Performance Testing of a Small Vertical-Axis Wind Turbine

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1. Introduction

Development of wind energy use in urban environments is of growing interest to industry and local governments as an alternative to utility-based and non-renewable forms of electric production [1]. Although most performance testing for small-scale wind turbines is conducted in outdoors wind testing sites, wind tunnel testing can provide a good reference for maximum possible performance under ideal flow conditions [2]. As part of McMaster University research on the use of small vertical-axis wind turbines (VAWT) in urban settings, full-scale wind tunnel testing of a prototype 3.5 kW VAWT supplied by the industrial partner in the project, Cleanfield Energy Corp., was conducted on the NRC 9 m x 9 m Low Speed Wind Tunnel in Ottawa. The specific objectives of wind tunnel testing were: experimental determination of the nominal power curves and determination of the structural integrity, safety, and operation characteristics of the system. The power curves show the relation between the rotary speed of the wind turbine and the produced power, for a range of wind speeds. Since this was the first run of this particular VAWT design, the controlled environment of the wind tunnel was the ideal place to test and expand the operational envelope of the turbine and its safety margins.

2. Test setup and instrumentation

Figure 1 shows a picture of the test setup in the wind tunnel.

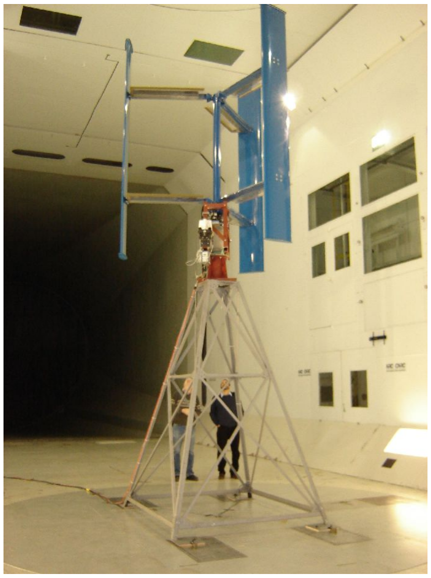

Figure 1: VAWT in NRC 9m wind tunnel

The turbine is a three-blade H-type Darrieus, with a diameter of 2.5 m and a height of 3 m. The blades have a NACA0015 profile with a chord of 0.4 m. The test was designed such that the operational envelope of the turbine would be slowly expanded. The tests were sequenced to start at the lowest wind speed and RPM, and continued until the most challenging conditions were reached at the end of the testing program. The generator and control system based on the electrical power produced and load applied were still under development during these tests. Consequently, to test the turbine, control and instrumentation systems had to be added to the VAWT test specimen. The following instruments and components were added:

Turbine speed measurement: A proximity sensor was used to measure the passing frequency of 6 equally spaced bolts, providing a resolution of 6 lines per revolution.

Mechanical load/torque measurement: In order to determine the aerodynamic performance of the turbine independently from the generator performance, a servo-controlled mechanical variable load was devised. A disc brake calliper was installed on a floating mount supported by a load cell, and driven by an electro-hydraulic servo-actuator. The load cell measures the torque produced by the turbine and transmitted through the brake.

Closed-loop speed control system: Because of the feedback interaction between the rotor dynamics and the aerodynamics of the system, the system is not self-regulating when operating on the front side of the torque vs. turbine speed curve (before reaching maximum torque). This means that a constant or slow-varying load will cause the turbine to either stop rotating, or it will lead to the “runaway” condition, in which the turbine speeds up to the stable back side of the torque curve. An active closed-loop speed control system was devised, which made use of the turbine speed measurement and the servo-controlled variable load system to accurately regulate the rotary speed of the turbine, using a high gain proportional control law. The proportional gain is made larger than the largest positive slope of the torque curve in order to guarantee the stability of the control system. Due to time delays inherent to the system and hardware, as well as a dead band in the brake servo-actuator, the resulting control torque is in general pulsating.

3. Power curve measurements

Each data point collected during testing was averaged 120s, to account for the pulsating nature of the torque time trace. During tests, the control system was able to maintain the turbine speed within ±2.5 RPM of the set point. The calculated power was then based on the average rotary speed measurement and the average torque measurement in this interval.

Figure 2 shows the power curves for all the wind speeds tested. The wind speeds shown in the figure legend are nominal values for each experimental run; the actual wind speeds vary slightly among data points in the same run, and more significantly between multiple runs at the same nominal speeds.

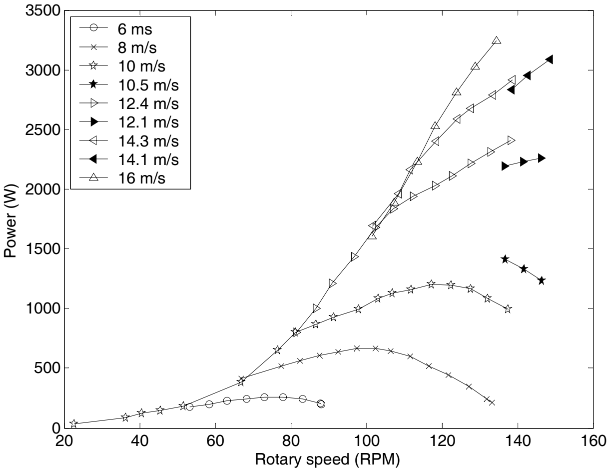

Figure 2: Power curves for nominal wind speeds (dimensional form).

Wind turbine performance is often characterized in non-dimensional form as a power coefficient C_p, given by:

$$C_p = \frac{P}{\frac{1}{2}\rho u_{wind}^{3} A}$$

where P is the power produced by the turbine and A is the area swept by the turbine rotor. This coefficient is a function of the tip speed ratio $\lambda = u_{blade} / u_{wind}$,where for an H-type Darrieus turbine, this parameter is constant over the entire blade. Figure 3 shows the dimensionless power curves in terms of C_p vs λ for all tested wind speeds. The curves collapse very well. There is a slight discrepancy at u_{wind}= 6 m/s which is not unexpected, as in this condition the airflow over the blades is slow, resulting in low Reynolds numbers which influences the lift and drag behaviour of the airfoil. The collapse of the curves suggests that the dimensional power performance of the turbine should be reliably predicted from the C_p curve for all rotary speeds and for all wind speeds between 8 and 16 m/s. The maximum power coefficient occurs at a tip speed ratio of approximately 1.6, and reaches a value close to 0.3.

The range of tip speed ratios for power production was determined to be 0.8<λ<2.2 for all cases, which is lower than the range for most other small VAWT. This is a result of the relatively high solidity ratio of the turbine.

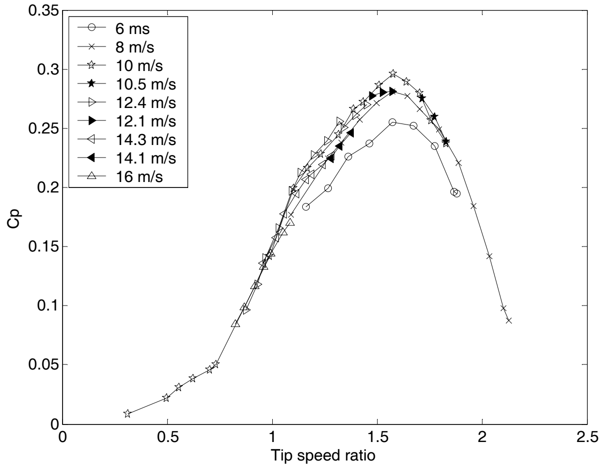

Figure 3: Dimensionless power curves

4. Conclusions

Wind tunnel testing was successfully conducted to determine the performance behaviour of the 3.5 kW VAWT under ideal wind conditions. The test results showed that the turbine is able to reach its rated power at 14 m/s. The minimum wind speed needed for power production was 6 m/s, and the turbine was tested operationally up to a wind speed of 16 m/s, and with the locked rotor up to 20 m/s. The maximum power coefficient obtained during testing was approximately 0.3, at a tip speed ratio of around 1.6. The turbine is currently undergoing rooftop testing, where in addition to performance measurements, force and vibration measurements will also be performed.

5. References

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[2] Blackwell, B., Sheldahl, R., Feltz, L., *Wind Turbine Performance for the Darrieus Wind Turbine with NACA0012 Blades*, Sandia National Laboratories report No. 76-0130, (1976).