Overview of wind energy research and development at NRC-IAR (Canada)

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Abstract – During the last few years, the Aerodynamics Laboratory of the National Research Council of Canada’s Institute for Aerospace Research has been deploying considerable effort towards the re-establishment of various wind energy research and development programs. These programs range from studies of the aerodynamics of wind turbine blades to the optimization of wind turbine sitting over terrain with complex topography. Numerical and experimental techniques have been developed and are often combined to perform the studies. This paper presents an overview of the Aerodynamics Laboratory capabilities as well as typical data obtained for a number of wind energy related studies.

1. INTRODUCTION

The National Research Council of Canada (NRC) has promoted research into wind energy since the 1960s. During the 1970s, NRC developed experimental vertical-axis (Darrieus-type) wind turbines (VAWTs) [1] and a numerical aerodynamic model [2] which permits the estimation of the performance of these machines as well as the analysis of the effects of various design parameters. In the 1980s, NRC and Hydro-Québec (a Canadian electric-utility company) jointly developed and built Éole [3] (Fig. 1), the world’s largest Darrieus-type VAWT. To develop Éole, a tremendous amount of experimental and numerical research was carried out at NRC. The analytical aerodynamic model, developed in the 1970s, was improved [4] and used in combination with a set of wind tunnel test programs to study the aerodynamics of the blades and the performance of Éole. The wind tunnel testing was performed in the NRC facilities.

Fig. 1: Éole – world’s largest VAWT, Québec, Canada

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With the development of the above wind turbines, NRC research activities contributed to the basic science of VAWTs, with particular reference to their aerodynamic performance. The NRC is well known for its expertise in this area, and the Aerodynamics Laboratory of its Institute for Aerospace Research (NRC-IAR) has recently been increasing its involvement in wind energy related research and development (R&D) programs. These programs fall into three distinct categories:

1. Prediction of wind turbine aerodynamic performance: using a range of numerical tools, including a suite of high-fidelity Computational Fluid Dynamics (CFD) capabilities that can be used for detailed calculations, the Aerodynamics Laboratory has the capability to study the aerodynamics of airfoils/blades designed for use on wind turbines and to predict wind turbine power output. The CFD tools of NRC-IAR provide high-fidelity models, such as Detached Eddy Simulation (DES) and Large Eddy Simulation (LES) models of turbulence that allow accurate investigations of the complex unsteady flows over wind turbine rotor blades including phenomena, such as dynamic stall. NRC-IAR also has the capability to predict annual energy output based on the wind climate at a desired site and the power curve of the proposed turbine. The NRC has been using these numerical tools to help several small Canadian wind turbine manufacturers optimize their turbine designs.

2. Wind tunnel testing of wind turbines: using the NRC-IAR world-class 9 m x 9m Wind Tunnel [5], the Aerodynamics Laboratory has recently tested newer and quieter designs of VAWTs for commercial clients. It is also actively pursuing research opportunities to study experimentally wind energy-related issues, from blade sections to wind farms, using NRC-IAR facilities.

3. Accurate simulation of wind environment for use in predictions of wind turbine and wind farm output: the NRC-IAR Aerodynamics Laboratory is currently studying the wind environment over complex terrain, where a novel model-manufacturing technique is used to allow the correct aerodynamic behaviour to be simulated at a relatively small model scale in the wind tunnel. This concept has been shown to be effective on a demonstration model in the 1.0 m x 0.8 m configuration of the 0.9 m x 0.9 m NRC-IAR Pilot Wind Tunnel [5]. A sample wind farm site with complex terrain is being tested in the 3 m x 6 m Propulsion and Icing Wind Tunnel [5] in order to demonstrate and validate the process for larger models.

An overview of the NRC-IAR Aerodynamics Laboratory capabilities, including samples of results obtained for a number of research investigations in the three categories, are presented in the following sections.

2. TURBINE BLADE AERODYNAMICS - DYNAMIC STALL

The experimental VAWT developed by NRC was of the constant speed type [6]. The various operating ranges of the constant speed turbines are indicated by hatched areas on the typical characteristic curve in Figure 2. At lower values of the speed ratios ($1 < \frac{V_t}{V} < 4$, $V$ and $V_t$ are wind and rotor tip speeds, respectively), the turbine is operating in an environment where the angles of attack of the blade sections are at or above static stall, and where dynamic effects, more particularly dynamic stall, are considered to have significant effect on turbine maximum power output.

To understand better the complex phenomenon of dynamic stall and its effects on the rotors of wind turbines, an experimental test program [6] was carried out in the 2 m x 3 m Low Speed Wind Tunnel of the NRC-IAR [5]. The test program consisted of the experimental investigation of the instantaneous pressures and dynamic stall of a NACA
0018 airfoil, due to unsteady oscillations in pitch. The wing section was a two-dimensional segment of the actual blade profile as used in the experimental VAWT, and the blade model spanned the test section from floor to ceiling as shown in Figure 3. Tests were performed at a wind speed representative of the equatorial tip speed of the turbine (45.7 m/s) and a constant pitching frequency of 0.55 Hz.

The experimental simulations were performed for turbine speed ratios representative of the various performance regions of VAWTs (Fig. 2). The instantaneous surface pressures measured around the airfoil were integrated to obtain normal and chord force coefficients under dynamic flow conditions. Figure 4 shows the instantaneous lift and drag coefficients derived from the integration of the instantaneous pressure distributions on the airfoil. Dynamic lift and drag measurements obtained for turbine speed ratios of 2 and 5 are compared in Figures 4a and 4b, respectively. These comparisons confirm the importance of the dynamic stall at low speed ratios, where maximum angles of attack could reach as high as 30°, well beyond the static stall angle. For such operating conditions, dynamic stall has to be included in the numerical models for rotors performance prediction.
3. TURBINE ROTOR AERODYNAMICS

3.1 Performance prediction

NRC-IAR is dedicated to the development of the wind energy industry through both numerical and experimental modelling of novel wind turbine designs. On the numerical side, in 1974, R.J. Templin [2] of the Aerodynamics Laboratory of NRC-IAR developed an aerodynamic theory for VAWTs, later named the single stream tube (SST) model. This SST model was an application of the classical Betz-Glauert momentum theory of windmills plus blade element theory to address the complex geometries of Darrieus-type VAWTs. Its predictions were in reasonable agreement with measurements of the overall performance, but it had some deficiencies. The SST model was superseded by the development of the multiple stream tube (MST) theory at Sandia National Laboratory (SNL), in the USA, in 1975 [7].

The double multiple stream tube (DMST) model was further developed by a few other research groups [8-11] although there are limitations inherent to the simple momentum theory. In the DMST model, the upwind and downwind rotor faces are treated separately, with the upwind face element having a direct influence on the downwind face element. The velocity in the downstream wake of the upwind face element is used as the free stream velocity for the downwind face element when calculating the induced velocity at the downwind face element using momentum theory. This introduces a better representation of the physics of VAWT aerodynamics.

The aerodynamic performance of the 224 kW experimental VAWT of NRC (retired), located on the Magdalen Islands in Québec, Canada, was analyzed using a recently developed DMST computer program [12]. The turbine consisted of a two-bladed rotor with equatorial diameter of 24.4 m and an axial height of 36.6 m. The blades were of extruded aluminium with a 0.61 m chord and NACA 0018 cross section. The operating speed of the rotor was 36.6 RPM.

![Fig. 4: Turbine speed ratio effect on blade’s dynamic stall](image)

Fig. 4: Turbine speed ratio effect on blade’s dynamic stall
In Figure 5, the power coefficient, which is a non-dimensional parameter expressing the turbine efficiency in converting aero kinetic power in the wind to mechanical power, is shown with a comparison between the results with and without the effects of dynamic stall. A noticeable difference occurs only at lower turbine speed ratios where the blades operate most of the time in dynamic stall conditions. A comparison of DMST predicted results with the field test data is presented in Figure 6. Overall, a good correlation is obtained, with the dynamic stall results predicting a better maximum shaft power output. The comparison between the results with and without dynamic stall effects also shows the large effect of dynamic stall on the maximum power output of the turbine.

Fig. 5: Power coefficient of the 224kW Magdalen Islands VAWT

Fig. 6: Shaft power output of the 224kW Magdalen Islands VAWT

Using these simple modelling methods, small consultation projects are often completed for small wind turbine companies. The relative performance of new designs are evaluated and compared with historical results such as the Darrieus turbine studied at NRC [2]. Although physically simple, these models can account for novel blade shapes, blade motion profiles, representative atmospheric boundary layers, and other design changes that manufacturers are currently investigating. These studies are often used in the early stages of product development, to demonstrate a concept and to secure funding for further development and more detailed studies. In this way, NRC-IAR acts as an independent consultant, either confirming or disproving the technical merit of designs in the early stages.
3.2 Performance measurement

Once a wind turbine design has moved beyond the conceptual stage, experimental testing is used to measure and/or confirm performance. The NRC-IAR’s 9 m × 9 m Low Speed Wind Tunnel facility, shown in Figure 7, is the ideal place to test turbines with a swept area of up to 20.3 m². For horizontal axis wind turbines, this limit is satisfied by a rotor diameter of 5 m or less; the limit results from the maximum swept area blockage that allows for reliable blockage-corrected estimates of wind speed in the wind tunnel test section. Full-scale wind turbine testing automatically preserves Reynolds number similarity, however, representative scale-model testing is possible depending on the size and airfoil characteristics of the full-scale turbine.

![Fig. 7: NRC-IAR’s 9 m Wind Tunnel](image)

The 9 m × 9 m Wind Tunnel can achieve wind speeds of about 50 m/s, with turbulence intensity on the order of 0.75 %. Turbulence-generators can also be used to induce uniform elevated turbulence levels or representative atmospheric boundary layers, Figure 8. This capability can improve the simulation of the turbine’s performance if the client wishes.

Wind turbine performance is typically evaluated using two metrics. First, the available aerodynamic power can be measured by mounting the turbine on the external balance of the wind tunnel. For horizontal axis turbines, the aerodynamic moment is given by the roll balance component; for vertical axis turbines, it is the yaw component that is studied. These values can be compared with the electrical power output of the wind turbine generator which is typically absorbed by the municipal electricity supply grid.

Over the past few years, NRC-IAR has worked with commercial wind turbine clients at full scale, as shown in Figure 9. These experimental campaigns often involve research and development work [13], as shown in Figure 10, where NRC wind tunnel data (symbols) was used for model validation (lines).

Another facility suitable for wind energy experimental tests is the 3 m × 6 m Propulsion and Icing Wind Tunnel which can be equipped with spray bars in winter, providing an ideal test location for studies of wind turbine icing.
**Fig. 8:** Turbulence generators installed at the test section inlet of the 9 m × 9 m Wind Tunnel

**Fig. 9:** VAWT testing in the NRC-IAR’s 9 m test section

**Fig. 10:** Wind tunnel performance data used in research [13]

**Fig. 11:** NRC-IAR’s 3 m x 6 m Propulsion and Icing Wind Tunnel
4. WIND FARMS – WIND CLIMATE OVER COMPLEX TOPOGRAPHY

With the strong growth of Canada’s wind-energy sector, a need has been recognized to reduce wind-farm planning and development times. A methodology is being developed in the Aerodynamics Laboratory of the NRC-IAR, based on physical modelling in a wind tunnel, to determine with precision the wind characteristics over a relatively large land area with relatively complex topography. The main application is to provide a tool to wind-farm developers to help maximize the energy production from a specific proposed wind farm. This includes determining variations in mean wind speed and turbulence intensity with height, the scales of turbulence, and fluctuations of wind direction and elevation angle to optimize better turbine location and select an appropriate classification.

In the first of two phases of this research, the development of a competency in physical modelling of the flow over complex topography has been addressed. This includes the selection of appropriate model scale, surface roughness and flow speed through a series of wind tunnel investigations performed in the Pilot Wind Tunnel of the NRC-IAR which has a closed-loop circuit with an open-jet test section. Measurements were performed over a scaled model representing a section of a wind farm that is currently being installed in the Gaspésie region of Québec, Canada. An array of spires was placed at the inlet of the test section to simulate an atmospheric boundary layer.

The first phase was initiated with a thorough literature review on modelling of the atmospheric boundary layer (ABL) over complex terrain, including air stability considerations. It was quickly recognized that even the most refined commercial software packages have difficulties in simulating the ABL in complex topographic regions due to the presence of flow-separation. Therefore a physical-modelling approach was selected. Issues relating to surface-roughness modelling, Reynolds-number sensitivity and step-size sensitivity of topographic models were specifically targeted in the literature review.

A wide search of anemometry technology was undertaken. Turbulent Flow Instrumentation (TFI) fast-response four-hole pressure probes (Cobra Probes) were selected for their ease of operation. The probes provide the wind velocity fluctuations, the local static pressure and the vertical and horizontal wind directions.

Smooth (top)  
Terraced (bottom)  
Fig. 12: Wind tunnel models of complex topography
One of the pivotal goals of this project is to demonstrate that rapid fabrication of the topographic model (built-up from topographic layers and thus presenting a stepped or ‘terraced’ surface) can provide the same aerodynamic fidelity as that obtained with an exact replica of the full-scale terrain. This stepped-surface technique is less expensive to fabricate than an exact replica with its fine detail of the terrain. Samples of the smooth- and terraced-surface models are shown in Figure 12.

4.1. Experimental results and discussions

The benefits of placing wind farms in regions of complex topography are shown in Figure 13. Vertical profiles of wind-speed and turbulence intensity at two locations over the terrain are compared to measurements of the undisturbed ABL, with a schematic of a typical wind turbine to be installed on the site. It is evident that flow acceleration over the steep escarpments causes an increase in wind-speed and a decrease in turbulence intensity which are beneficial for the potential wind-energy resource and for turbine classification.

![Fig. 13: Benefits of complex topography for wind farms](image)

A major goal for this phase of the project was to select appropriate testing parameters for future large-scale model tests. Figure 14 shows vertical profiles of wind-speed and turbulence intensity at one turbine location, measured at four reference wind-speeds.

![Fig. 14: Reynolds-number sensitivity](image)
The three highest wind speeds show good agreement in the profile shapes, while the lowest-speed profile shows some differences, indicating Reynolds-number independence above a specific threshold. Near-wall spectral measurements (Fig. 15) also provide evidence of the eddy surface layer (ESL) that is a high-Reynolds-number characteristic observed in ABL flows. The ESL is identified by a spectral decay with a -1 slope, compared to the -5/3 slope characteristic of the inertial subrange.

Flow visualizations (not shown here) have provided identification of the surface streamline patterns over each of the three models. The major differences between models are the extent of the separated-flow regions, indicating an effect of roughness on the overall ABL characteristics. Only near-wall differences due to roughness are observed for the flow up steep escarpments. Near separated-flow regions and over relatively-flat sections of terrain, greater roughness effects are observed (Fig. 16).

Due to the coarsely-spaced large steps in these regions, the localized disturbances to the flow are much larger and extend a greater distance from the surface for the largest terrace sizes. These effects indicate that the smaller terraces will provide adequate increase in turbulence near the surface for proper modelling, while mitigating the large-disturbance effect of large terraces in regions with mild slopes.
4.2 Next steps

Results observed in the first phase of this research regarding the effects of scale, Reynolds number and surface roughness [14] have provided a basis for the next set of wind-tunnel tests.

The second phase of the project is currently underway, for which wind-tunnel tests are being made over a scaled model of the entire Gros-Morne wind farm in the 3m x 6m Propulsion and Icing Wind Tunnel of the NRC-IAR. Once validated, the technique will be offered to wind-farm developers to provide improved predictions of potential wind resources and to select turbine placement and classification.

The terrain model for this second phase has a plan-form area of approximately 60 m$^2$ and was manufactured at the NRC-IAR’s Aerospace Manufacturing Technology Centre in Montreal. A large-scale robot/gantry system was used to manufacture the model.

5. CONCLUDING REMARKS

With its world class facilities and its computational capabilities, the Aerodynamics Laboratory of NRC-IAR contributes to research and development programs to addressing the needs of the Canadian and international wind energy industry. The laboratory will build upon the tremendous expertise it has acquired over the years, in the area of vertical axis wind turbines, to contribute to the advancement of science in all aspects of wind energy, from the understanding of the fundamental aerodynamics of turbine blades, to the simulation of wind turbine rotors, to wind farm siting for maximizing power output.

REFERENCES


