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INTERNATIONAL COLLABORATIVE RESEARCH IN WIND TURBINE ROTOR AERODYNAMICS

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ABSTRACT

Five organizations from four countries are collaborating to conduct detailed wind turbine aerodynamic test programs. Full-scale atmospheric testing will be conducted on turbines configured to measure aerodynamic forces on rotating airfoils. The purpose of these test programs is to come to a better understanding of the steady and unsteady aerodynamic behavior of wind turbine rotors, and provide information needed to build accurate aerodynamic models for design codes. Stall, dynamic inflow, yaw conditions, and tower effects all contribute to unknown aerodynamic responses. These unknown responses make it extremely difficult to produce cost-effective wind turbine designs. Turbines behave unexpectedly, experiencing power surges and higher fatigue loads than predicted. In order to evolve state-of-the-art wind turbine designs, these aerodynamic effects must be quantified and understood. This paper describes a coordinated international research effort that is underway to accelerate this key research area, and help develop a more thorough understanding of wind turbine aerodynamics.

NOMENCLATURE

c	Blade chord length (m)
C	Aerodynamic coefficients (lift, drag, moment)
k	Reduced frequency = $\omega c/(2V_t)$
M	Mechanical load (N-m)
nc	Number of pressure tap locations around the chord
nm	Number of mechanical load measurement locations
ns	Number of instrumented span locations
nt	Number of time steps in a 5-minute data record
nw	Number of instrumented wind measurement locations
p_a	Ambient pressure (kPa)
$p_{i,j}$	Pressure at span location i, chord location j (Pa)
Re	Reynolds number = cV_t/υ
t	Time (sec)
T	Ambient temperature (°C)
V_w	Wind speed (m/s)
V_t	Local blade total velocity (m/s)
α	Angle of attack (degrees)
α^*	Effective pitch rate = $\delta\alpha/\delta t$ (rad/s)
α^+	Effective nondimensional pitch rate = $\alpha^* c/(2V_t)$
ϕ_y	Wind direction relative to nacelle position (deg)
ϕ_r	Blade azimuth angle (deg)
θ	Blade pitch angle (deg)
υ	Coefficient of kinematic viscosity (m^2/s)
Ω	Rotor speed (RPM)
ω	Blade rotation rate (rad/sec)

BACKGROUND

NREL has been conducting full-scale atmospheric unsteady aerodynamics research testing at the National Wind Technology Center (NWTC) near Golden, Colorado. This project, called the "Combined Experiment," is being conducted on a 3-bladed, 10 m diameter downwind horizontal axis wind turbine. The turbine is instrumented to fully characterize wind inflow, power production, tower structural modes, and aerodynamic and structural responses of the rotating blades. Research to date has provided insight into previously unknown wind turbine aerodynamic phenomena. Resulting data sets have been used to develop a better understanding of steady and unsteady aerodynamic wind turbine effects (stall, dynamic inflow, yaw, tower effects) and to improve aerodynamic models implemented in design codes.

Recently, several European Community members have begun their own similar detailed aerodynamic test programs. In addition to the NREL tests, projects are now underway at The Netherlands Energy Research Foundation (ECN), Delft University of Technology in The Netherlands (TUD), and RISØ National Laboratory in Denmark. A combined effort is underway between the Royal Imperial College of London (ICL) and Rutherford Appleton Laboratory (RAL) in the United Kingdom. An international group has been organized to coordinate these test programs under an International Energy Agency (IEA) agreement. This agreement has been officially sanctioned under the IEA as "Annex XIV Field Rotor Aerodynamics."

Aerodynamic test programs are typically very expensive and time consuming, yielding large volumes of data and requiring extensive data reduction. Each turbine configuration that is investigated experimentally may exhibit different aerodynamic response characteristics. Consequently, it would be very beneficial to cooperate in conducting these tests and analyzing the data. The Annex XIV research will build on past experience like the NREL programs to further understand wind turbine aerodynamics. This type of collaborative effort can also help establish links and confidence between the U.S. and European counterparts. This paper describes the objectives of the projects, facilities of the participating members, tasks to be carried out, and expected information to be obtained.

IEA ANNEX XIV PARTICIPANTS AND FACILITIES

ECN is the operating agent for the Annex XIV Field Rotor Aerodynamics cooperative research agreement. Their test bed is a 2-bladed, 25 m diameter upwind custom turbine with an adjacent test control building and machine shop. It is located at the ECN facility near Petten, The Netherlands. One of the 12.5 m blades has been instrumented at three spanwise locations with 48 pressure taps each, and Scanivalve pressure instrumentation. The blade is an Aerpac 25 WPX, has a NACA 4418-24 profile, tapers from 1.562 m at the hub to .412 m at the tip, and has 12 degrees of linear twist. ECN conducted extensive studies to minimize adverse frequency response effects of pressure tubes 1 m in length over a frequency range of 0 to 40 Hz. They also developed a spherical 5-hole probe used to make angle of attack measurements. They initially mounted the blade vertically on a test stand at their site to statically check the measurement system prior to installation on the machine (Schepers 1992).

The NREL test bed machine is a Grumman Windstream 33, rated at 20 kW. It is a 10 m diameter 3-bladed downwind stall-controlled turbine. The blades are untwisted constant-chord length (0.5 m) with NREL S809 airfoils. The machine is located at the NWTC near Golden, Colorado. One blade is instrumented at four spanwise locations (30%, 47%, 63%, and 80%) with 28 pressure taps each to directly measure chordwise aerodynamic forces. Taps are also installed at intermediate locations to measure spanwise pressure distributions. The pressure measurement system is based on Pressure Systems Incorporated (PSI) ESP-32 pressure transducers located in the instrumented blade, and a custom-built, computer-controlled pressure calibration system mounted on the rotor. The resulting bandwidth for rotating aerodynamic measurements is DC to 100 Hz. Other lower-bandwidth structural and inflow measurements are also provided (Butterfield, 1992).

TUD has a 10 m diameter, stall-controlled test bed machine, an adjacent test control building, and machine shop at their facility. It is located at the Open Air Research Facility of the Delft University of Technology in Delft, The Netherlands. Their turbine is instrumented to make on-blade aerodynamic pressure tap measurements at four spanwise locations, 30%, 50%, 70%, and 90% span. The machine and its pressure instrumentation configuration are very similar to the NREL setup. It is a 10 m diameter, 3-bladed, zero-twist, constant 0.5 m chord, rigid hub machine. The main differences are that it has an NLF(1)-0416 airfoil, and operates upwind. TUD has developed an impressive computer-controlled system that lets them quickly see resulting pressure distribution data and integrated pressure forces in the field (Bruining, 1993).

RISØ's test bed is a 19 m diameter, stall-controlled turbine rated at 95 kW. It is a standard "Tellus T-1995" 3-bladed upwind turbine manufactured by Danish Wind Technology. It is located at the Test Station for Wind Turbines near Roskilde, Denmark. The rotor has 8.2 m NACA 63_n-2nn LM fiberglass blades with a root chord of 1.09 m, tip chord of 0.45 m, and 15 degrees of twist. The measurement technique used by RISØ differs from those of the other participants in that the aerodynamic forces are measured directly on separated blade section segments mounted on force transducers, and are not determined from integrating measured blade surface tap pressures (Madsen, 1991).

The UK contribution is a collaborative effort between the ICL and RAL. ICL has developed a pressure measurement system and tested its operation on sections of the instrumented 8.5 m LM airfoil in the wind tunnel. The airfoil is identical to that used by RISØ. RAL will install the instrumented blade and measurement system on a full-scale 17 m diameter Wind Harvester wind turbine. The Wind Harvester is located at the RAL facility near Harwell, Oxfordshire. It is a 45 kW, 3-bladed upwind turbine with side fans that keep it yawed into the wind. The pressure measurement system uses Scanivalve 32-channel pressure transducers connected to surface pressure taps at six span locations from 20% to 80%. It should provide a frequency response in the range of DC to 100 Hz.

TASKS AND MEASUREMENT CAMPAIGNS

The collaborative Annex tests will lead to a data base that provides information about 2D-3D differences and unsteady characterization in stall, and serves as a design basis for stall controlled turbines. The information will be based on pressure tap measurements at different radial positions and direct measurement of aerodynamic forces. Other measurement methods will also be used to provide additional insight into the physics of stall (i.e., flow visualization). The participants will perform the following tasks:

(1) Define a specific joint measurement program that all participants will follow.

(2) Critique and evaluate instrumentation layouts, data reduction techniques, test plans, and measurement requirements of all participants' projects. Develop test matrices and define data exchange formats and media.

(3) Develop a common data base format under which data sets from all participants will be stored and accessed. Define data set characterization criteria to enable comparison of various turbines under like conditions and allow resulting measurement differences to be examined and explained.

There are three types of experiments that will be performed. The first type will provide data sets during conditions when the machine experiences a "constant" angle of attack: $\alpha=\alpha_{mean}$. Since these conditions are rare in an atmospheric field testing environment, participants may also try to obtain data sets during non-rotating or slow rotating conditions. All participants will try to obtain constant angle of attack data sets over the range of -5° to +40° in 5° increments, as shown in Table 1. Each data set will be 150 cycles in length, and a total of 10 data sets of this type are possible. These will yield insight into aerodynamic properties under more or less stationary conditions, allowing comparison with 2D wind tunnel data to validate and substantiate measurement systems. Typical mean Reynolds number values at 70% span for the participant's turbine configurations are also shown in Table 1.

The second type of experiment will provide data sets during periods of 1P cyclic variations in angle of attack as defined by: $\alpha=\alpha_{mean}+\Delta\alpha\cdot\cos(\Omega t)$. This will be accomplished by making measurements on the operating machine at various angles of yaw misalignment The desired range of yaw misalignment is from -40° to at 10° increments, as shown in Table 1. These data records will also be 150 cycles in length, and a total of 90 data sets of this type are possible. Typical expected reduced frequency values k for 1P variations at 70% span are also shown in Table 1. These data sets will provide information to enable yaw-induced dynamic stall effects to be quantified.

The third type of experiment will provide instantaneous angle of attack variation data. This will be made by those participants who can manually change pitch angle during operation. 5° to 10° abrupt pitch-ups and pitch-downs will be performed. An unknown number of short duration data sets will result from these experiments. Expected resulting nondimensional pitch rate values of α^{+} are shown in Table 1, assuming a blade pitch rate on the order of 10° per second. Tests will be conducted so the pitch change occurs completely within the unstalled lift region, between unstalled and stalled operation, and completely within stall. The data sets will provide unsteady aerodynamic response information related to a controlled abrupt angle of attack variation. This data will be useful for quantifying delayed and dynamic stall effects caused by inflow, tower shadow, or pitch-control operations.

The ranges of possible unsteady aerodynamic responses due to these types of cyclic and instantaneous angle of attack variations are extensive. Resultant lift and drag forces depend not only on α^{+} and k, but also on:

- The initial angle of attack prior to the dynamic variation
- The amplitude of variation, and whether or not the variation transitions through stall, and
- If transition is into stall or out of stall.

It would be impossible and impractical to define a test matrix with enough dimensions to completely explore unsteady response sensitivity over the full range of possible driving conditions. It is difficult to even define what ranges of α^{+} and k are relevant and affect the performance of a given turbine. The Annex tests will concentrate on a practical defined subset of tests to quantify basic responses of the specific configurations, and allow relative comparisons to be made. The participants may also perform analyses to define ranges of α^{+} and k observed in the resulting data sets. This requires extensive data analysis, and is an ideal area for further collaborative research.

TABLE 1. DATA MEASUREMENT TEST MATRIX

	α_{mean} (°)	ϕ_y (°)	Re	k	α^{+}
ECN	-5 to +40	-40 to +40	1.8×10^6	.04	.002
TUD	-5 to +40	-40 to +40	0.9×10^6	.07	-
NREL	-5 to +40	-40 to +40	0.7×10^6	.07	.002
RAL	-5 to +40	-40 to +40	1.0×10^6	.05	-
RISØ	-5 to +40	-40 to +40	1.0×10^6	.05	-

DATA FILE CONTENTS AND FORMAT

Three different types of files will be provided for each data set:

File 1: This will be a text log file that contains information about the data set, measurement techniques, defective or questionable channels, operator notes, and quantities measured. This file also designates the measurement locations, such as the pressure tap coordinates at each instrumented span location.

File 2: This will be a data file that contains statistical summaries and all time-series values for all channels in the data set except pressure coefficients. This includes azimuth angle, rotor speed, pitch angle, ambient pressure and temperature, wind speed, wind direction, mechanical loads, integrated pressure coefficients, and angle of attack. The first four lines of the file contain average, standard deviation, minimum, and maximum values for each channel. The following lines contain the time series. The format of the file is shown in Table 2.

Files 3+: These will be data files that contain statistical summaries and all time-series pressure coefficient values for the data set. There can be up to *ns* of these files. Each contains the pressure distribution from a single span location *i* where *i* varies from 1 to *ns*, the total number of instrumented span locations. The format of these files is shown in Table 3.

TABLE 2. FORMAT OF DATA FILE 2

	ϕ_r	Ω	θ	p_a	T	V_{w1}-V_{wnw}	ϕ_{v1}-ϕ_{vnw}	M_1-M_{nm}	C_1-C_{nc}	α_1-α_{nc}
average	-	-	-	-	-	-	-	-	-	-
standard deviation	-	-	-	-	-	-	-	-	-	-
minimum	-	-	-	-	-	-	-	-	-	-
maximum	-	-	-	-	-	-	-	-	-	-
t_1	-	-	-	-	-	-	-	-	-	-
.	-	-	-	-	-	-	-	-	-	-
.	-	-	-	-	-	-	-	-	-	-
.	-	-	-	-	-	-	-	-	-	-
t_{nt}	-	-	-	-	-	-	-	-	-	-

TABLE 3. FORMAT OF DATA FILES 3 TO 3+*ns*

	ϕ_r	$p_{i\,1}$-$p_{i\,nc}$
average	-	-
standard deviation	-	-
minimum	-	-
maximum	-	-
t_1	-	-
.	-	-
.	-	-
.	-	-
t_{nt}	-	-

CONCLUSION

An International Energy Agency agreement called "Annex XIV - Field Rotor Aerodynamics" has been established. Five organizations from four countries will collaborate to conduct full-scale atmospheric testing on wind turbines instrumented to measure aerodynamic forces on rotating airfoils. Tests will be conducted on various configurations of turbines from 10 m to 25 m in diameter. The participants will define a specific joint measurement program, and will critique and evaluate test plans, define test matrices, analyze data, and establish data exchange formats and media. A data base will be produced that provides information about 2D-3D differences and unsteady characterization in stall, and will serve as a design basis for stall-controlled turbines. Data sets will help identify delayed stall and dynamic stall effects caused by inflow, yaw misalignment, and tower wake. Resulting information will enable better understanding of wind turbine steady and unsteady aerodynamic behavior, and provide data needed to build accurate aerodynamic models for design codes.

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