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Understanding the Aerodynamics and Aeroacoustics of Wind Turbine Blades

Eric Paterson1, William Devenport1,
Ricardo Burdisso2, and Aurelien Borgoltz1

Aerospace and Ocean Engineering
Mechanical Engineering
Virginia Tech, Blacksburg, VA

2013 NAWEA Symposium
6-8 August, Boulder, CO

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Introduction

- Aerodynamic performance and aeroacoustics are tightly coupled
- Engineering design tools based upon *steady-inflow* experimental data on *2D blade sections*, and upon empirical acoustic models
- Improved methods needed for airfoil selection, control methods, wind-plant configuration, etc.
- Wind-tunnel testing and fidelity-CFD experiments are critical for developing fundamental knowledge, new methods, and empirical data

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Recent Field Data

S. Oerlemans and J. G. Schepers (2009)

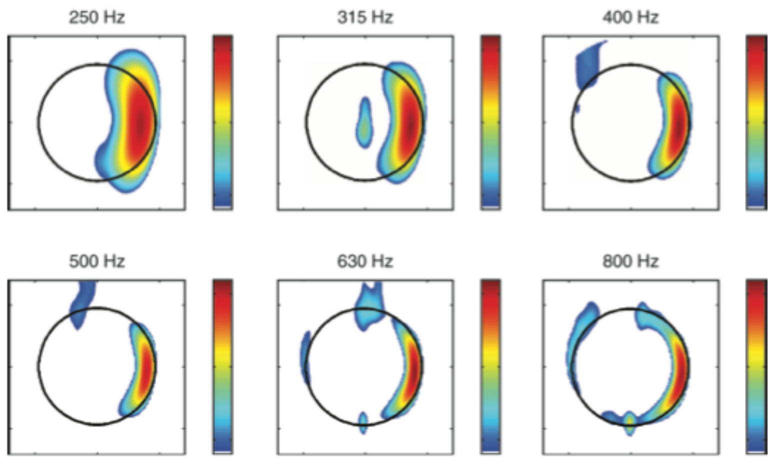
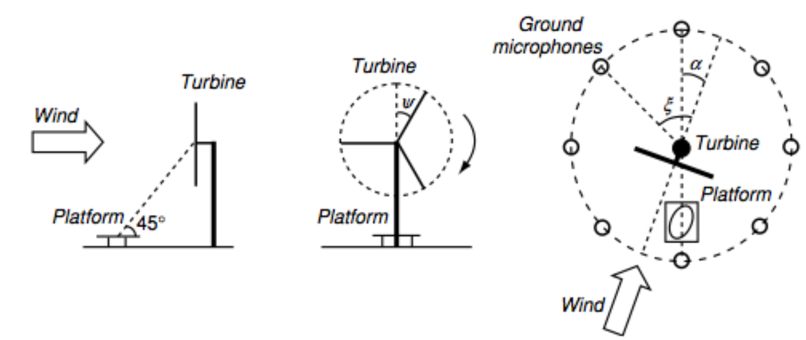


Figure 9: Measured source maps for Turbine 1.



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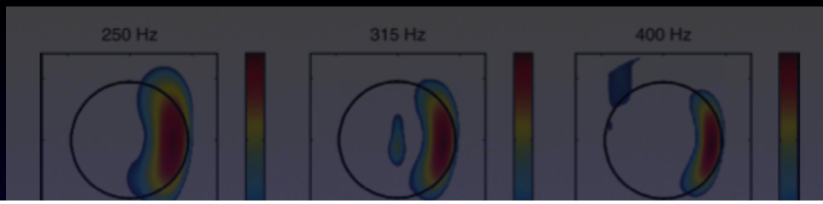
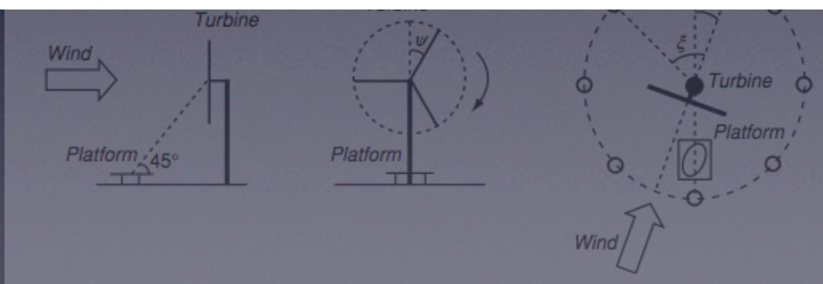


- Due to trailing edge noise directivity and convective amplification, noise emitted to the ground is produced during the downward movement of the blades

- This causes a swishing noise during the passage of the blades



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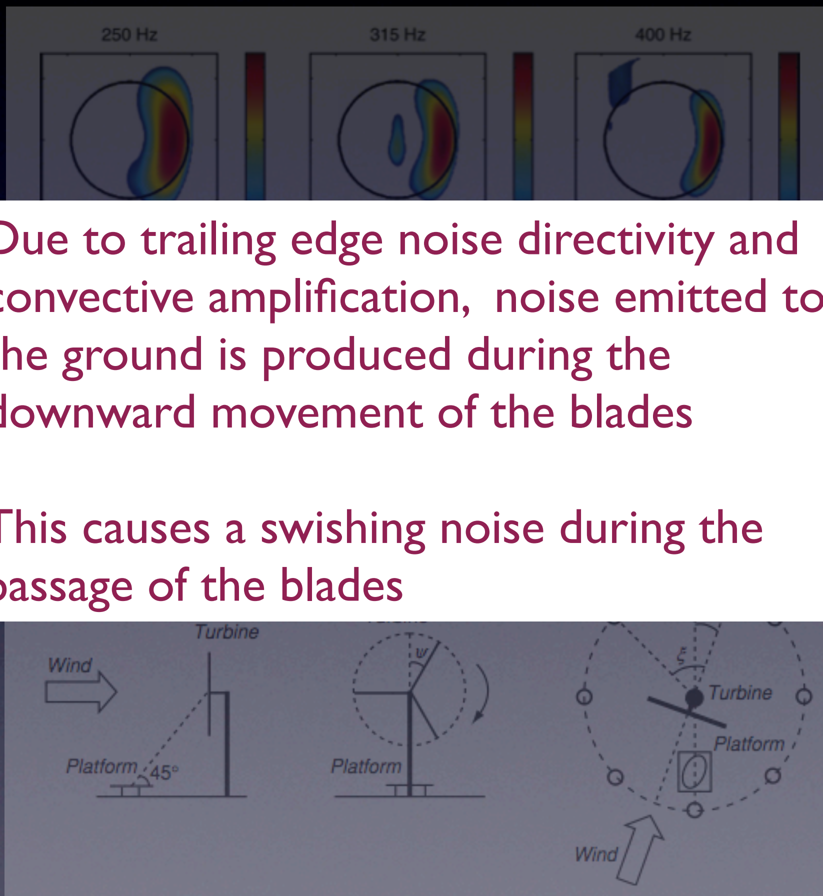

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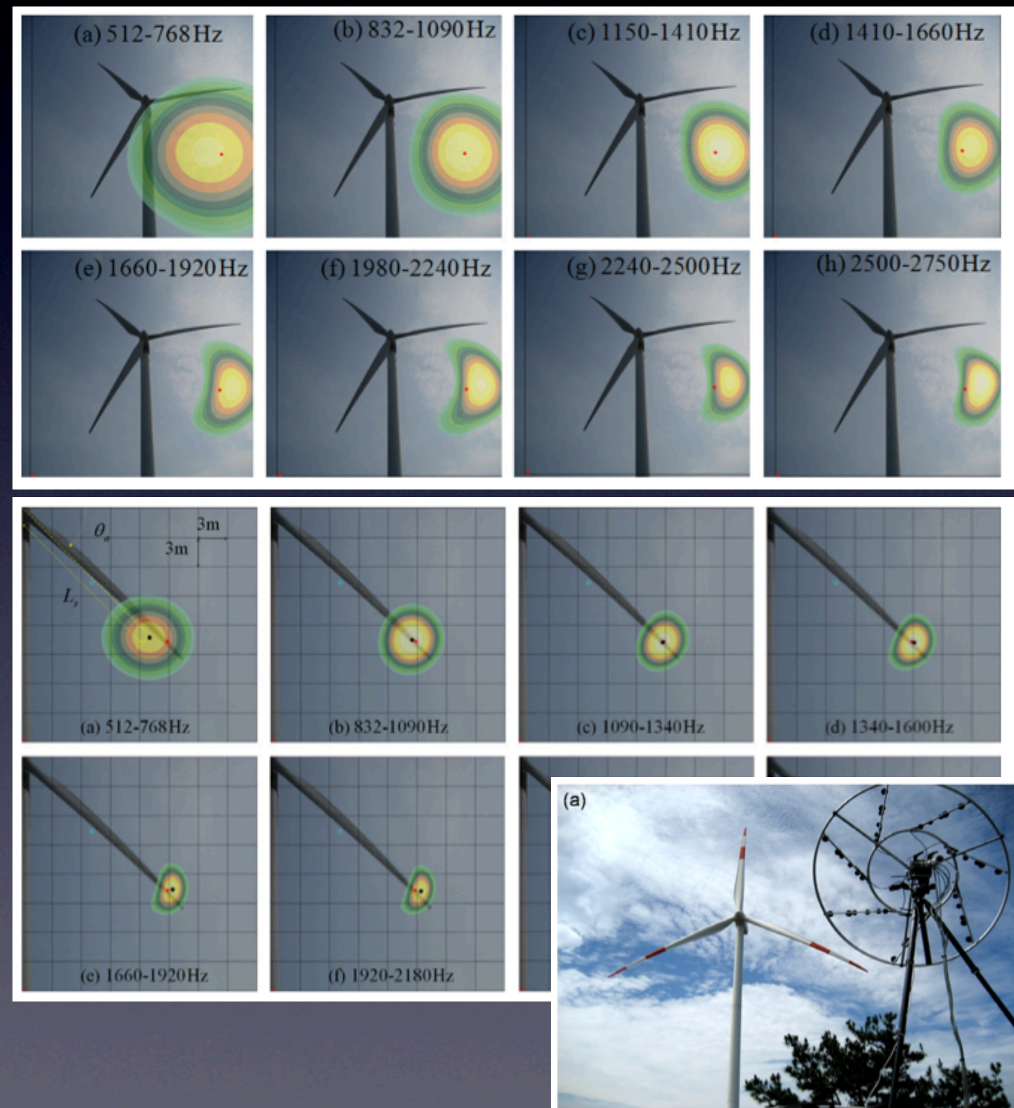
G.S. Lee, C. Cheong, S.H. Shin, S.S. Jung (2012)



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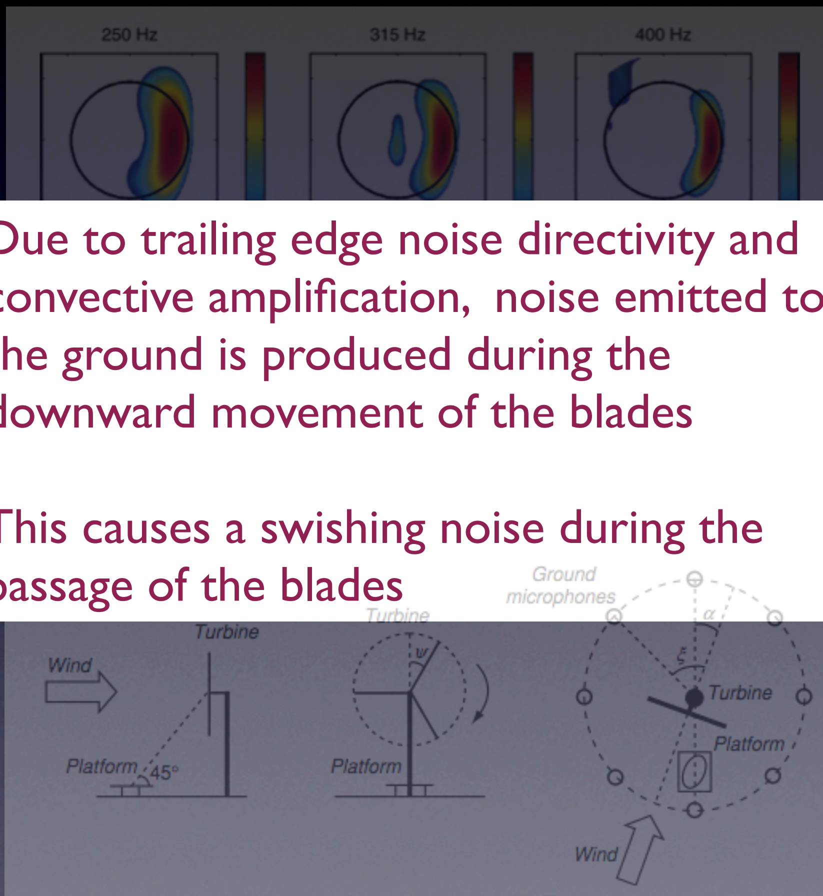

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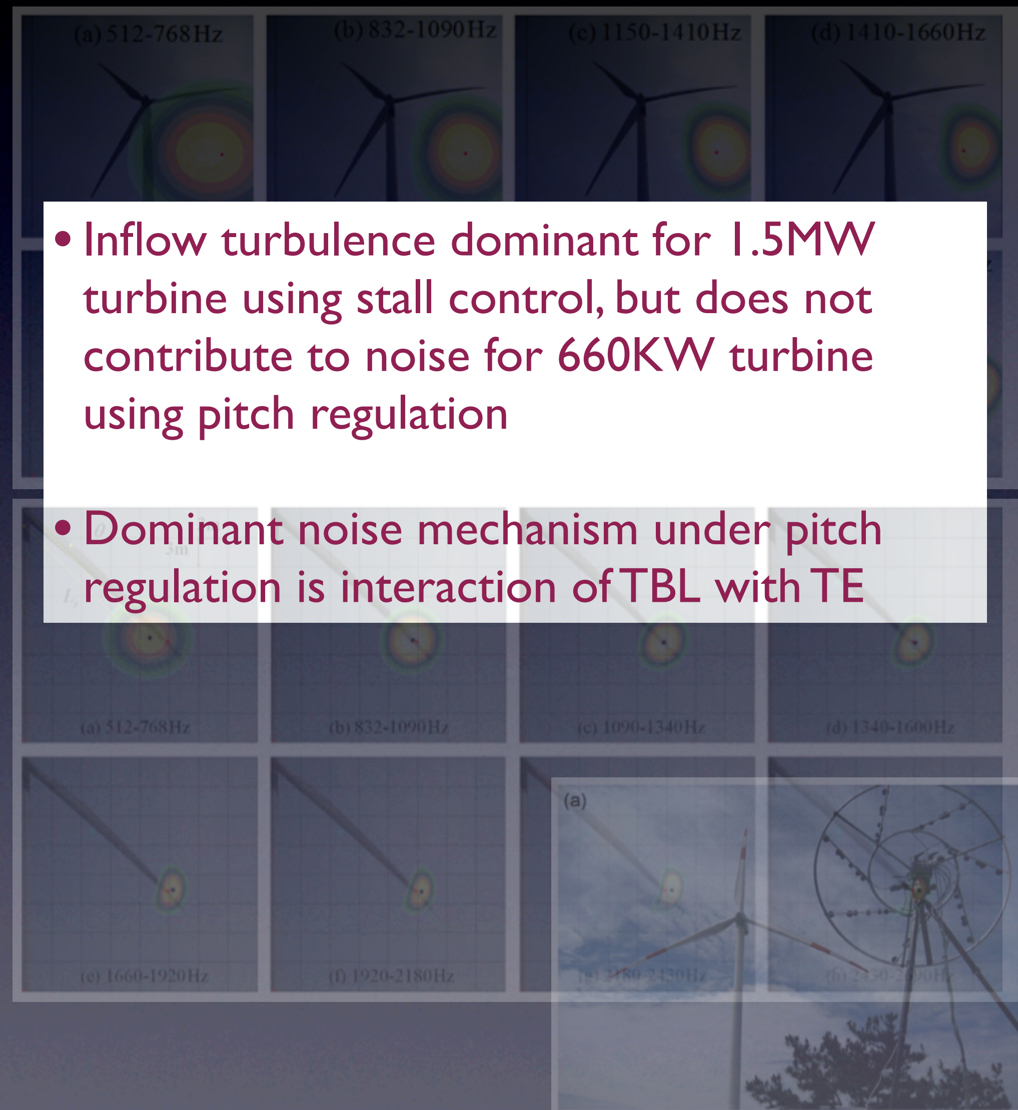

- Inflow turbulence dominant for 1.5MW turbine using stall control, but does not contribute to noise for 660KW turbine using pitch regulation
- Dominant noise mechanism under pitch regulation is interaction of TBL with TE

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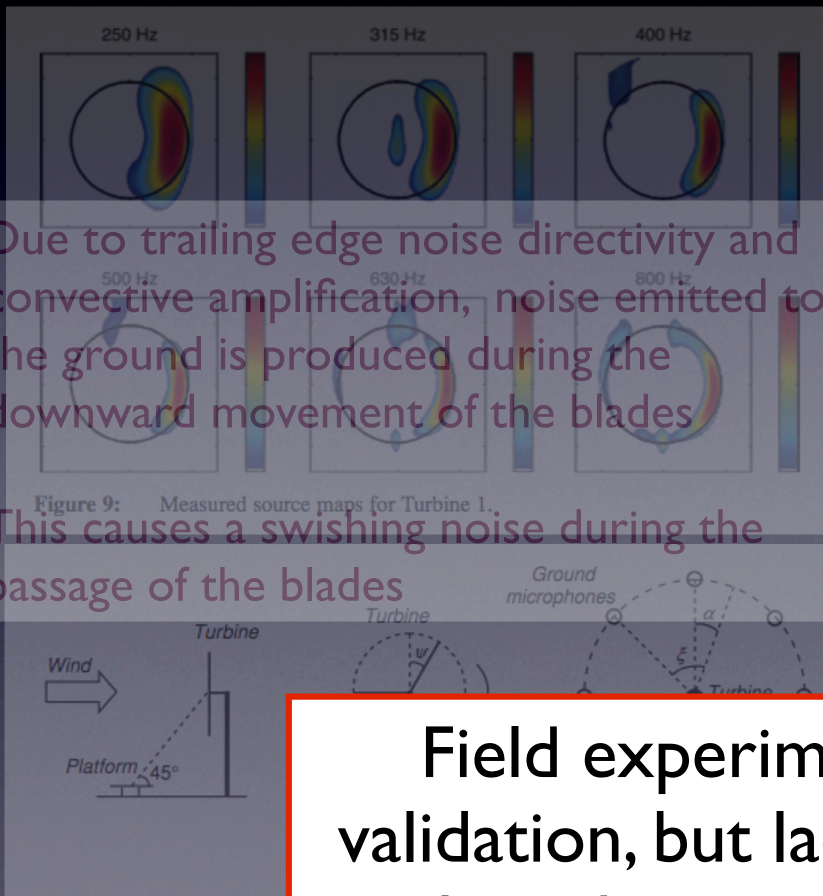

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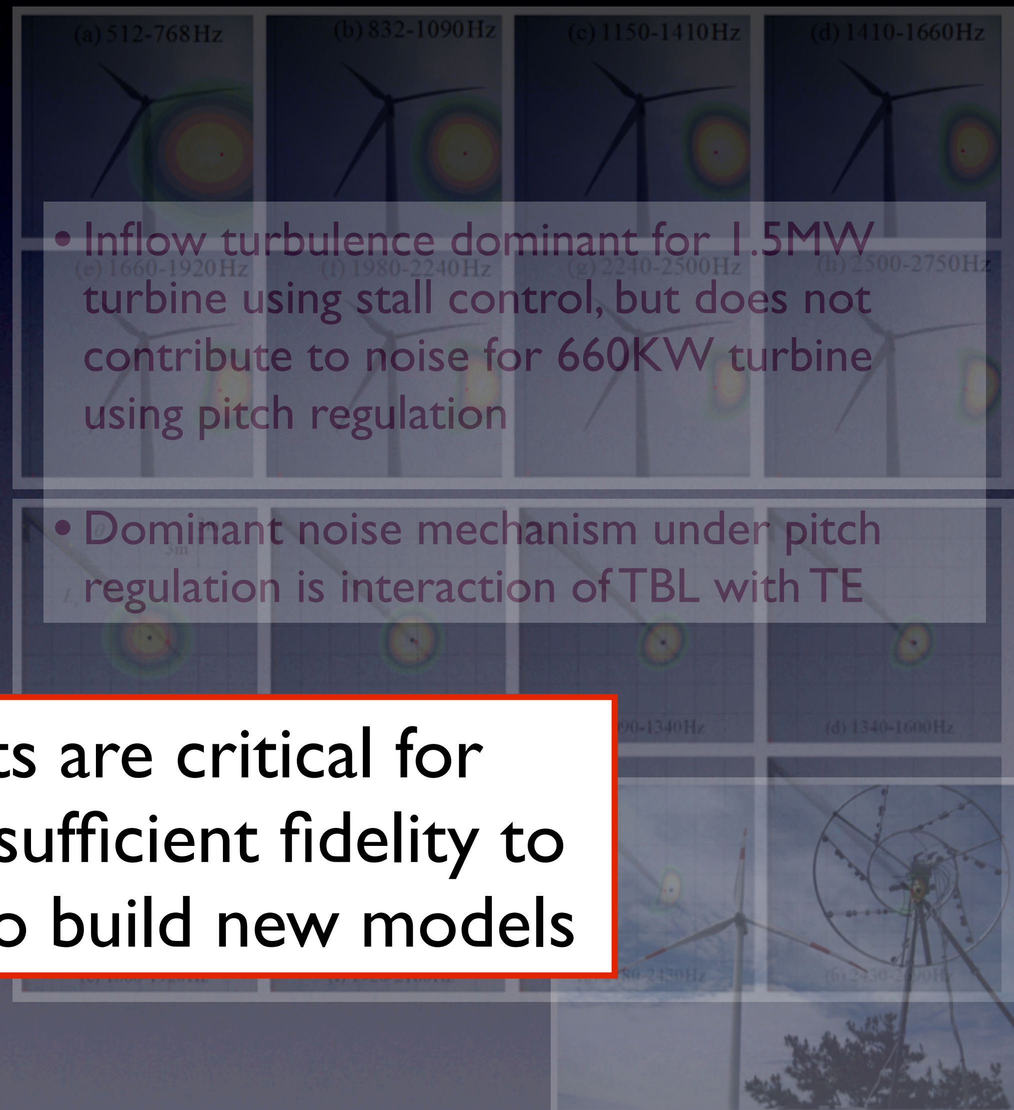
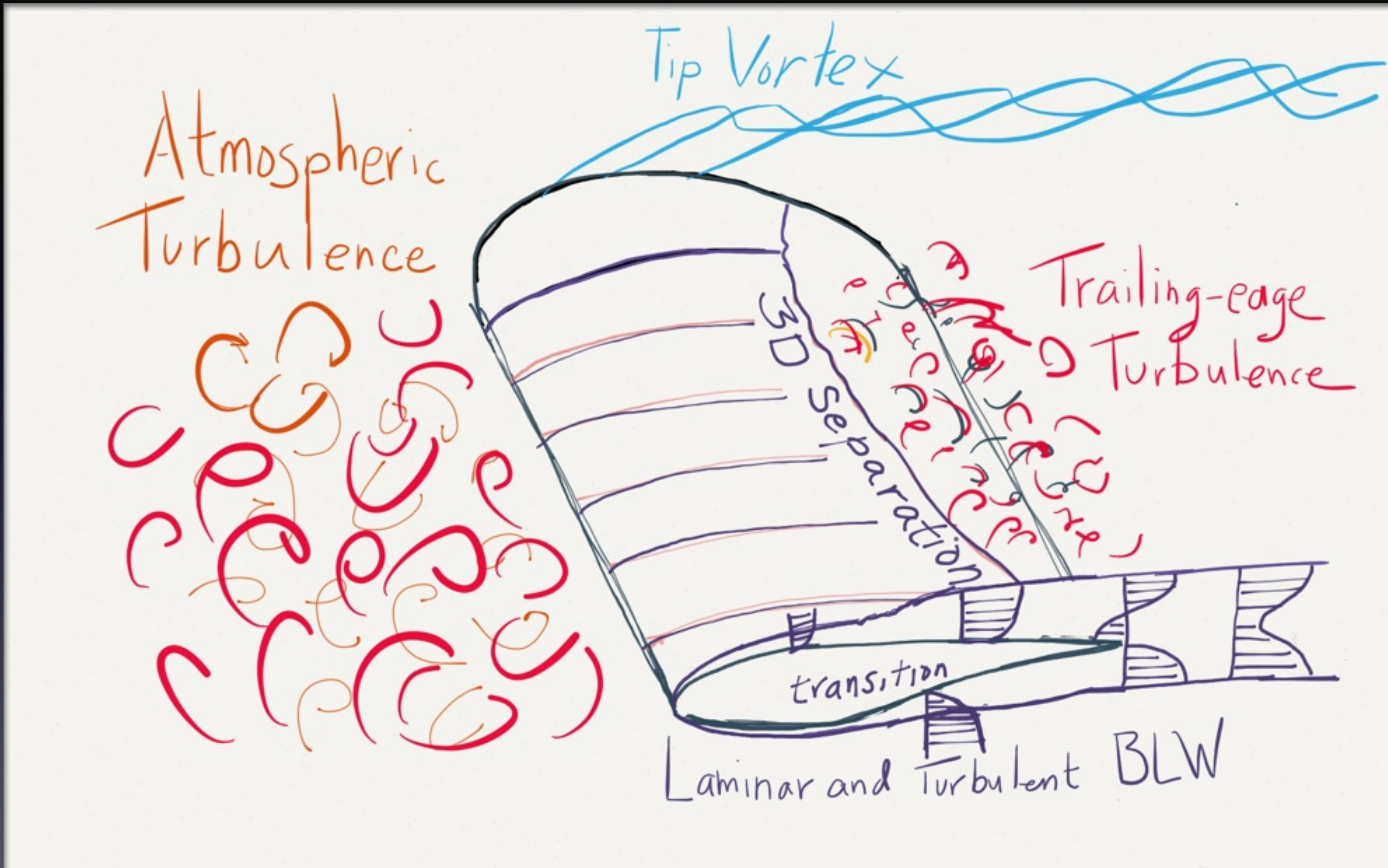


- Inflow turbulence dominant for 1.5MW turbine using stall control, but does not contribute to noise for 660KW turbine using pitch regulation
- Dominant noise mechanism under pitch regulation is interaction of TBL with TE

Field experiments are critical for validation, but lack sufficient fidelity to explain physics or to build new models



Fluid dynamics of wind turbine blades

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Aeroacoustic sources

1. Inflow-turbulence noise
   - Generation of unsteady lift
   - Interaction with both LE and TE
2. Airfoil self noise
   - Interaction between boundary layer and blade surface
     1. laminar BL vortex shedding
     2. TE vortex shedding
     3. tip-vortex noise
     4. flow separation
     5. <u>turbulent BL interaction with TE</u>
   - *How does inflow-turbulence affect self noise mechanisms?*

Engineering models

- Aerodynamic Performance: e.g., NREL's AeroDyn
  - BEM - Blade Element Momentum Theory
    - Based upon steady Lift and Drag data
    - Corrections for 3D and unsteady effects
  - Does not provide relevant data for acoustics

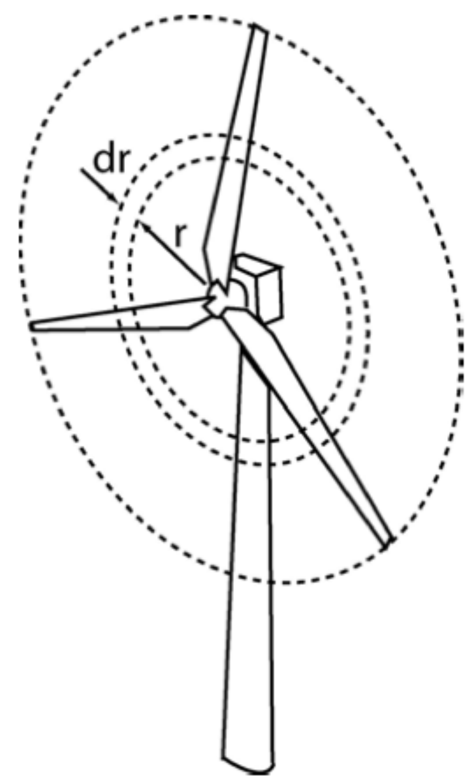

Figure 1. Annular plane used in blade element momentum theory

Engineering models

- Aeroacoustic models
  - NAFNoise (Moriarty et al. [ca. 2005])
    - Empirical models for
      - TBL-TE noise
      - Sep/Stall noise
      - LBL-VS noise
      - TEB-VS noise
      - turbulent inflow noise
    - XFOIL for boundary layer

Brooks et al. 1989 (TBL-TE, Sep/Stall, LBL-VS, TEB-VS noise)

Amiet, 1975 (turbulent inflow noise)

Engineering models

- Aeroacoustic models (cont.)
  - S. Oerleman (2009)
    - Broadband trailing edge noise only
    - Three steps: 1) strip-theory & RFOIL for aerodynamics, 2) TE noise source strength, 3) directivity and convective amplification
  - Glegg et al. (2010)
    - 2D RANS CFD for aerodynamics
    - TKE profiles used to estimate radiated TE noise
  - Tadamas and Zangeneh (2011)
    - 3D RANS CFD for aerodynamics
    - FW-H model for noise radiated to far field
  - S. Lee et al. (2013)
    - strip-theory & XFOIL for aerodynamics
    - Integral form of the FW-H model

Engineering models

- Aeroacoustic models (cont.)
  - S. Oerleman (2009)
    - Broadband trailing edge noise only
    - Three steps: 1) strip-theory & RFOIL for aerodynamics, 2) TE noise source strength, 3) directivity and convective amplification
  - G

- Lack of consensus on best approach
- Limited use of fidelity CFD and CAA
- Lack of ABL turbulence
- Lack of 3D, rotational, and unsteady effects

  - Ta
    - 3D RANS CFD for aerodynamics
    - FW-H model for noise radiated to far field
  - S. Lee et al. (2013)
    - strip-theory & XFOIL for aerodynamics
    - Integral form of the FW-H model

Methods

- Virginia Tech Stability Wind Tunnel
  - Largest university owned anechoic tunnel in the US
  - Largest *effective* test section size of any anechoic wind tunnel in US.
  - Unique worldwide testing capability for wind energy. It is the only facility where aeroacoustic testing of wind turbine blades can be performed at *full-scale conditions*
- CFD and the PSU Cyber Wind Facility
  - Ingestion of ABL turbulence key driver for unsteady loads and bearing/ gearbox failure
  - Fidelity simulation tool for coupled aero-hydro-structure beyond current state-of-the-art
  - Cyber facility needed for: experiment design, test-bed, turbine design, controls concepts and testing

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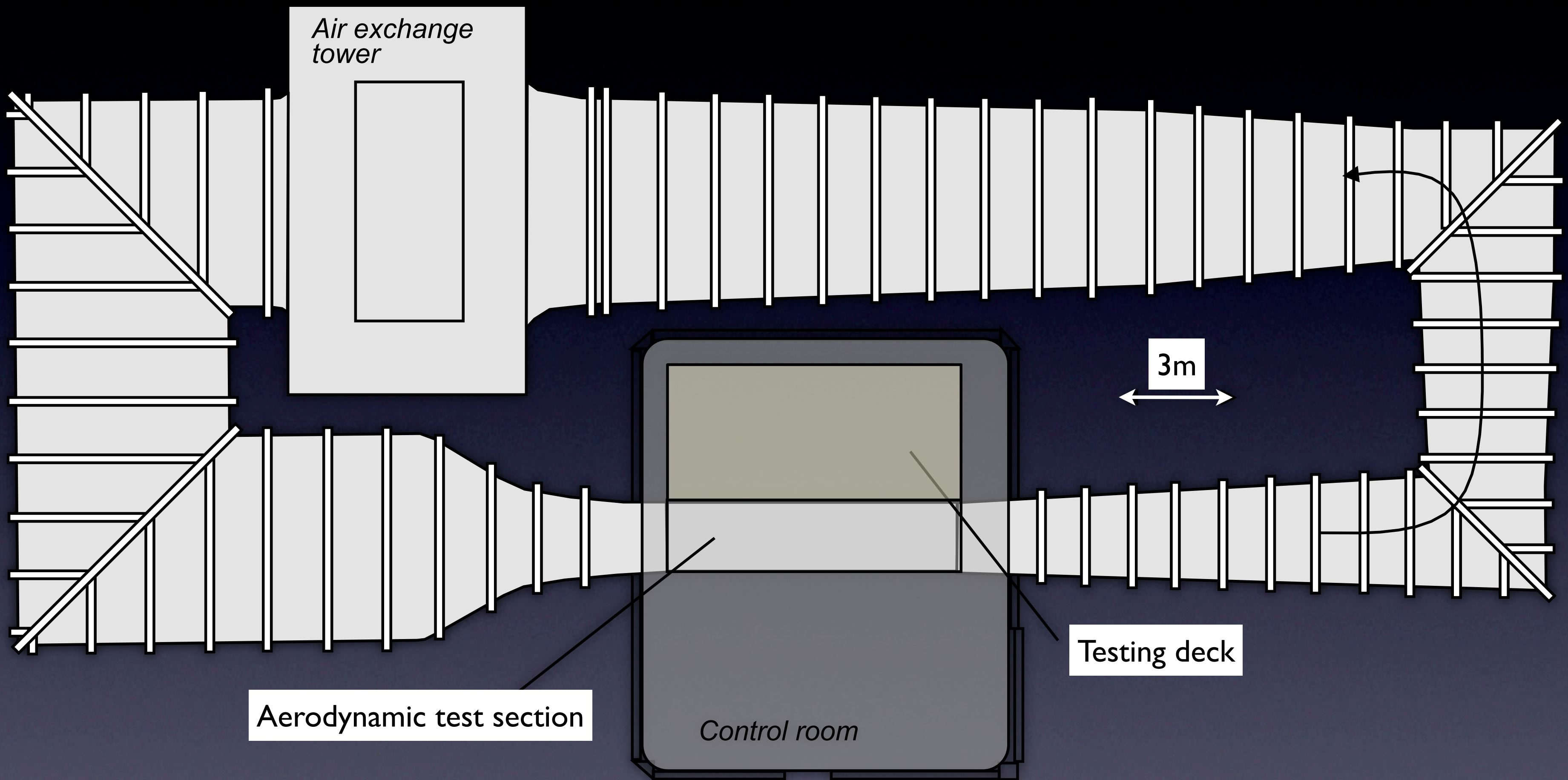
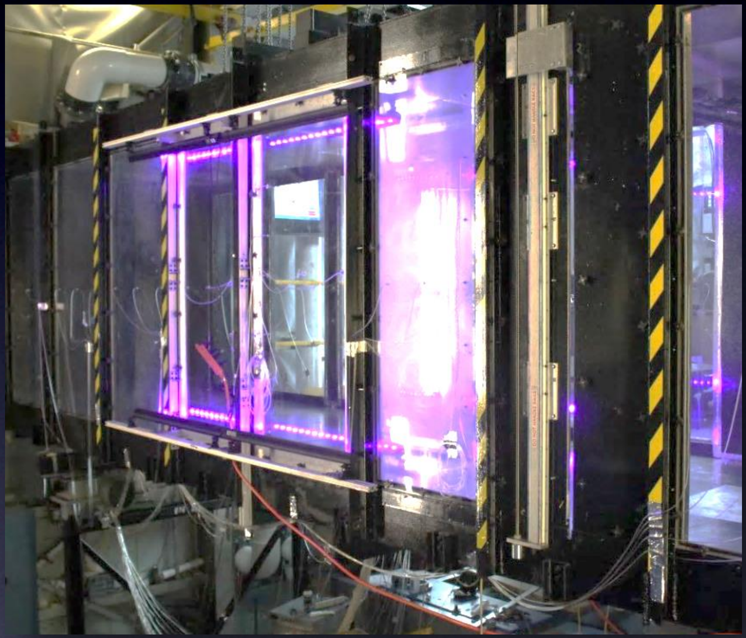
Stability Wind Tunnel

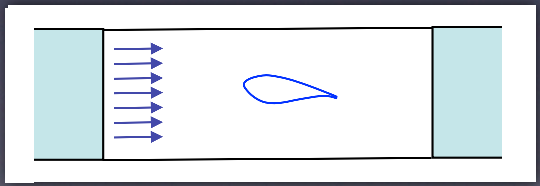


- Built 1940 at Langley, to VT in 1958
- Closed circuit, 6'x6'x24' test section
- Serves research, education, outreach

- 15' dia., 600 h.p.
- Flow speeds to 80+m/s
- Extremely low turb. level (0.01-0.03%)
- Cost center

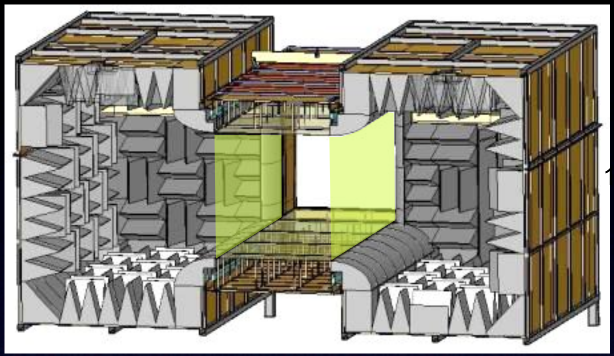
Hardwall Test Section

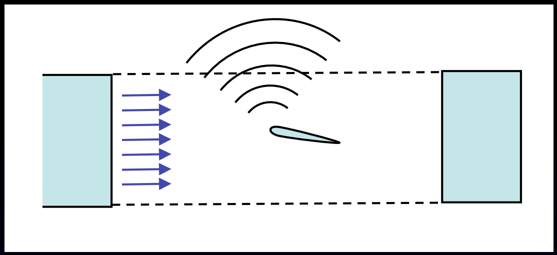




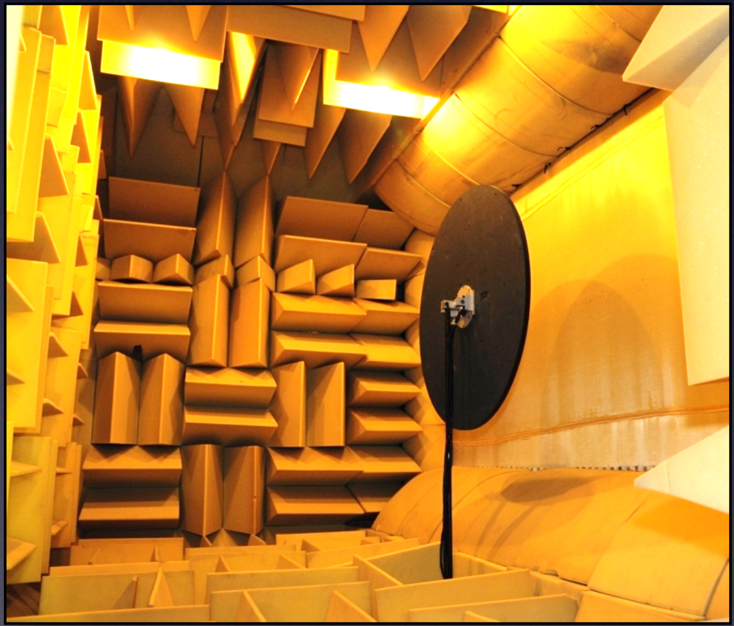
- Closed circuit
- 6’ x 6’ x 24’ test section
- Extremely low turbulence level (0.01-0.03%)

Novel Hybrid Test Section





Tensioned Kevlar sidewalls separate test flow from anechoic chambers



- Interchangeable with aerodynamic test section
- Acoustically open, aerodynamically closed, combines the good aerodynamics of hardwall test sections, and the good acoustics of open jet test sections…
- … much larger models, no jet catcher, longer test section to separate model noise from background.

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Wind Energy Applications

Recent Projects

- Blade acoustics and aerodynamics
- Trailing-edge treatments to control noise
- Lift-management devices
- Thin, thick, and highly loaded airfoils
- Blunt trailing edges
- Tripping, bug patterns
- 360 degree behavior

Data acquisition and processing

- Microphone phased array systems (AVEC)
- Wake scanning
- Airfoil surface pressure scanning (~500 channels)
- Wall pressure lift sensing
- Computerized visualization systems
- Computerized turntable systems
- Flow control system
- Expanded machining, model design capability
- Infrared thermography for transition detection
- Doppler global for airfoil boundary layer measurement

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Example of Noise Measurements

- Phased array measurements of a 2-foot chord NACA0015 airfoil were made at various speeds and angles of attack.
- A 60-inch diameter phased array comprising 63 microphones was used.
- Airfoil self noise due to the turbulent boundary layer-trailing edge interaction was identified.
- Using a turbulence grid upstream of the model, noise due to the interaction between the incoming turbulence and the leading edge of the airfoil was also observed.

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Airfoil Noise: Experimental Setup

Devenport et al. (2010)

Anechoic Chamber

Test Section

Phased Array

Kevlar Wall Between Anechoic Chamber and Test Section

NACA0015 Airfoil

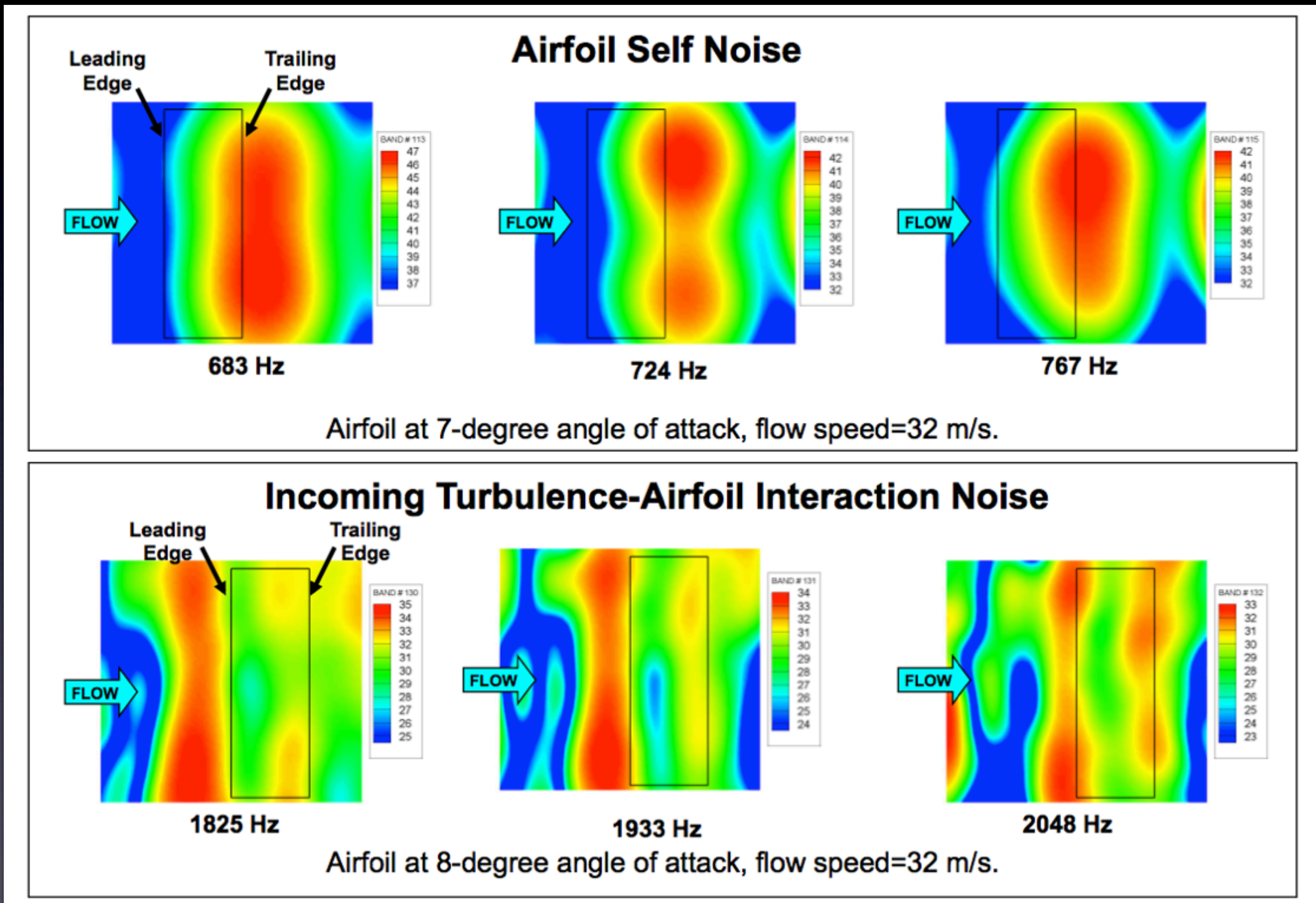
Turbulence Grid

integral scale is 3.2 inches

turbulence intensity 3.9%

Airfoil Noise: Preliminary Results

Burdisso et al. (2013)



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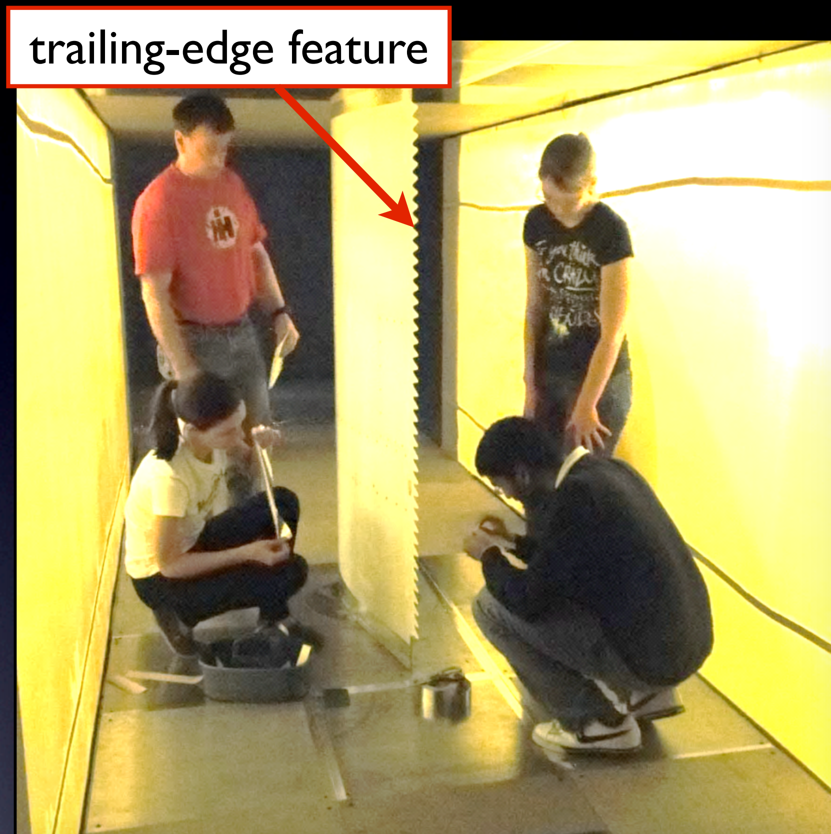
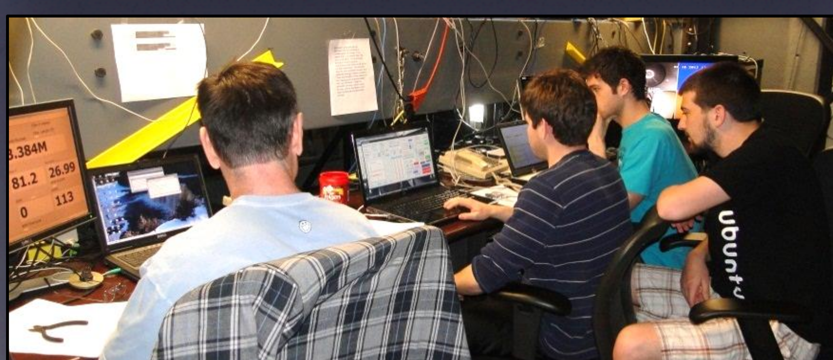
Teaching

(~400 AOE/ME/ESM students per year use tunnel)





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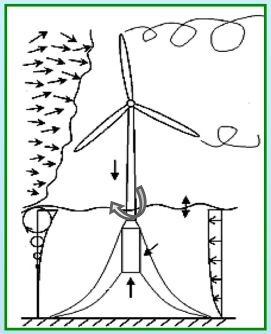
CWF for Offshore Wind Energy



MESOSCALE, WEATHER
(URANS/WRF)

ATMOSPHERIC BOUNDARY LAYER TURBULENT WINDS
(4-D LES)

WAKE TURBULENCE BLADE-WAKE-ATMOSPHERE
(Actuator Vortex Body Embedding within LES)

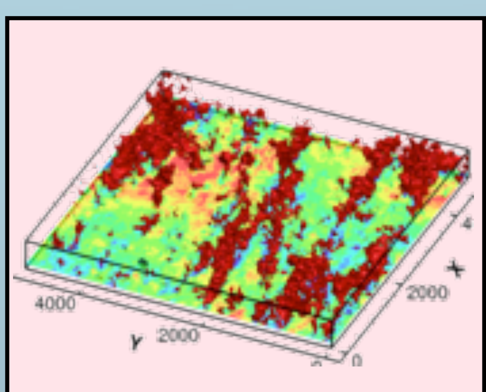
PLATFORM-WAVE HYDRODYNAMICS and 6-DOF MOTIONS
(Hybrid URANS/LES +VOF)

***BLADE AERODYNAMICS, SPACE-TIME LOADINGS**
(Hybrid URANS/LES)

WAKE-TURBINE INTERACTIONS
(wind plant)

BLADE AND *TOWER ELASTIC DEFORMATION
(FEM, Modal model + FSI)

*Shaft Torque, *Drivetrain Loadings



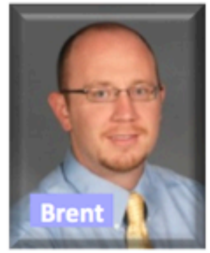
CYBER WIND FACILITY

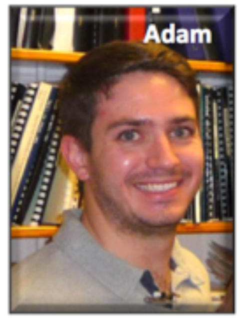
- highly resolved 4-D cyber data
- coupled atmospheric turbulence-blade loadings-shaft torque data
- coupled wave structure – platform motion – turbine loadings data
- experiment design, test-bed, turbine design, controls concepts and testing
- advanced correlations for ALM and other design tools using look-up tables

*sensors, controllers, diagnostics

The PSU Cyber Wind Facility Team

PIs: Jim Brasseur, Eric Paterson, Sven Schmitz, Rob Campbell, Sue Haupt (NCAR)





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PhD student, Mechanical Engineering

Alex Dunbar, ARL/PSU Fellowship
PhD student, Mechanical Engineering

Javier Motta-Mena, DOE
PhD student, Mechanical Engineering

Ganesh Vijayakumar, NSF
PhD student, Mechanical Engineering

Adam W. Lavely, ARL/PSU Fellowship
PhD student, Aerospace Engineering

Pankaj K. Jha, DOE
Graduate Student, Aerospace Engineering

Amir Mehdizadeh
Postdoctoral Fellow,
German Research FoundatioDn

Di Zhang, VT-ARC GRA
PhD student, VT Aerospace Engineering

Industry Partner: GE GR

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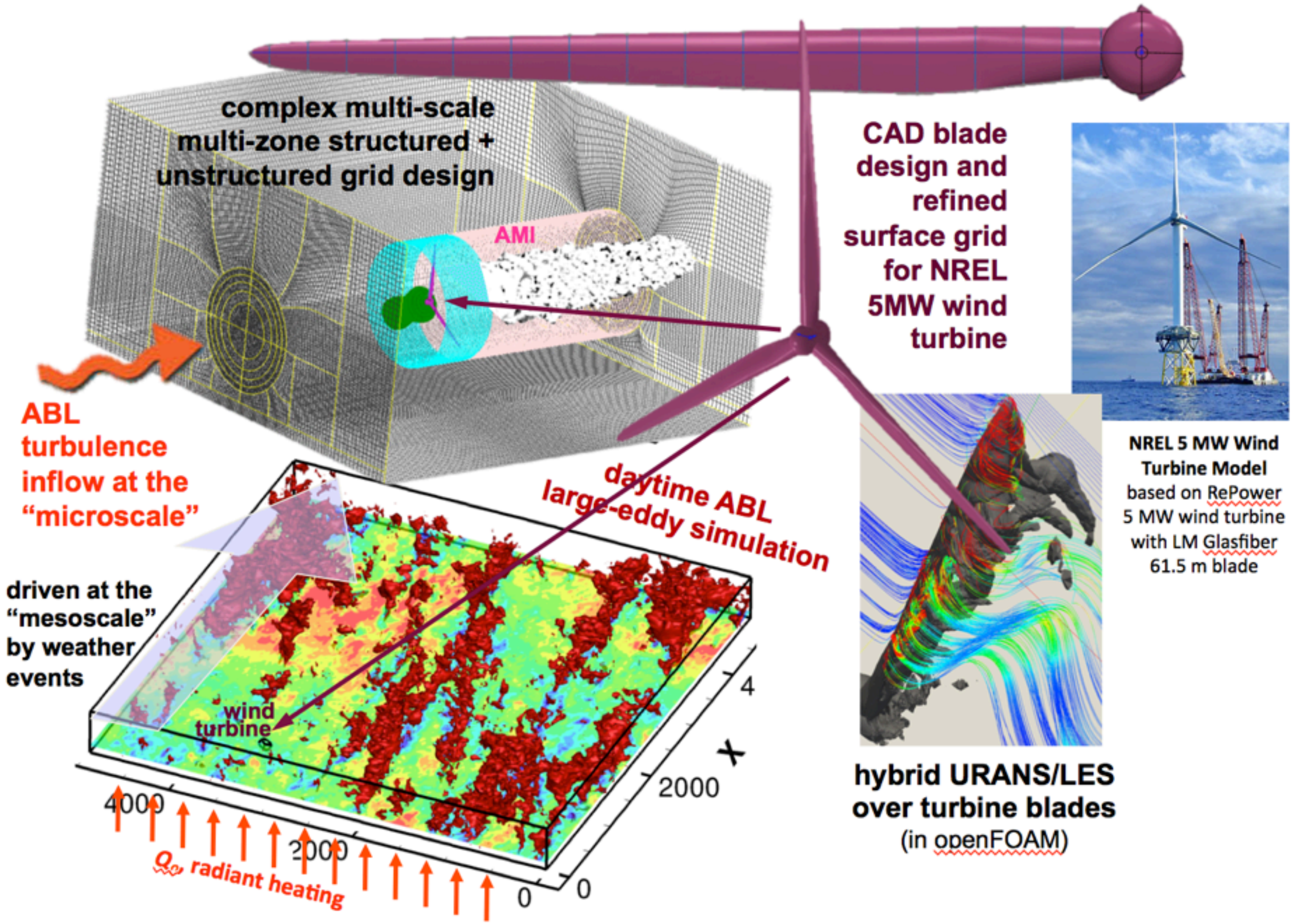
The Current Cyber Wind Facility (CWF 1.0)



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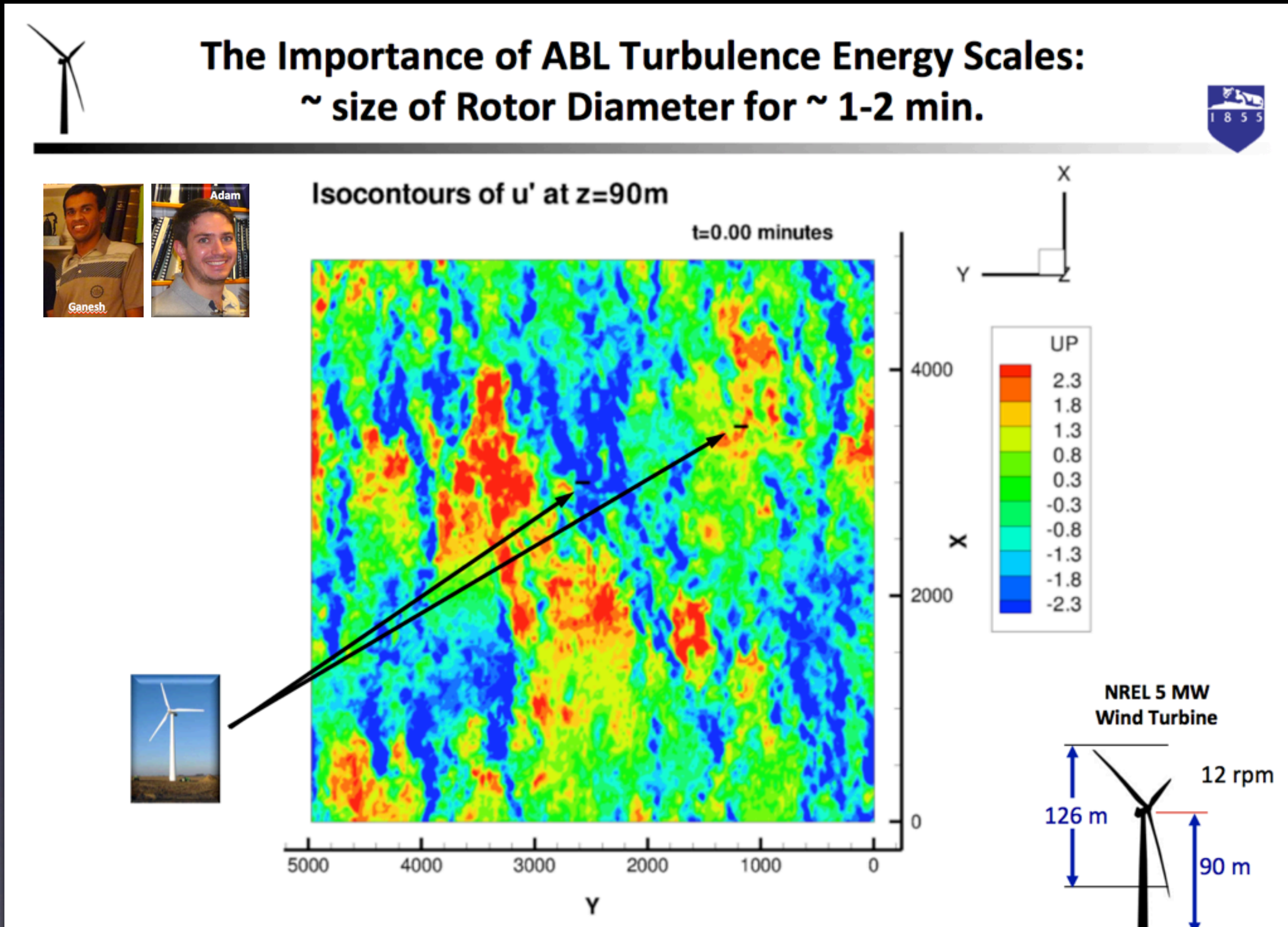
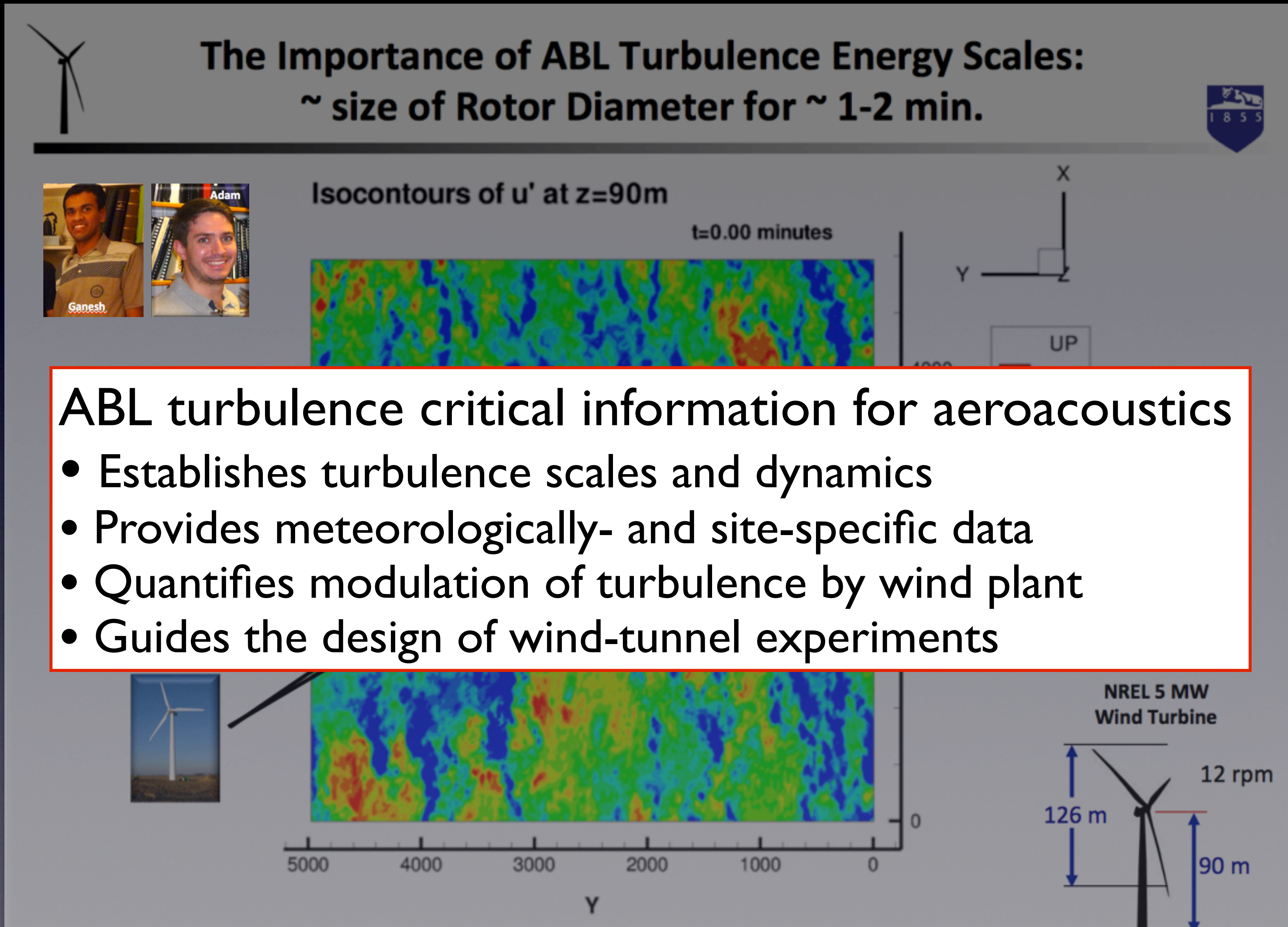
ABL LES



ABL LES

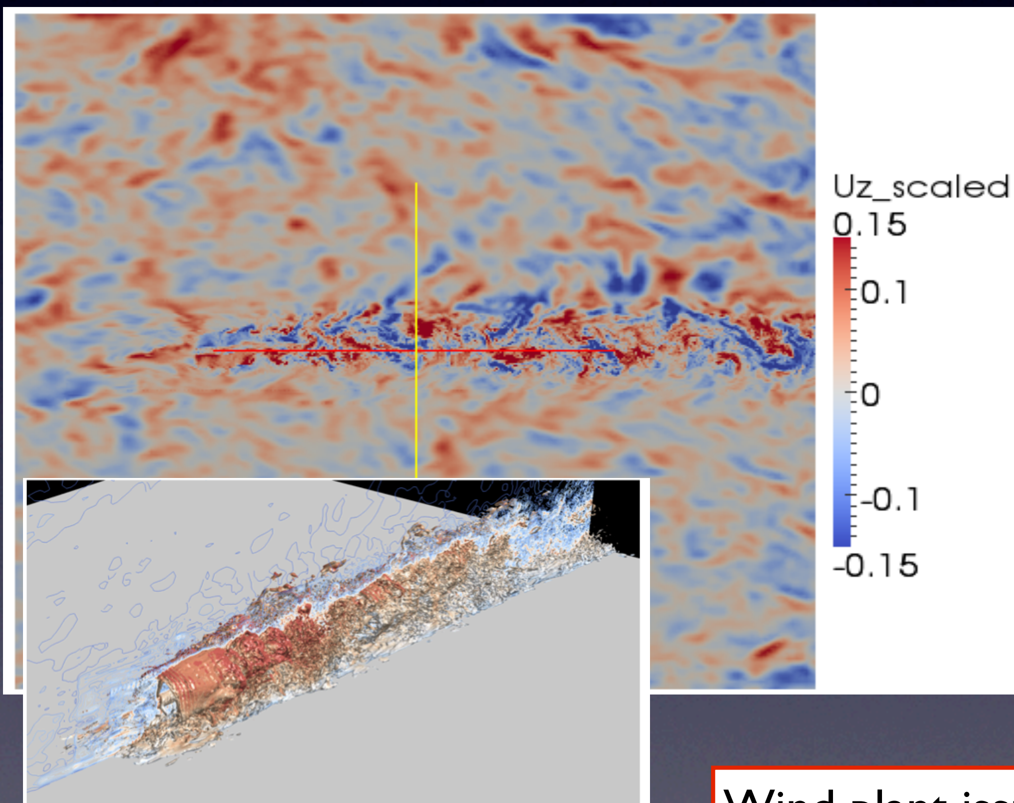


ABL turbulence critical information for aeroacoustics

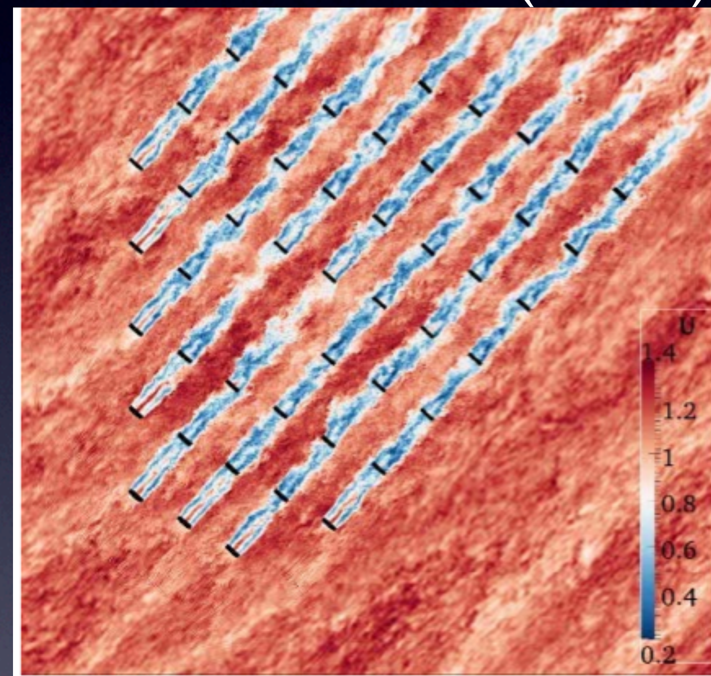
- Establishes turbulence scales and dynamics
- Provides meteorologically- and site-specific data
- Quantifies modulation of turbulence by wind plant
- Guides the design of wind-tunnel experiments

Turbine-turbine interaction

Wind Turbine Wake Modeling using LES and Actuator-Line Method



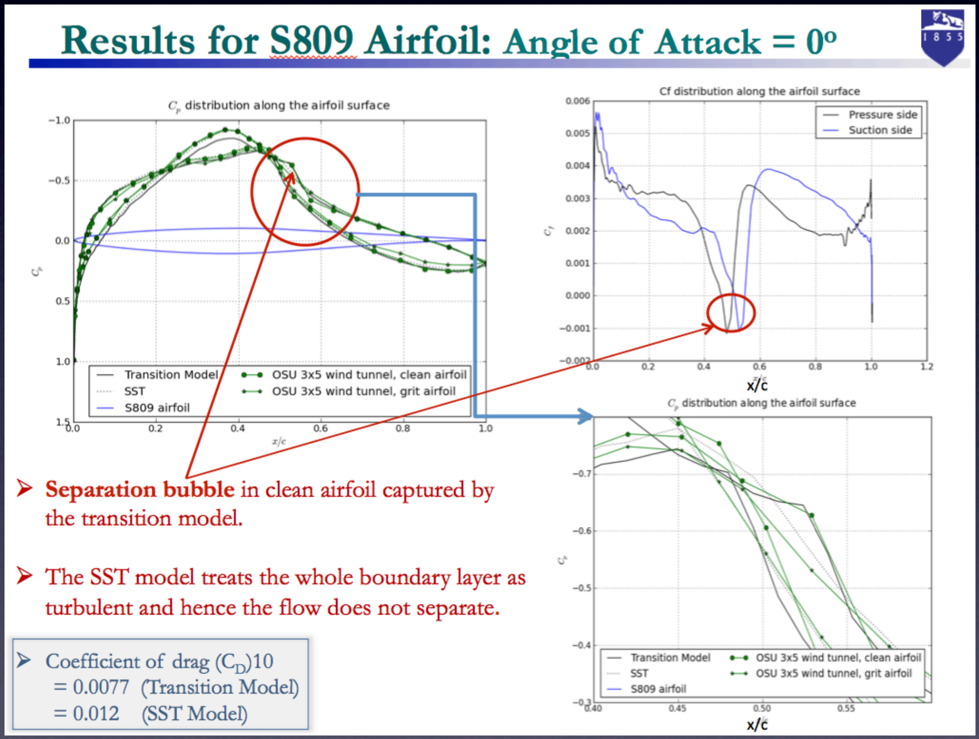
M. Churchfield (NREL)



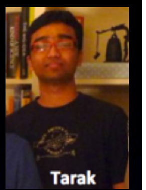
<u>Wind plant issues</u>: change in turbulence will impact inflow noise and noise propagation.

Transition & BL modeling

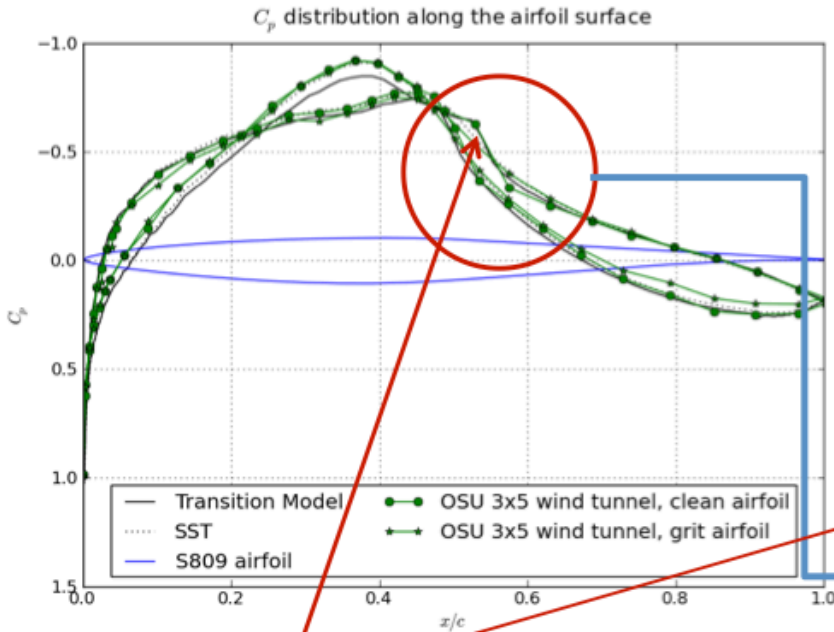
- Open-source interpretation of the Langtry-Menter model (Langtry 2009)
- Model capable of predicting natural, bypass, and separation-induced transition
- Amenable to integration with DES or SAS hybrid models
- Currently studying effects of transient change in AOA on transition

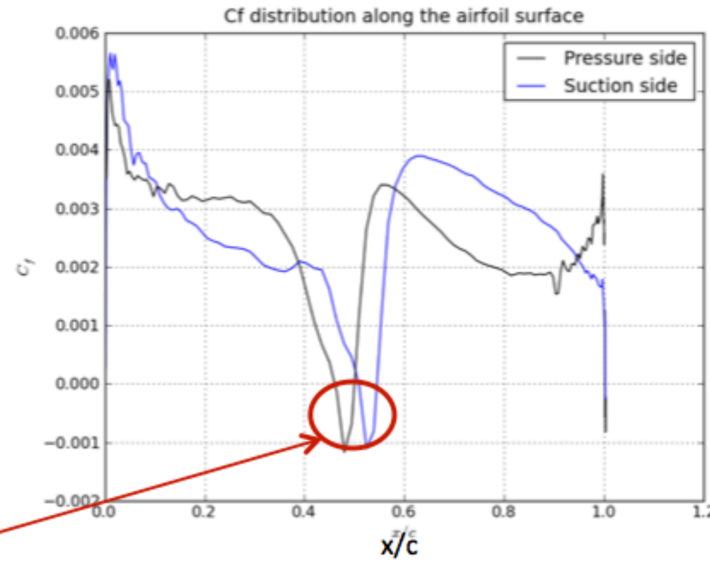


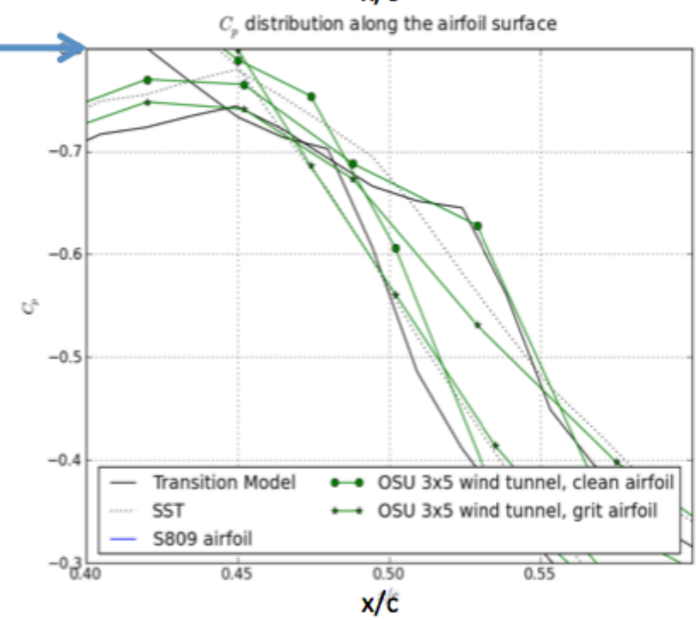
Transition & BL modeling



Results for S809 Airfoil: Angle of Attack = 0°







- **Separation bubble** in clean airfoil captured by the transition model.
- The SST model treats the whole boundary layer as turbulent and hence the flow does not separate.

- Coefficient of drag (C_D)10
  = 0.0077 (Transition Model)
  = 0.012 (SST Model)

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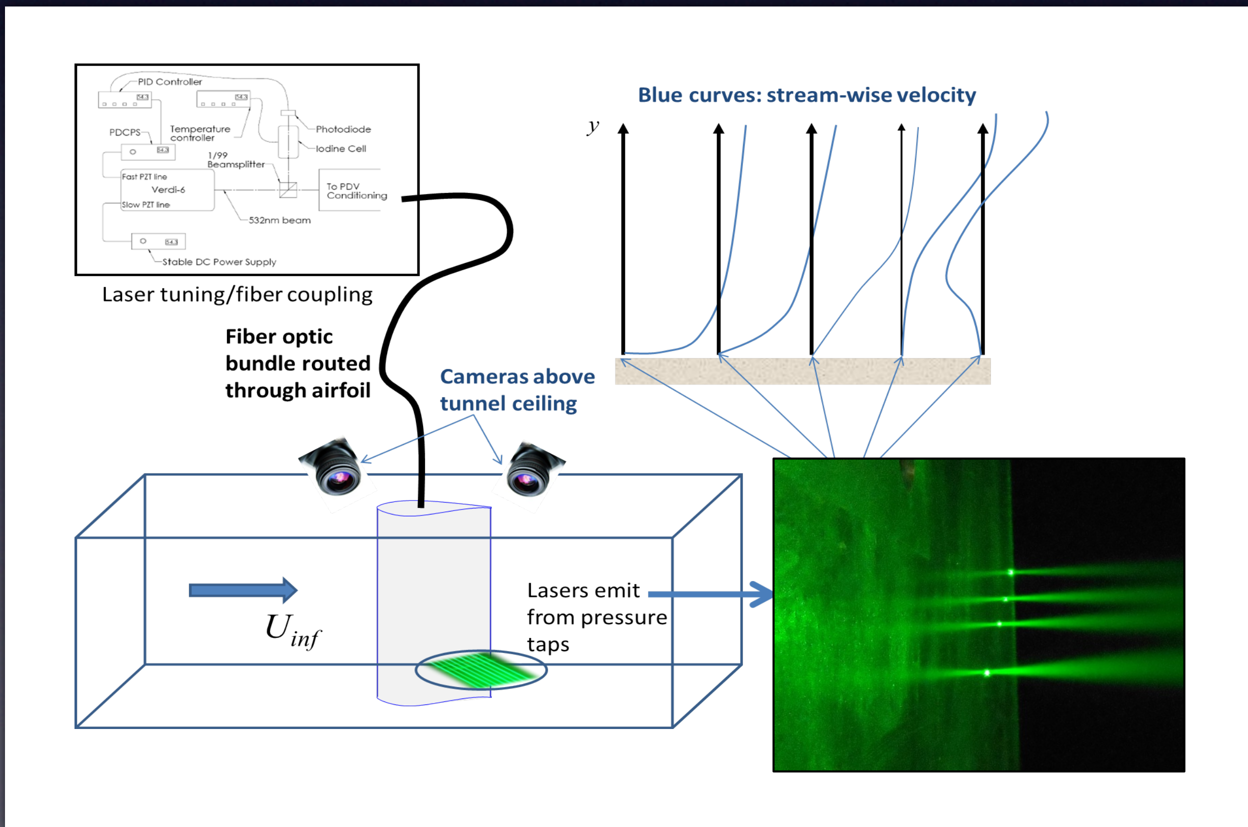
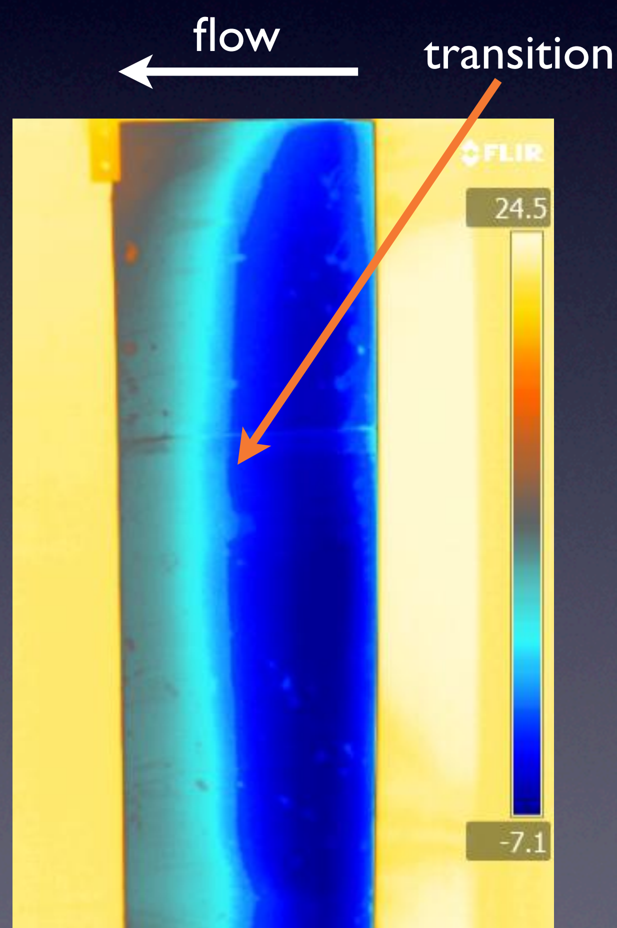
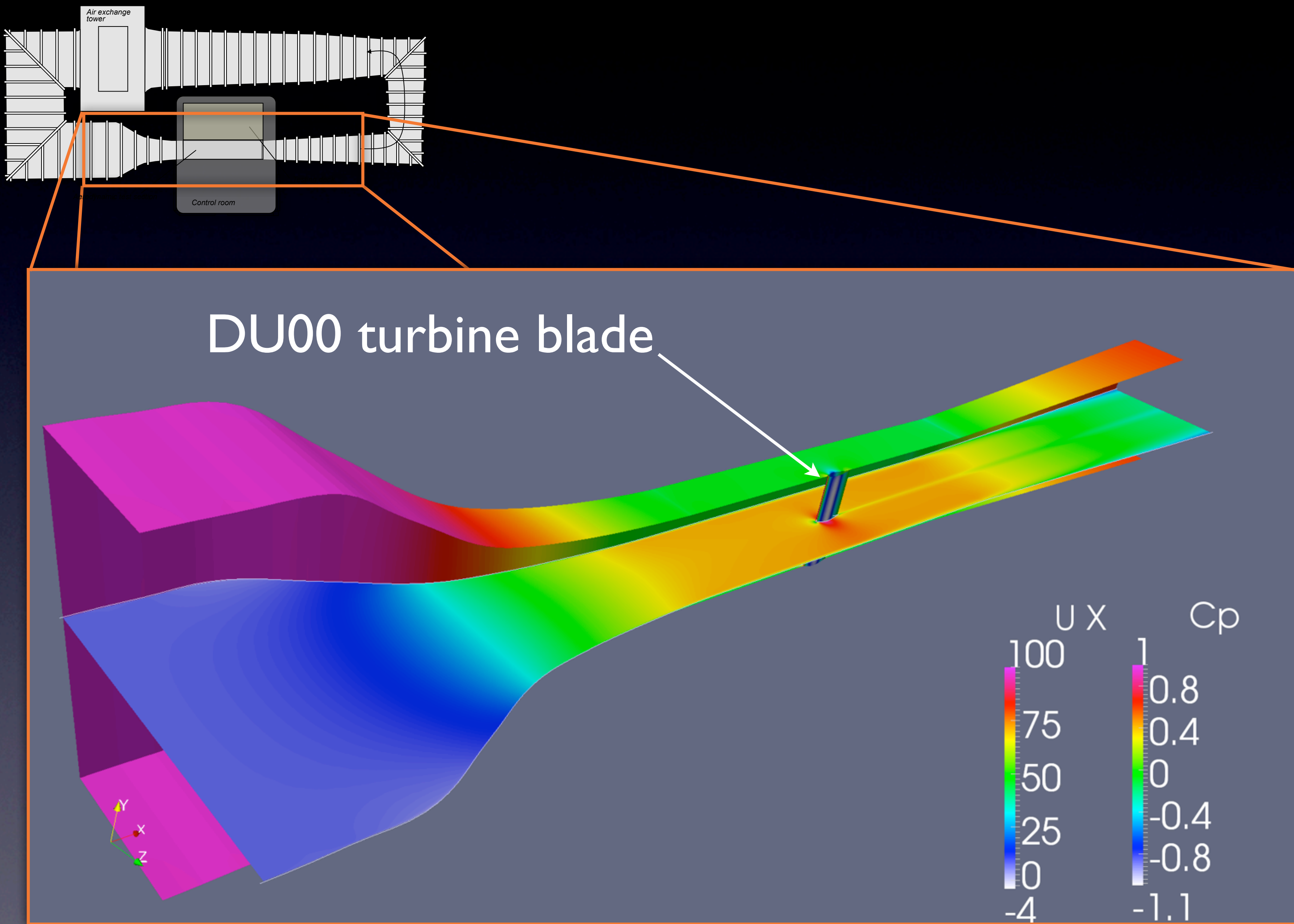
Transition & BL experiments

- Laser-based DGV measures profile normal to the surface. IR camera detects thermal gradients associated with transition to turbulent flow.
- Development in 2013

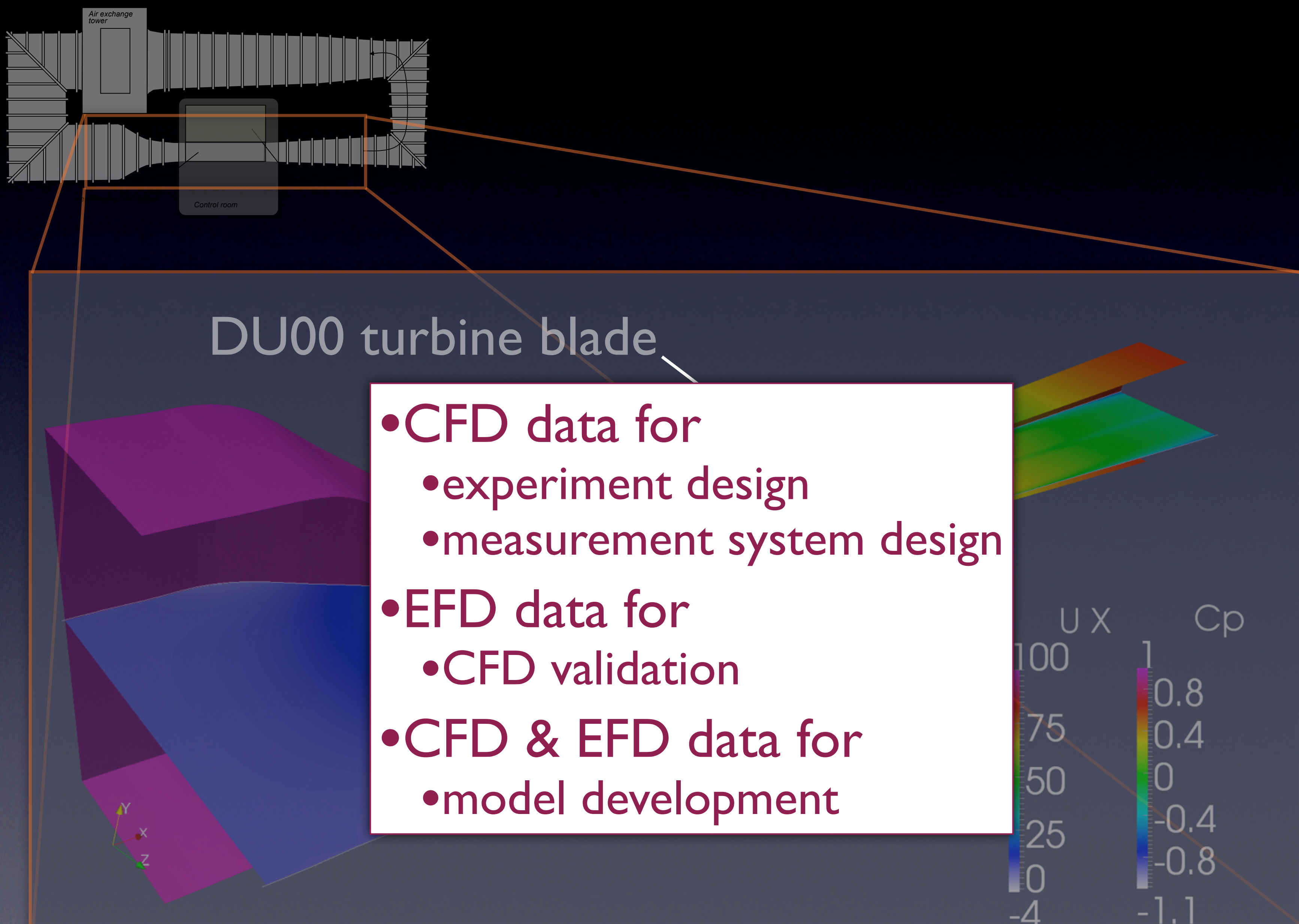




Complimentary CFD & EFD



Complimentary CFD & EFD



- CFD data for
  - experiment design
  - measurement system design
- EFD data for
  - CFD validation
- CFD & EFD data for
  - model development

Conclusions

- Aerodynamic performance and aeroacoustics are tightly coupled
- State-of-the-art CFD and CAA should be brought to bear on wind-turbine aeroacoustics
  - Improved designs, flow-control/noise-abatement devices, and multi-objective control algorithms
- Complementary laboratory experiments and fidelity CFD required to advance technology

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CREATe to be
on 6th Floor

McBryde Hall, home to the new VT Center for Renewable Energy and Aerodynamic Testing (CREATE)

CREATe

Virginia Tech Center for Renewable Energy and Aerodynamic Testing

VirginiaTech
Invent the Future

References

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[2] T. F. Brooks, D. S. Pope, and M. A. Marcolini. Airfoil self-noise and prediction, volume 1218. National Aeronautics and Space Administration, Office of Management, Scientific and Technical Information Division, 1989.

[3] R. Burdisso, H. Carmago, W. Devenport, Private Communication, 2013.

[4] W. J. Devenport, J. K. Staubs, and S. A. Glegg. Sound radiation from real airfoils in turbulence. *Journal of Sound and Vibration*, 329(17):3470–3483, 2010.

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