor which was never previously investigated. A similar rotor, with 1800 mm diameter, also designed by Piggott (2010), has already been studied with wind tunnel experiments and Blade Element Momentum (BEM) simulations, Hosman (2012), along with

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Fig. 1. A typical Piggott wind turbine.

extensive field testing, Leary et al. (2012b). Although not exactly the same rotors, due to their similarity, a comparison of the results obtained in the present study and those of Hosman (2012) is made in Section 4.1. The second objective of the present work is to access the employment of two BEM codes in simulating the performance of the tested rotor. Both codes employed are provided at no charge by respected institutions. The first code is WT_Perf by the National Renewable Energy Laboratory (NREL) of the United States of America ⟨http://wind.nrel.gov/designcodes/⟩. WT_Perf is part of a suite of Computer Aided Engineering tools for wind turbines from NREL. This software is an established reference among BEM tools, descending from a code originally developed by the Oregon State University in the 1980s decade. WT_Perf first appeared (under this name) in 1996, and is being continuously improved ever since by NREL. The second code is Qblade ⟨http://qblade.de.to/⟩, a General Public License software developed by David Marten at the Hermann Föttinger Institute of the Berlin Technical University Department of Experimental Fluid Mechanics. Qblade was first released in 2011 and has already been successfully validated against both WT_Perf and wind tunnel test data of full scale wind turbines, Marten et al. (2013). The computational simulations also serve the purpose of cross checking the experimental results and vice versa. The codes were employed from an end user perspective, a detailed explanation of BEM theory being out of the scope of the present work. The third goal of this work is to point out the most interesting lines of improvement of the existing rotor design, based on the insights obtained from the experimental and computational results.

2. Experimental set up

2.1. Wind tunnel

The experiments were performed in a closed circuit wind tunnel with an open test chamber of 5 m length and 2 × 2 m cross section. The facility belongs to the Associação para o

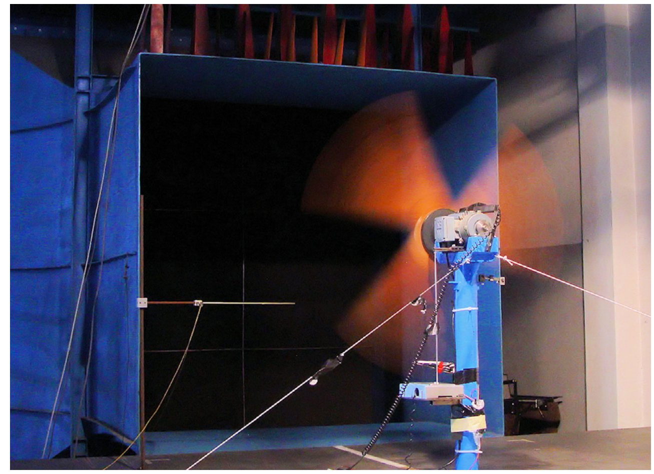

Fig. 2. Wind turbine rotor during a test run.

Desenvolvimento da Aerodinâmica Industrial, a non-profit organization closely associated with the Mechanical Engineering Department of the University of Coimbra. The wind tunnel blower is powered by an electronically controlled 184 kW electric motor directly coupled to the blower. A continuous variation of the motor's rotational speed is possible, translating in the capacity to continuously vary the wind speed from 0 to 26 m/s. The boundary layer thickness on the floor of the test section where the wind turbine was placed has a height of 150 mm and the turbulence levels are lower than 5%, Santos (2000).

Wind speed measurements without the wind turbine rotating were performed with a Pitot probe connected to an EMA 84 pressure transducer. The Pitot probe was placed 650 mm from the tunnel exit, 700 mm from the left side of tunnel wall and at a height of 600 mm. The experimental error in the wind speed measurements is estimated as 1%. An image of the rotor during a test run is presented in Fig. 2. Although open test chamber wind tunnels are less sensitive to blockage than their closed test section counterparts, blockage effects are still present. As such, corrections in the wind speed were calculated following the AGARD-AG-336 (1998) report on open test section wind tunnels and were estimated as a 2% increase relative to the measured free stream wind speed.

2.2. Turbine test stand

The wind turbine rotor test stand was designed so that the rotor's axis was located at the centre of the wind tunnel test section and placed at 1500 mm from its exit. Given the lack of rigidity of the wind tunnel's test section floor the stand was braced with two steel cables. The assembly can be seen in Figs. 2 and 3.

In order to apply a load to the wind turbine rotor, a dynamometer was devised around a continuous current SEW EURODRIVE GN80N electric motor working as a brake, with the wind turbine rotor directly coupled to the electric motor's shaft. The electric motor was integrated in a circuit with a resistive load that could be varied by means of a rheostat so that its output current, and thus the resisting torque, could be continuously adjusted, effectively working as a variable load brake. The electric motor's case was supported by two roller bearings, with an Ultraship 75 digital scale restraining it from rotating with the rotor's torque as can be seen in Fig. 3. The transmission linkage between the brake and the scale consisted of a metal torque arm bolted to the lower part of the electric motor's case and a vertical metal stick link contacting the plate of the digital scale. The calibration of the torque measuring device was performed by locking the turbine rotor to

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