Wind Energy Aerodynamics – Rotor, Wake, and Wind Plant

Stanford Seminar for Faculty and Students
Stanford, CA

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Scott Schreck, PhD
NREL’s National Wind Technology Center

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National Wind Technology Center

- Turbine technology since 1977 (SERI)
- Development of design and analysis codes
- Pioneers in component and field testing
- Unique test facilities
  - Blade Testing
  - Dynamometer
  - CART turbines
- Modern utility-scale turbines
- Approx. 160 staff on-site
- Budget approx. $35M
- Many CRADAs with industry
- Leadership roles for international standards
Critical Elements for 20% Scenario

300 GW by 2030

• 80% Land 20% Offshore

• Improved Performance
  – 10% reduction in capital cost
  – 15% increase in capacity factor
  – Address Wind Farm underperformance

• Mitigate Risk
  – Reduce O&M costs by 35%
  – Foster the confidence to support continued 20% per year growth in installation rates from now until 2018

• Enhanced Transmission System (AEP)
  – $60 billion cost estimate over 20 yrs
  – 19,000 mi of line
  – Supports 200-400 GW addition

• Policy, Communication & Outreach

• Infrastructure Development
Electrical Power Generation by Source

3700 TWh Annually
(0.42 TW Continuous energy use)

Source: Electric Power Monthly, March 15, 2010
http://www.eia.doe.gov/cneaf/electricity/epm/epm_sum.html

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
20% Requires 300 GW - Land & Offshore

Cumulative Installed Capacity (GW)

- Offshore
- Land-based

Projected
Actual
Wind Resource Distribution
How Much Wind is Available … Really?

Excludes PTC, includes transmission costs to access 10% existing electric transmission capacity within 500 miles of wind resource.

Source: Black & Veatch/NREL
Technology Evolution

Evolution of Commercial Wind Technology

The 1980's
- Altamont Pass, CA
- Kenetech 56-100kW
- 17m Rotor
- 50kW
- 100kW

The 1990's
- San Clemente, CA
- Micon 700-225/40
- 29.6m Rotor
- 300kW
- 500kW
- 750kW
- Mehuken, Norway
- Vestas V52-850kW
- 52m Rotor

2000 & Beyond
- Liverpool Bay, UK
- Siemens SWT-3.6MW
- 107m Rotor
- 3.6 MW
- 2.5 MW
- 1.5 MW
- Aberdeen, Scotland
- North Sea (45m water depth)
- REpower 5MW
- 126m Rotor
- 5 MW

Credit: NREL Historical Photos

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
Wind Turbine Scale – Present and Future

- 2.5 MW - typical commercial turbine installation
- 5.0 MW prototypes being installed for testing in Europe
- Clipper Wind Power developing an 8.5 MW turbine
- Most manufacturers have a 10 MW machine in design
- Large turbine development programs targeting offshore markets
- Development Outpacing Test & Validation Capability
Stanford stadium overhead image from web address below. Use rectangle above to scale.

http://msrmaps.com/image.aspx?T=4&S=10&Z=10&X=2871&Y=20716&W=1&qs=Nelson+Road%7cStanford%7cCA&Addr=Nelson+Rd%2c+Stanford%2c+CA+94305&ALon=-122.1601053&ALat=37.4320765
Structure Size and Weight – Implications

Baseline blade mass curve = WindPACT baseline
Advanced blade mass curve = LM advanced design

WindPACT Static Load Design:
\[ y = 0.2113x^{2.8833} \]

WindPACT Baseline Design:
\[ y = 0.1452x^{2.9158} \]

LM Advanced Blade Design:
\[ y = 0.4948x^{2.53} \]

WindPACT Final Design:
\[ y = 0.1527x^{2.6921} \]
Technology Challenges Remain

Wind plant energy production

- Example
  - 200 wind turbines @ 2 MW
  - 36% cap factor → 1.26x10^9 kWh/yr
  - 5 ¢/kWh, 1% AEP underproduction
  - $630K/year = $12.6M/plant lifetime
- 1% - 10% underproduction common

Turbine O&M cost prediction

- Blade delamination, cracking
- Gear, bearing failures
- Unanticipated fatigue loading
Wind Turbines vs. Aircraft

• Overall cost
  – Aircraft: 600 USD/lb
  – Wind turbine: <6 USD/lb

• Wing/blade cost
  – Aircraft: >600 USD/lb
  – Wind turbine: <9 USD/lb

• Lifetime fatigue cycles
  – Aircraft: $10^6$
  – Wind turbine: $10^8$

• Inspection/maintenance
  – Aircraft: Daily/weekly
  – Wind turbine: Six months/one year
Fundamental Challenges

Current engineering approach
- Linearized and reduced order
- Partitioned for tractability
- Limited scale range and interaction

Physics and numerics
- Coupled and nonlinear
- Broad scale range
- Multiple physics
NREL UAE Phase VI Turbine in NASA Ames 80’x120’
Max rotational augmentation of 3X parked
Deviation same as 15 – 20 % TI, ~10 Hz
Flow Field Topology

(CFD courtesy of N. Sørensen, Risø National Laboratory)

Off-surface structures 3-D and complex
Topology responsive to operating condition

$U_\infty = 15 \text{ m/s}$
Nonzero Yaw – Dynamic Stall

Mean $C_n$ maxima = 1.5X - 3X static stall levels
Rise times = 0.1 - 0.2 sec (1/8 - 1/4 cycle)
Flow Field Topology

Vortex convection not radially uniform
Operating condition drives 3-D deformation

\[ U_\infty = 13 \text{ m/s} \]
\[ \text{Yaw} = 30^\circ \]
\[ \Delta t = 11.4 \text{ msec} \]

\[ U_\infty = 15 \text{ m/s} \]
\[ \text{Yaw} = 40^\circ \]
\[ \Delta t = 9.8 \text{ msec} \]
Control Effectiveness

- Test results for advanced MIMO control
- Integrated blade pitch-generator torque control
• Real-time sensing of inflow velocity field
• Independent blade pitch actuation
Implications of Blade Flow Physics

Blade flow fields
- Amplified loads
- Highly unsteady
- Large bandwidth
- Energetic vortices
- 3-D flow fields
- Commonly occur

Control impacts
- Bandwidth
- Nonlinearity
- Sensors/actuators
- State identification
- Actuator authority
- Feasibility

Difficult to understand & predict
Challenging to control
Drive COE
Wake Structure Development

- Axial velocity
- Turbulence intensity

Sørensen, EWEC 2007

Danmarks Tekniske Universitet
Wake Dynamics – Meandering

LIDAR (gray scale) tracks wake velocity
Model (red) assumes passive transport

Graphic courtesy of J. Mann, Risoe-DTU
9 turbine park simulation
Complex Topography Effects
Turbine, wind farm, PBL; similar dimensional scales

Farm / inflow interactions not quantified

Characterization & prediction remain an issue

Detailed inflow information required for turbine design and optimized control

Diurnal variation

Growing concerns include:
- Quality of the downwind resource
- Microclimatology changes
- Agriculture impacts
- Permitting
Unification Across Models & Scales

Treating Multi-Scale Flow Interactions Among Models

Mesoscale Models

LES Models

CFD Models

temporal and spatially varying BCs

parameterizations

Mesoscale, LES and CFD models normally run separately
LES and CFD models use constant or periodic boundary conditions
Some work already underway in linking these types of models
Include terrain and variable land-use into LES models
PBL Parameterizations

Models cover multiple spatial scales, but not all encompassing. For $\Delta x < 1$ km, but problems exist – e.g., “double booking” turbulence.
Climate effects

- Understand and predict wind resource variability
- Wind plant and local/regional/global climate
Computational Modeling Scales

- Cell Size (m)
  - Climate Effects
  - Mesoscale Processes
  - Micrositing & Array
  - Turbine
- Domain Size (m)
  - 10^7
  - 10^5
  - 10^4
  - 10^3
  - 10^1
  - 10^{-5}
Deep Water Modeling Requirements

Fully coupled aero-hydro-servo-elastic interaction

Wind-Inflow:
- discrete events
- turbulence

Waves:
- regular
- irregular

Aerodynamics:
- induction
- rotational augmentation
- skewed wake
- dynamic stall

Hydrodynamics:
- scattering
- radiation
- hydrostatics

Structural dynamics:
- gravity / inertia
- elasticity
- foundations / moorings

Control system:
- yaw, torque, pitch
Large Facility Requirements

New Large Blade Test Facilities:

- Boston, MA with Massachusetts Technology Collaborative
- Corpus Christy, TX with University of Houston

DOE NOI for 5-15 MW Dynamometer

A 45-meter wind turbine blade undergoing fatigue testing at the NWTC, July 2004.
Multi-MW Turbines at NWTC

DOE 1.5 MW GE Turbine:
- Model: GE 1.5SLE
- Tower Height: 80 m
- Rotor Diameter: 77 m
- DOE owned; used for research and education

Siemens 2.3 MW Turbine:
- Model: SWT-2.3-101
- Tower Height: 80 m
- Rotor Diameter: 101 m
- Siemens owned and operated
- Multi-year R&D CRADA; aerodynamics and rotor performance
Questions?

Scott Schreck, PhD
NREL’s National Wind Technology Center

Phone: (303) 384-7102
Email: scott.schreck@nrel.gov