SAND2007-4920C

Wind Turbine Modeling and Control Investigation

Student Symposium - August 7, 2007

Jonathan Berg

Analytical Structural Dynamics (1523)

in conjunction with Wind Energy Technology (6333)

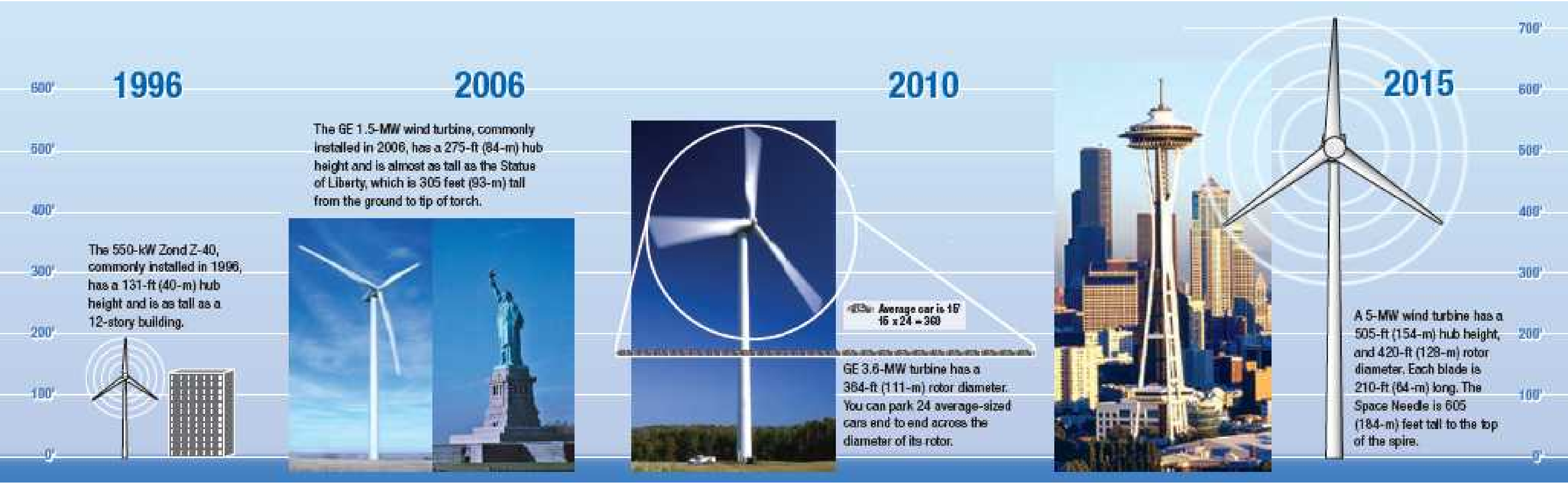
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Overview

- Background
  - Wind Energy Trends
  - Theory of Operation
- Research Question
- Results

Wind Energy Trends – Size

Wind Power Today – May 2007 issue:



Rated power:	1.5-MW	3.6-MW	5.0-MW
Tower height:	275-ft (84-m)	400-ft (122-m)	505-ft (154-m)
Rotor diameter:	230-ft (70-m)	364-ft (111-m)	420-ft (128-m)

http://www.nrel.gov/docs/fy07osti/41330.pdf

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REpower 5-MW

http://www.ocean.udel.edu/windpower/docs/5m_uk.pdf

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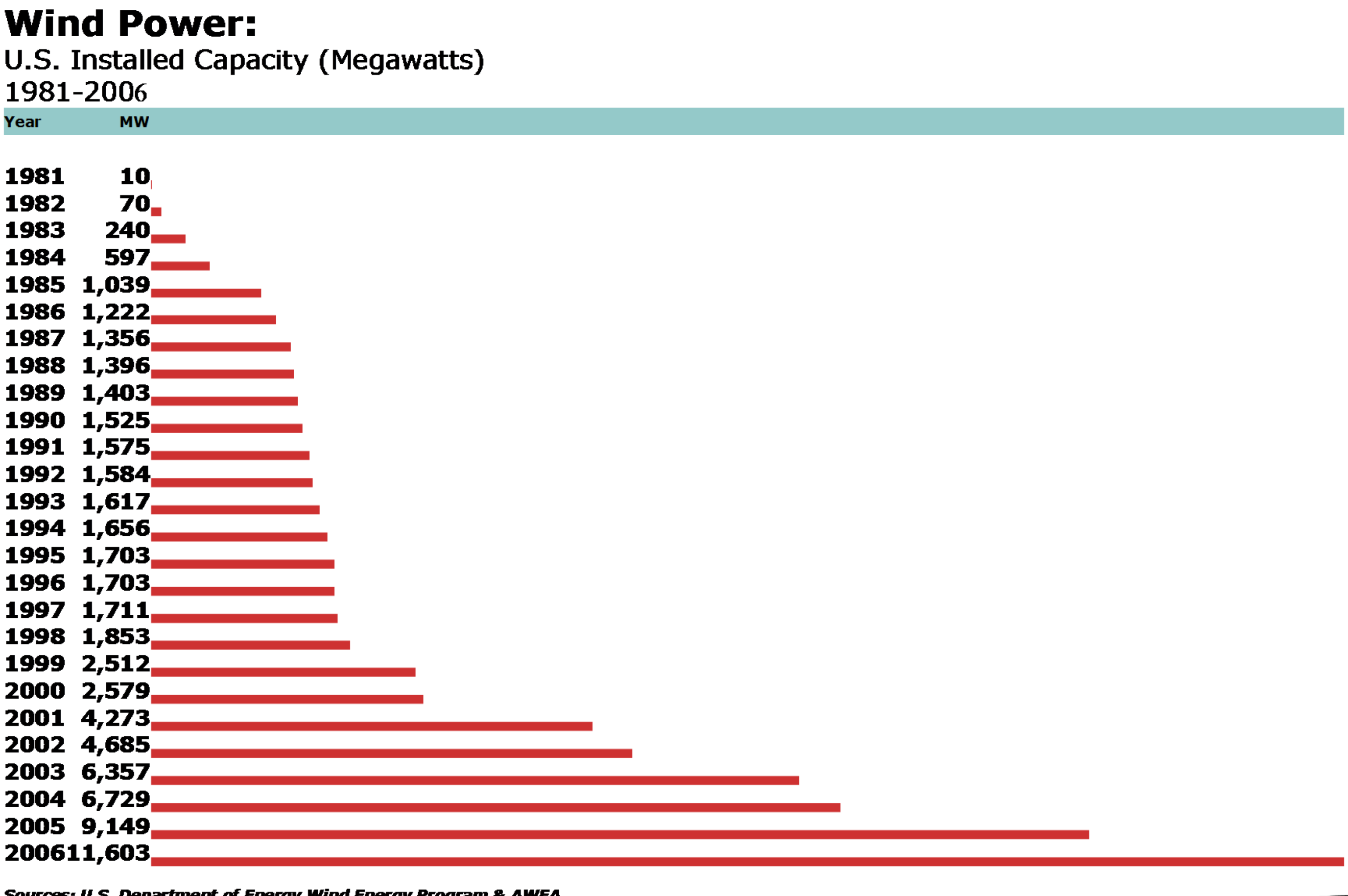
Wind Energy Trends – Installation



http://www.awea.org/faq/instcap.html

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Aerodynamics

F_L – lift force

F_D – drag force

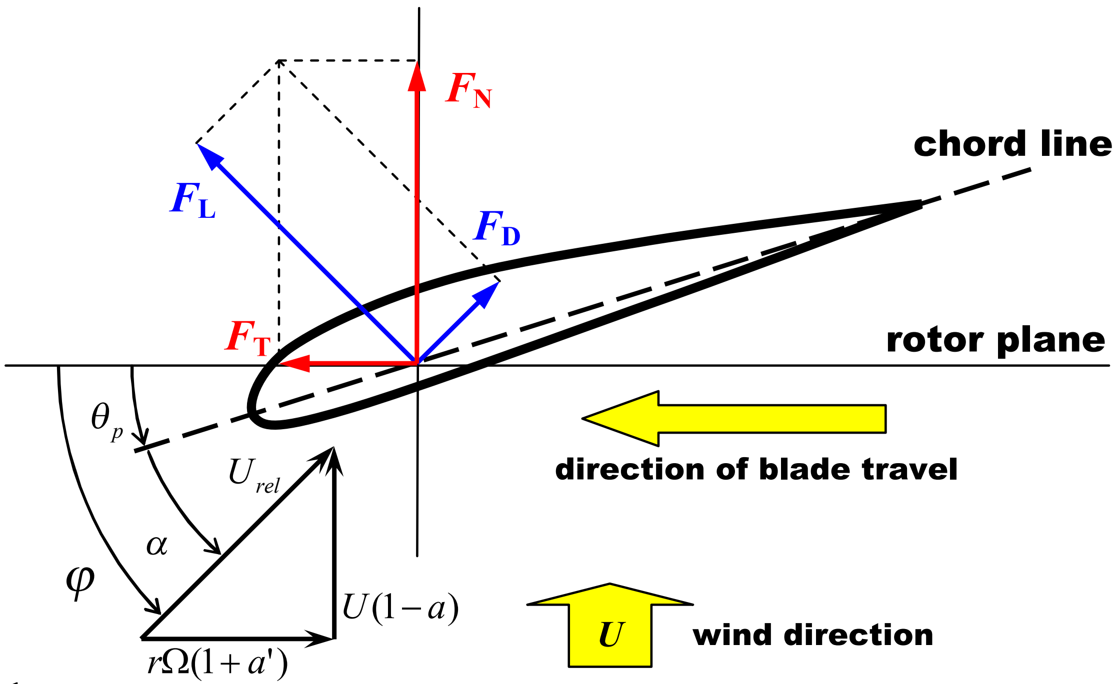
F_N – normal force

F_T – tangential force

θ_p – local pitch angle

α – angle of attack

φ – angle of relative wind



Wind Power

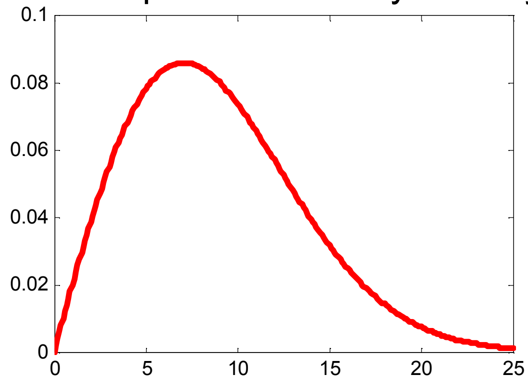
- **Available power**
  - **Proportional to rotor diameter squared (swept area)**
  - **Proportional to wind velocity cubed**
- **Power coefficient & Betz limit**

$$C_P = \frac{\text{rotor power}}{\text{available wind power}} = \frac{P_{rotor}}{\frac{1}{2}\rho A U^3}$$

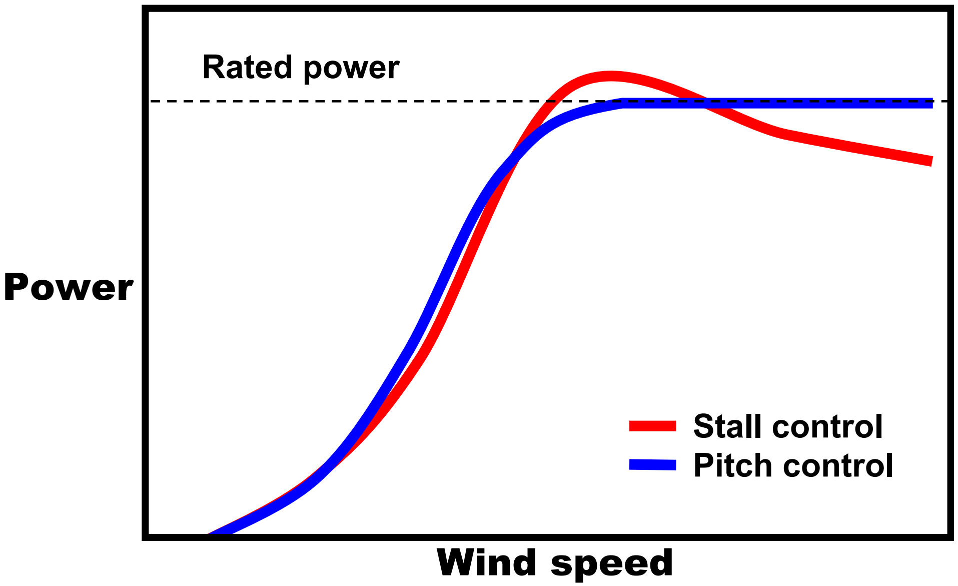
  - **$C_{P,max}$ = 16/27 = 0.593**
  - **a = 1/3 at max C_P**

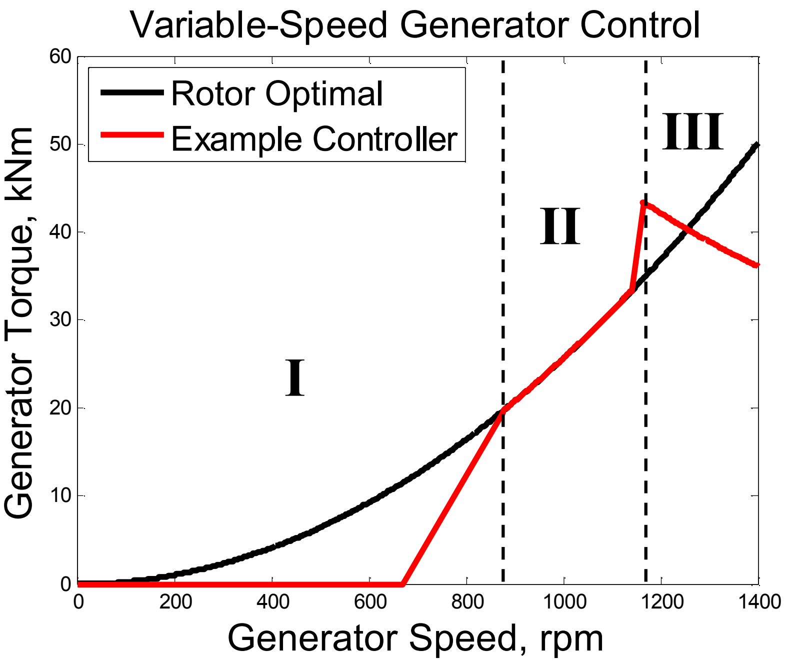
$$P_{wind} = \frac{1}{2}\rho A U^3$$

Wind Speed Probability Density



Power Curve





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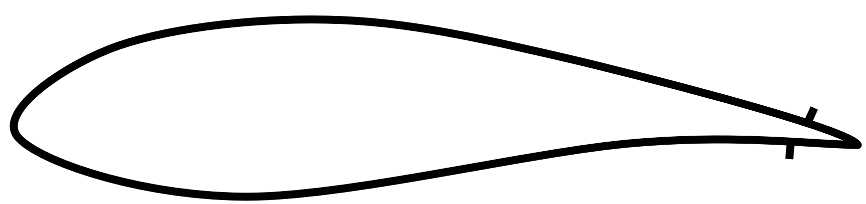
Active-aero Control

- **Active-aero**
  - **Local load control along blade**
  - **Quick response to wind gusts**
- **Microtabs**
  - **Small devices (1% of chord)**
  - **Placed near trailing edge**
  - **Substantial change in lift**



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Research Question

- Problem: cyclic and random loading produces fatigue in drive-train, blades, and other structures
- Question: What knowledge (sensors) could help reduce fatigue loads and what is the relative impact?
  - Answer dependent upon control device
  - Relative impact influenced by control system
- Sub-Question: What benefits can be obtained by going from collective pitch to individual pitch? To active-aero? What is the design methodology?

Turbine Parameters

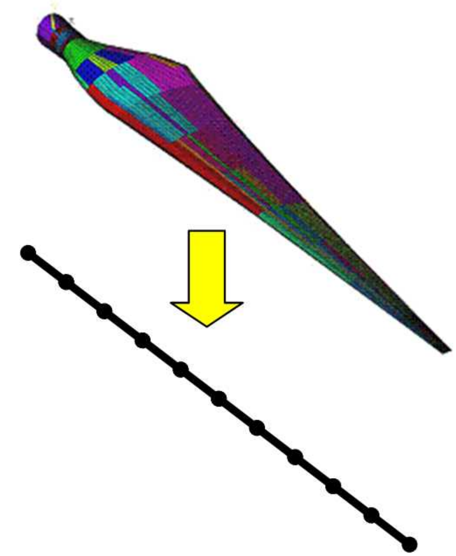
- CART – Controls Advanced Research Turbine
  - 600 kW rated power
  - 2 blades
  - 42 rpm rated rotor speed
  - 43.3 m rotor diameter
- NREL Baseline 5MW
  - 3 blades
  - 12.1 rpm rated rotor speed
  - 126 m rotor diameter

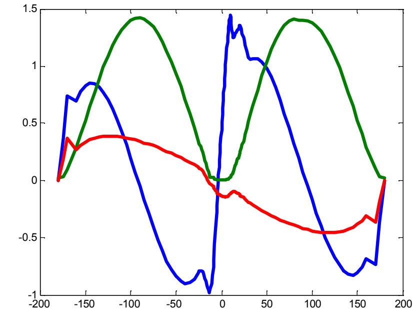
FAST Simulation

- **FAST** (Fatigue, Aerodynamics, Structures, and Turbulence)
  - Maintained by NREL
  - Configurable for many types of wind turbines
- Tried to understand capabilities of model
- Became familiar with basic turbine response
- Advisors suggested that building my own model would be informative

Building the Model

- Structural dynamics
  - Finite Element theory
    - Represent blade as simple beam
    - Beam is divided into elements
  - Modal reduction
- Aerodynamics
  - Blade Element Momentum theory
  - Utilize lift and drag coefficient test data





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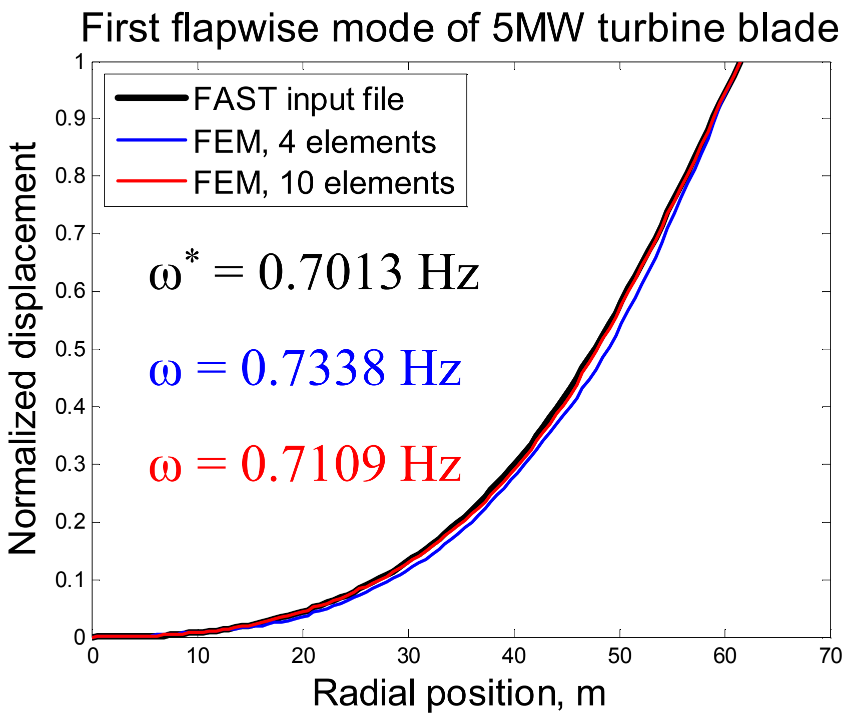
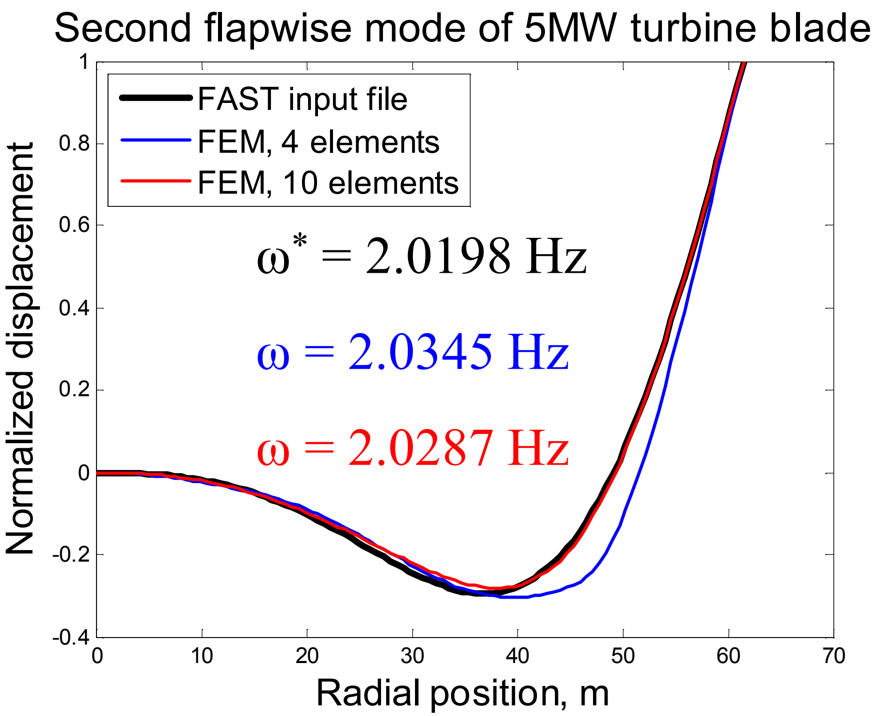
Verification of Blade Structural Dynamics





* - from http://wind.nrel.gov/public/jjonkman/NRELOffshrBsline5MW/NRELOffshrBsline5MW.pdf

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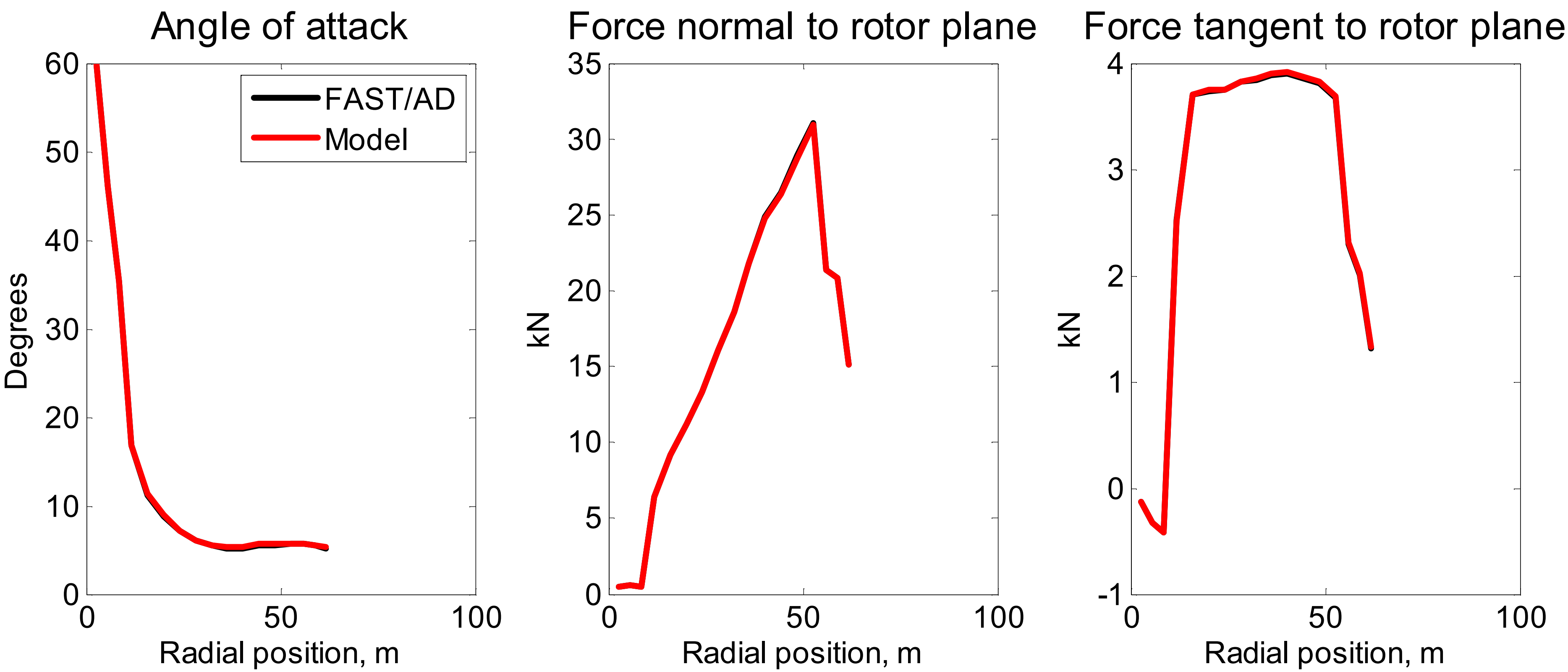
Verification of Blade Aerodynamics

5MW turbine rotating at 12.1 rpm in 12 m/s wind



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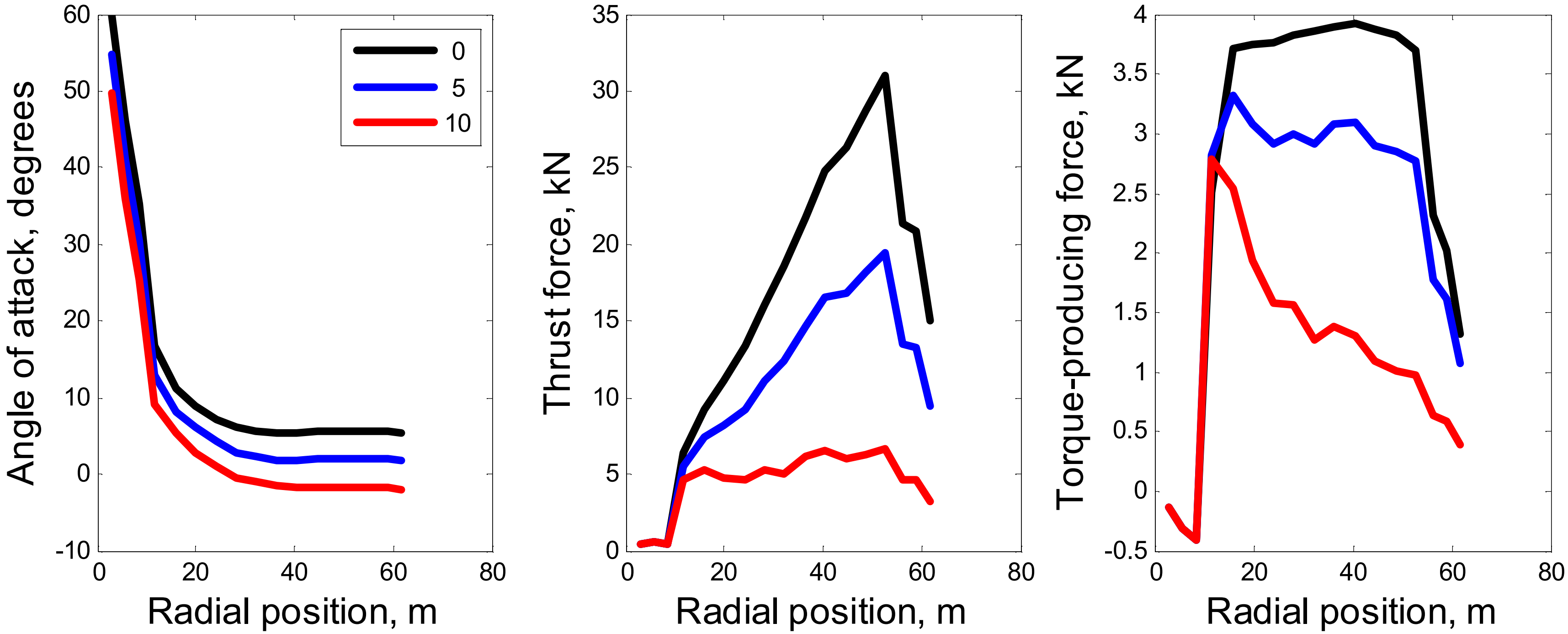
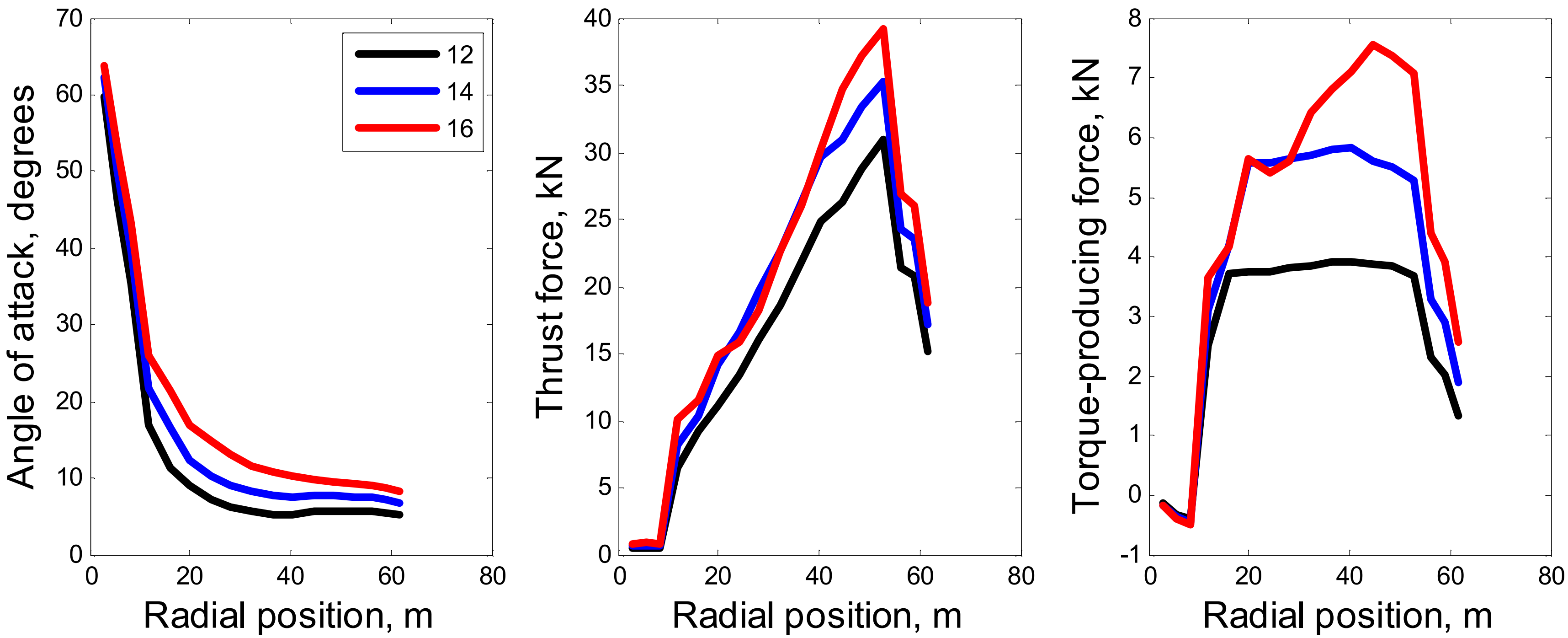
Effect of Blade Pitch

5MW turbine rotating at 12.1 rpm in 12 m/s wind



Effect of Wind Speed

5MW turbine rotating at 12.1 rpm with 0° pitch



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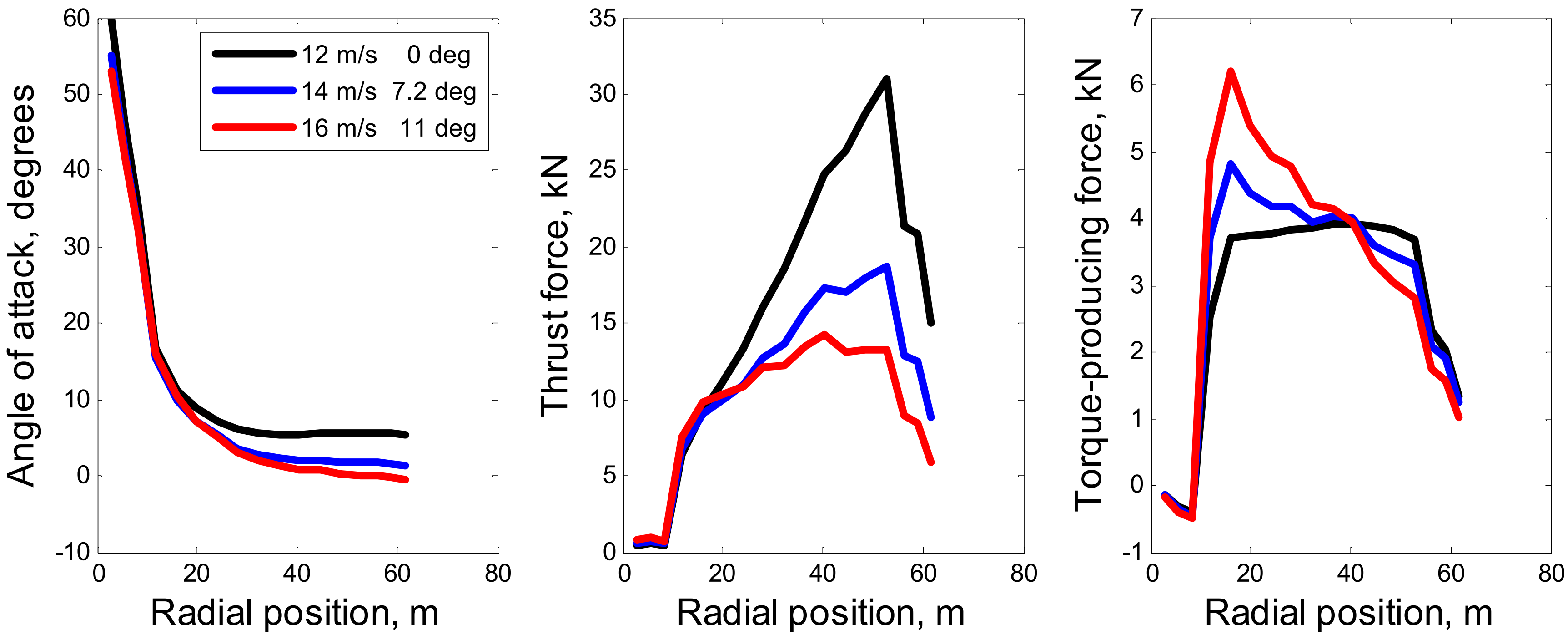
Pitch Adjusted for Constant Torque

5MW turbine rotating at 12.1 rpm



Control Overview

- Industry Standard
  - Variable speed generator control
  - Collective pitch control
  - Sensors: shaft speed, wind speed & direction, power output
- Current Research
  - Cyclic pitch control
  - Individual pitch control
  - Sensors: inflow / angle-of-attack, wind mapping (Lidar), strain gages, blade deflection (cameras)

Control Papers

- Olsen, et. al. "Low Wind Speed Turbine Project Conceptual Design Study: Advanced Independent Pitch Control" 2004
  - Assume knowledge of angle-of-attack
  - Reduced amplitude of variations in shaft speed and power output
  - Extreme flap load reduced by 37.5%
  - More demand on pitch drive
- Larsen, et. al. "Active Load Reduction Using Individual Pitch, Based on Local Blade Flow Measurements" 2005
  - Cyclic pitch: infer shear wind state from load measurement
  - Individual pitch: each blade seeks the average angle-of-attack of all blades
  - Load is reduced compared to collective pitch
  - Mixed results in comparison of cyclic & individual

Accomplishments

- Acquired greater understanding of current wind turbine technology
- Produced model of blade structure dynamics and aerodynamics
- Developed better understanding of the limitations of current models

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Acknowledgments

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- Support: Todd Griffith, Don Lobitz, David Wilson
- Manager: Tom Baca

References

- Manwell, McGowan, and Rogers. *Wind Energy Explained*. John Wiley & Sons Ltd, 2002.
- Burton, Sharpe, Jenkins, and Bossanyi. *Wind Energy Handbook.* John Wiley & Sons Ltd, 2001.
- Cook, Malkus, Plesha, and Witt. *Concepts and Applications of Finite Element Analysis*. John Wiley & Sons Ltd, 2002.
- Junkins and Kim. *Introduction to Dynamics and Control of Flexible Structures.* AIAA Education Series, 1993.
- NWTC Design Codes (FAST by Jason Jonkman). http://wind.nrel.gov/designcodes/simulators/fast/. Last modified 12-August-2005; accessed 23-May-2007.
- Jonkman and Buhl. “FAST User's Guide,” NREL/EL-500-38230. Golden, Colorado: National Renewable Energy Laboratory, 2005.
- Moriarty and Hansen. “AeroDyn Theory Manual,” NREL/EL-500-36881. Golden, Colorado: National Renewable Energy Laboratory, 2004.

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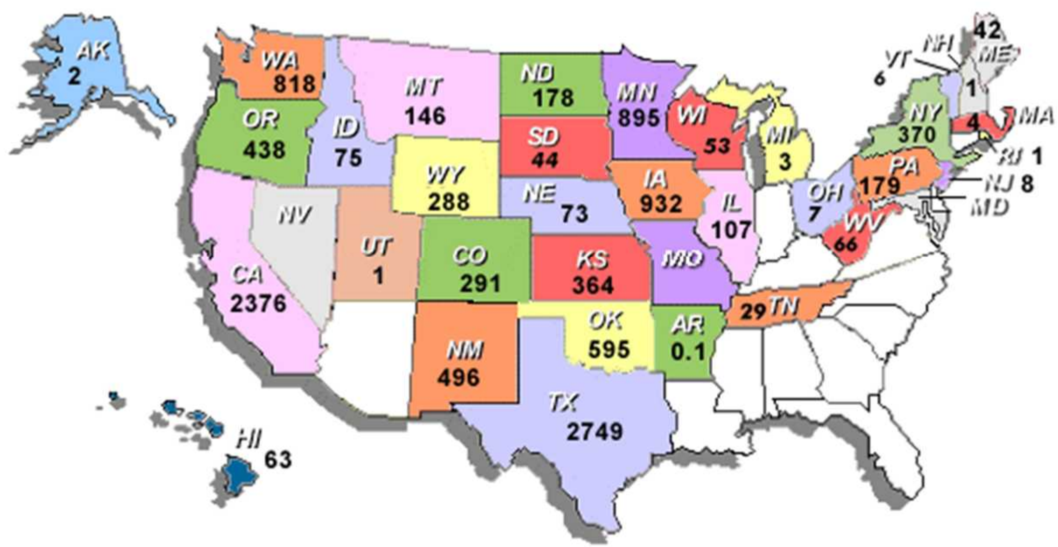
Extra Slides

U.S. Wind Energy

Wind Energy Projects
Throughout the United States of America



TOTAL INSTALLED U.S. WIND ENERGY CAPACITY: 11,699 MW as of March 31, 2007

http://www.awea.org/projects/

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NM Wind Energy

Existing Project or Area	Owner	Date Online	MW	Power Purchaser/ User	Wind Turbines
Llano Estacado Wind Ranch at Texaco, phase I	Cielo Wind Power	1999	0.66	Southwestern Public Service (Xcel Energy)	Vestas V-47 (1)
New Mexico Wind Energy Center	FPL Energy	2003	204	Public Service of New Mexico	GE Wind 1500 (136)
Llano Estacado Wind Ranch at Texaco, phase II	Cielo Wind Power	2003	1.32	Southwestern Public Service (Xcel Energy)	Vestas V-47 (2)
Caprock Wind Ranch	Babcock & Brown	2005	80	Xcel Energy	Mitsubishi 1 MW (80)
San Juan Mesa	Edison Mission Group	2005	120	Xcel Energy	Mitsubishi 1-MW (120)
Aragonne Mesa Phase I	Babcock & Brown	2006	90	Arizona Public services	Mitsubishi 1-MW (90)
		Total:	**496**		

http://www.awea.org/projects/newmexico.html

BEM Equations

$$\tan\varphi = \frac{U(1-a)}{\Omega r(1+a')}$$

$$F = (2/\pi)\cos^{-1}\left[\exp\left(-\frac{(B/2)[1-(r/R)]}{(r/R)\sin\varphi}\right)\right]$$

$$\varphi = \theta_p + \alpha$$

$$\sigma' = Bc/2\pi r$$

$$a = \left[1 + \frac{4F\sin^2\varphi}{\sigma' C_l \cos\varphi}\right]^{-1}$$

$$a' = \left[\frac{4F\cos\varphi}{\sigma' C_l} - 1\right]^{-1}$$

$$U_{rel} = \frac{U(1-a)}{\sin\varphi}$$

$$\mathrm{d}F_N = \tfrac{1}{2}\rho U_{rel}{}^2 (C_l\cos\varphi + C_d\sin\varphi)c\,\mathrm{d}r$$

$$\mathrm{d}F_T = \tfrac{1}{2}\rho U_{rel}{}^2 (C_l\sin\varphi + C_d\cos\varphi)c\,\mathrm{d}r$$

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