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Introduction

Applied research activities at the National Wind Technology Center are divided into several technical disciplines (Table 1). Not surprisingly, these engineering and science disciplines highlight the technology similarities between aircraft and wind turbine design requirements. More often than not, wind turbines are assumed to be a subset of the much larger and more comprehensive list of well understood aerospace engineering accomplishments and it is difficult for the general public to understand the poor performance history of wind turbines in sustained operation. Often overlooked are the severe environmental conditions and operational demands placed on turbine designs which define unique requirements beyond typical aerospace applications. It is the role of the National Wind Technology Center to investigate and quantify the underlying physical phenomena which make the wind turbine design problem unique and to provide the technology advancements necessary to overcome current operational limitations.

Table 1. NWTC R&D Disciplines

• Aerodynamics	• Aeroacoustics
• Materials	• Control Systems
• Structures	• Power Systems
• Fatigue	• Avian
• Meteorology	• Manufacturing

The National Wind Technology Center has five different research teams concentrating on different technology needs for turbine design, development, and deployment (Table 2). Two of these teams, Applied Research and Turbine Development, deal specifically with the development of advanced wind turbine technology. Applied Research addresses the more basic fundamental science issues needed to overcome long-term technology barriers. Turbine Development focuses on the development and deployment of advance turbine designs using current state-of-the-art technology. The Testing Team is responsible for developing the facilities and testing methodologies necessary to ensure both component and integrated system reliability of advanced designs under extreme conditions. The Applications and International Teams examine the unique issues involved with assessing wind as a natural resource, integrating wind technology with other energy producing systems, and deploying integrated wind technology systems into remote rural locations throughout the world.

Table 2. Current NWTC Research Teams

- Applied Research
- Cooperative Testing
- Applications Research
- International Wind Team
- Turbine Development Team

The Applied Research Team is responsible for defining the unique requirements for turbine design which exceed typical aerospace applications and to develop the technologies necessary to provide sustained turbine operations over a 30 year service life. These requirements require a much different design philosophy from other aerospace applications. Whereas aerospace designs are concerned with energy expenditure per unit performance, turbine designs must focus on energy capture per unit cost ($/kWh). Turbine designs are further constrained by extreme environmental events and conditions. Most of the activities within applied research (Table 3) can be directly attributed to the limiting design criteria from cost, environment, and reliability considerations. The focus of this paper is to highlight some of the current technology limitations and provide a brief overview of select initiatives within applied research.

Table 3. Current Applied Research Project List

Basic Research	Technology Development	Component Development
• Aerodynamics	• Design Codes	• Advanced Blades
• Inflow Characterization	• Controls	• Aerodynamic Devices
• Materials	• Flexible Structures	
• Power Electronics	• Reliability	
• Structures & Fatigue	• Adaptive Structures	
• University Programs	• Variable Speed	
	• Integrated Systems Analysis	

Inflow Dynamics

The random or stochastic nature of the wind is the single most unique design constraint which differentiates wind turbines from aircraft designs. The majority of today's wind turbines operate within the first 100 meters of the earth's surface. This region, which occupies the lowest portion of the planetary boundary layer (PBL), is extremely turbulent and driven by variations which occur with diurnal changes in atmospheric boundary conditions. The vertical variation of temperature and wind speed with height define the PBL behavior characteristics. During normal daytime turbine operations, the temperature normally decreases with height which contributes to a convectively unstable atmosphere. Under these conditions the largest and most energetic turbulent motions are associated with convective eddies or cells which are many times larger than even the largest wind turbines. These large eddies actively mix out the smaller, more compact turbulent structures which have a more direct impact on rotating wind turbine blades.

In contrast, a stable boundary layer is characterized by warmer air overlaying cooler air in contact with the earth's surface. Under such conditions, coherent or organized turbulent structures can develop which can exist for long periods of time due to the lack of the large scale, vertical mixing characteristic of unstable flows. These structures can be quite intense and, depending on their size and orientation, are capable of inducing large structural loads when flowing into the spinning rotor of a wind turbine. Interestingly, a disproportionate number of hardware failures have occurred during evening operations, attesting to the potential severity of this inflow condition on turbine performance.

Several years of dedicated research efforts at the National Renewable Energy Laboratory (NREL) and Sandia National laboratories (SNL) have resulted in the development of computer simulations to quantify these inflow environments. These codes provide excellent agreement with field test data at specific sites, matching both turbulent spectra and intensity. As will be shown later, recent developments at NREL permit simulated wind inflow environments to be used in conjunction with dynamic structural models in order to determine the fatigue cycle life of advanced designs. The ability to evaluate designs analytically under extreme inflow conditions provides invaluable insights into the performance of individual components and integrated systems at very low cost.

Defining the three-dimensional structure of these coherent vortical flows and the causal relationships between boundary layer structure, surface topology, and the atmospheric conditions which produce them remains a high basic science research priority. Ultimately, turbulence simulation codes that produce high resolution three-dimensional turbulent inflow information without the need for long-term empirical records will be achieved. Just as important is the need to understand the fine detail of the large scale coherent vortical flows that produce the low event/high cycle load conditions. Given the differences in turbine design architectures, these coherent flows can affect turbines in very different ways. It is necessary to simulate both the details of the coherent structure as well as the resulting turbine interaction in order to assess the damage potential. In the near future, advanced field measurement methods based on LIDAR type technology combined with a highly instrumented turbine platform will be used to address these research issues.

Steady Aerodynamics & Blade Design

One of the most notable wind energy technology achievements by the national laboratories has been the development of the NREL airfoil series (Tables 5). The airfoil and rotor package is an integral part of any turbine design. Historically, most utility class turbines have relied on constant speed architectures. The most novel innovation incorporated in the NREL airfoil series was the use of stall control to limit power excursions at high wind speeds. Progressive blade stall initiated at the hub and advancing toward the blade tip with increasing wind speed passively limits the peak design power production capability without sacrificing energy capture at lower wind speeds.

Table 5. NREL Airfoil Families

Blade Length	Generator Rating	Thickness Category	Root	Airfoil Family To		Tip
1-5	2-20	Thick		S823		S822
5-10	20-150	Thin		S804	S801	S803
5-10	20-150	Thin	S808	S807	S805A	S806A
5-10	20-150	Thick		S821	S819	S820
10-15	150-400	Thick	S815	S814	S825	S826
10-15	150-400	Thick	S815	S814	S809	S810
10-15	150-400	Thick	S815	S814	S812	S813
15-25	400-1000	Thick		S818	S827	S828
15-25	400-1000	Thick		S818	S816	S817

Turbine blades typically operate in a Reynolds number range from 250,000 to 6,000,000. Airfoil designers face a significant challenge due to the fundamental differences in airfoil performance in this flow regime. At low Reynolds numbers, laminar boundary layers can produce extremely high lift and low drag values but are sensitive to perturbations and transition effects. High Reynolds numbers are less sensitive but have higher drag and lower aerodynamic efficiency. Operating in the median range between the two can produce a rotor package with an extreme sensitivity to external blade conditions and unpredictable performance.

Sustained field operations usually result in aerodynamically "dirty" turbine blades and energy losses from blade surface roughness effects. Airfoil surface roughness is caused by a build up of dirt and insect debris accumulated during normal turbine operations. These deposits perturb flow over the airfoil and transition the boundary layer from a laminar to turbulent flow characteristic. This transition can have significant and unexpected consequences depending on the particular airfoil design. The ability to accurately predict aerodynamic performance is critical for a successful design process.

For example, in one notable case, blades inadvertently designed with a strong laminar separation bubble were shown to have radical behavior changes and poorly predicted field performance. The airfoil designs codes available at that time failed to predict the presence of a laminar separation bubble. When wind tunnel tested, the free stream turbulence intensity of the wind tunnel was sufficiently high to transition the boundary layer and eliminate the laminar separation bubble. Wind tunnel tests produced performance results that agreed with the design predictions. When installed in the field, the natural inflow turbulence level was significantly less than wind tunnel values and the presence of the laminar separation bubble drastically reduced the predicted field performance. Only when the blade was made aerodynamically "dirty" by adding surface roughness was the boundary layer transitioned and performance somewhat restored. Such examples underscore the need for basic research in developing design tools based on a thorough understanding of the underlying fundamental physics of the technology limitation.

Advances in two-dimensional airfoil prediction techniques have helped to eliminate some of the aforementioned difficulties. Research activities to advance current "state-of-the-art" airfoil design methods at the national laboratories include improvements to the Eppler code by adding laminar separation detection methods, recent initiatives to define the effects of turbulence intensity, and spectra on boundary layer transition, and continuing investigations of computational fluid dynamics techniques using the most recent Navier-Stokes solvers to predict near- and post-stall aerodynamic performance.

Unsteady Three-Dimensional Aerodynamics

Current aerodynamic design codes are derived from two-dimensional analysis methods that have been empirically validated using quasi-static inflow assumptions. Although these methods have provided a significant advancement over previous methods, the assumptions used are totally invalid for turbines operating in the field. From actual field measurements using NREL's "Combined Experiment," of 22,000 recorded turbine cycles less than 1% could be considered quasi-static.

Potentially, the most significant research opportunities in aerodynamics will be the extension of two-dimensional techniques to three-dimensional unsteady analysis methods for unsteady attached and dynamically separated flows. Practically speaking, this technology leap will be difficult and may take several years. The benefits, however, are worth the effort. Current advanced designs can capture approximately 75% of the theoretical Betz energy limit. Only a better understanding of rotors operating in an unsteady three-dimensional environment will help advanced designs achieve more efficient energy capture.

As mentioned previously, NREL has maintained an extremely active experimental three-dimensional aerodynamics research program for several years. The Combined Experiment has focused on the aerodynamic and structural response of turbines to stochastic inflows using actual field measurements. This program consists of four separate phases: Phase I, development of the required experimental measurement methods and data reduction techniques; Phase II, instrumentation and field measurement of a rectangular rotor; Phase III, instrumentation and field measurement of a rectangular airfoil with optimized twist; and Phase IV, wind tunnel tests of the complete turbine in the 80' x 120' NASA Ames wind tunnel. Phase III was recently completed this year and

Phase IV is scheduled for the summer of 1997. These experiments have provided invaluable insights into the characteristics and behavior of the flow interaction with three-dimensional rotors including the contribution of dynamic stall to the fatigue load process.

Design Code Development

Providing an understanding of the underlying physical phenomena unique to turbine development is only the first step for successfully technology advancement. The transfer and integration of that knowledge in the form of usable tools for design and analysis is also critical. The national laboratories have provided extensive technology transfer to the wind industry through the development of advanced codes. A complete listing of these codes is beyond the scope of this overview, however; recent advances and enhancements in some of the structural design codes highlight a few of the current applied research activities.

As with all engineering design problems, the level of required code sophistication depends on the design phase. The more complex the code, the less flexibility for rapid modifications to the basic structural design. The most recent and frequently used structural design codes developed by national laboratories provide a range of capability (Table 6). Rapid preliminary design and performance assessments are made using YawDyn. Intermediate designs using FAST can now couple inflow turbulence models for preliminary quantification of transient and fatigue loads to unsteady inflow. The most advance modeling method, ADAMS, has unlimited degrees of freedom and permits detailed structural analysis limited only by the complexity of the analysis model.

Table 6. Design Codes

Name	Purpose	Degrees of Freedom
• **YawDyn**	Preliminary Design	Blade flap, nacelle yaw
• **FAST**	Intermediate Design Fast Turbulence Simulations	Blade flap, edge, rotor teeter, drive train torsion, nacelle yaw, tower fore-aft, and side-side
• **ADAMS**	Final Design Detailed Loads & Responses Modal Analysis	Unlimited

Research opportunities include the design and development of codes capable of modeling extremely flexible structures with integrated control systems. Driving this requirement is the need to lower turbine production costs through various means including overall system weight. The resulting advanced designs are extremely dynamically active when compared with existing architectures. These same designs will most likely be driven at variable speed in order to maximize energy capture. System-coupled resonance from soft towers and flexible blades will have to be detected and controlled actively. Unfortunately, one of the current limitations is the ability to perform modal analysis for a rotating system. In order to design and implement the appropriate control paradigms, linearized code yielding the appropriate mass, stiffness, and damping matrices will be necessary.

Integrated Design & Analysis Process

Merging the various technical disciplines within applied research to focus on turbine design from an integrated systems analysis perspective has the potential for rapid technology advancement. For example, by integrating the currently available structural and inflow turbulence models a direct comparison can be made of turbine performance for radically different design concepts. In Figure 1, two different machines rated to similar maximum power production levels are compared. The differences in performance between this three-bladed rigid hub and two-bladed teetered hub can be directly contrasted when operated under identical inflow turbulence intensities. The cycle roll off behaviors reflect the differences in design philosophy between the two machines. In the very near future, this type of analysis will be coupled with fatigue life prediction methods (such as SNL's FARROW code) to give operational cycle life predictions for any known inflow environment.

NREL's variable speed research program offers a template for this type of approach. First, a fundamental analysis using closed form exact solutions (when possible) were performed to establish optimal performance improvement bounds. Analytic simulations were then used to determine the structural response and energy capture performance under a variety of actual "field" inflow conditions. This systematic evaluation also included an evaluation of control paradigms to optimize system performance and energy capture. Finally, validation by actual field experiment to calibrate the system design process and identify fundamental technology gaps for future research initiatives. The variable speed project has just entered the field validation portion of this integrated program.

Summary

In the future, an integrated multidiscipline approach will be necessary to evaluate advanced turbine designs. Any new turbine development program based on innovative and/or untested technology represents a significant cost and risk. It is the role of the national laboratories to help mitigate this risk by providing the advanced technology, analysis tools and innovative designs in order to promote wind as a viable renewable energy alternative.