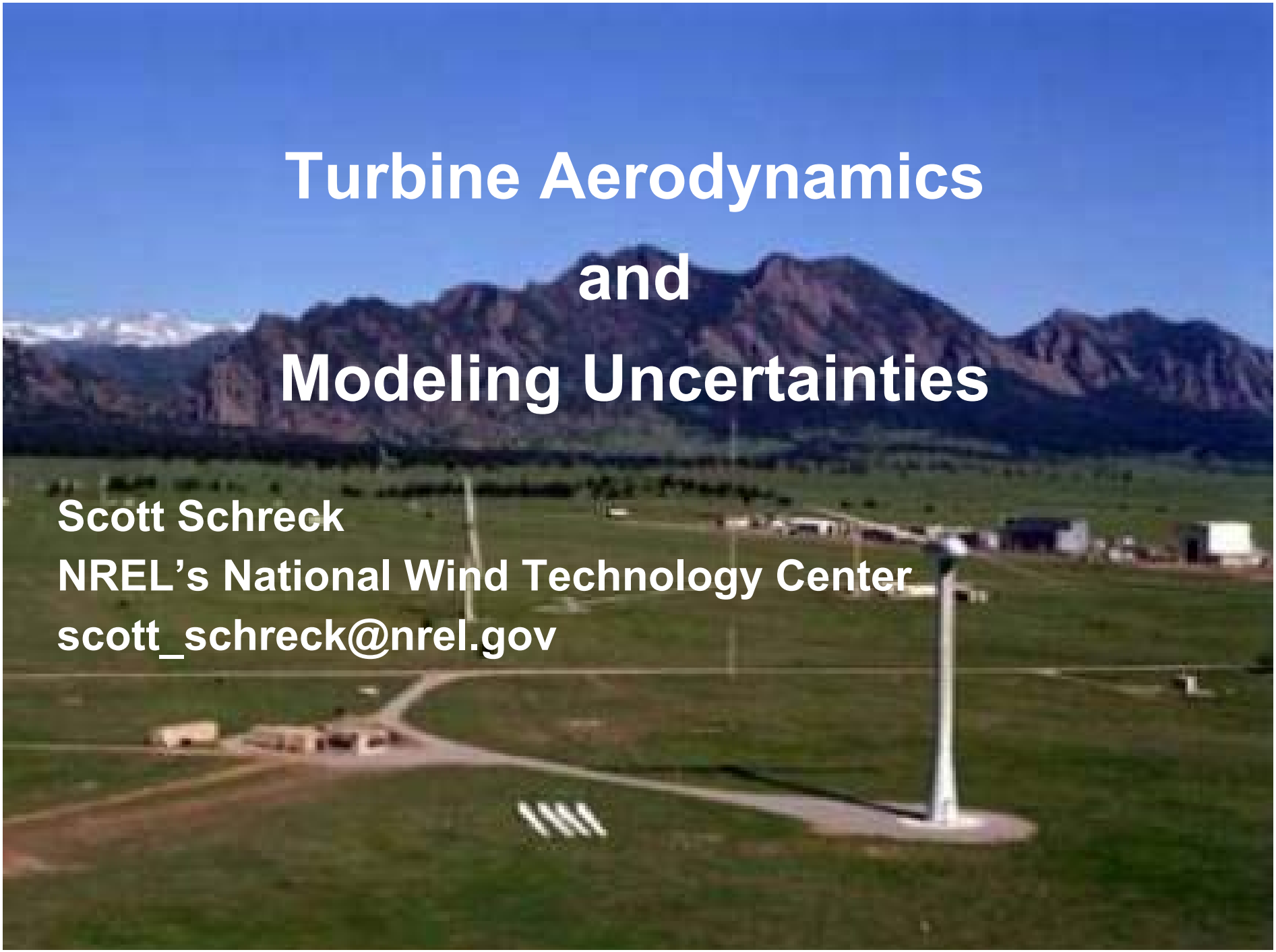

Turbine Aerodynamics and Modeling Uncertainties

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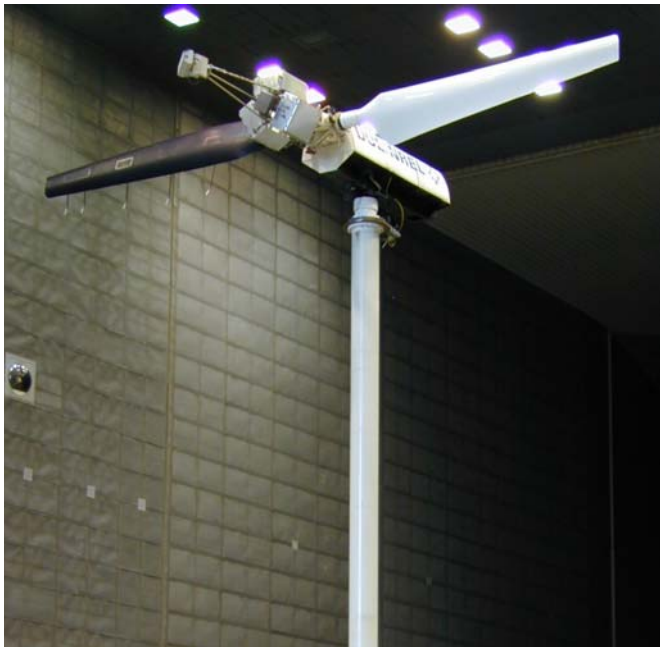
Aerodynamic Design Uncertainties

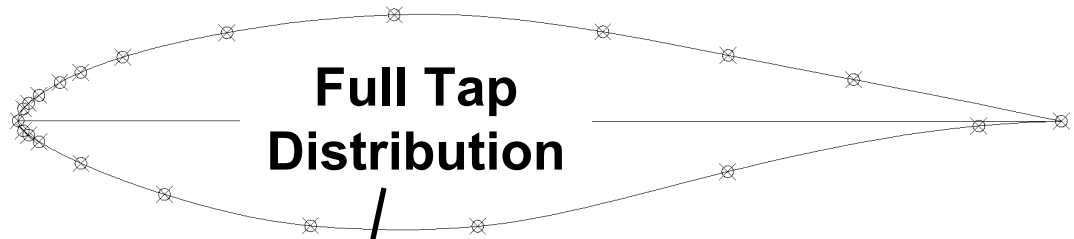
- Present modeling practice
  - Semi-empirical modeling
  - Safety factors, knockdowns
  - Incremental design changes
- Potential future capability
  - Physics based models
  - Reduced uncertainties
  - Innovation accelerated
- Physical understanding

Aerodynamics Measurements

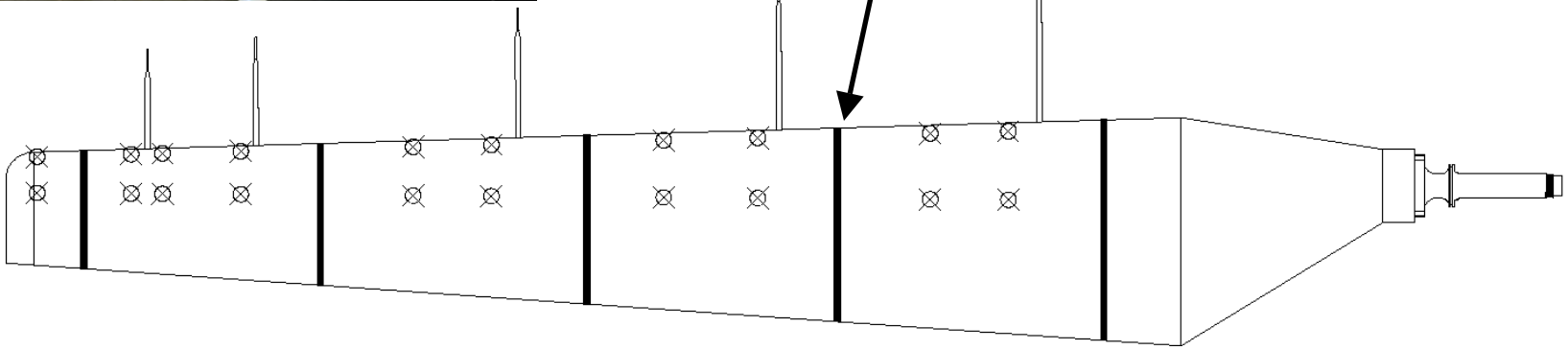
- Field experiments
  - Europe and U.S.
  - IEA Annexes 14, 18
  - High quality data
  - Inflow uncertainties
- Wind tunnel testing
  - NREL/NASA, MEXICO
  - Inflow control
  - Dynamic similarity
  - Detailed aero data

Wind Tunnel Test Turbine (UAE)





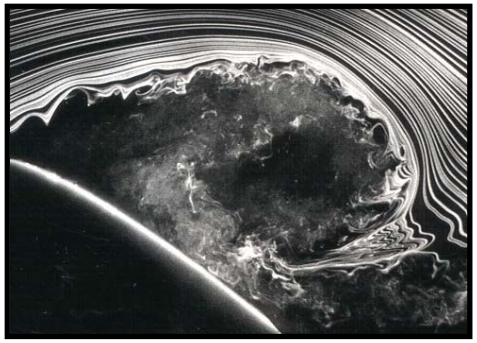
Full Tap Distribution



Blind Code Comparison

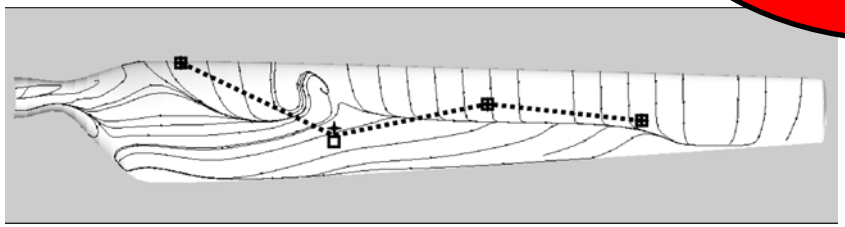
- Participants
  - Europe and United States
  - Industry, government labs, universities
- Procedure
  - Machine dimensions, masses given
  - Measured modal properties provided
  - Aero, structural response data withheld
  - Best engineering practice
- Assess code accuracy and reliability
  - Significant deviations from measurements

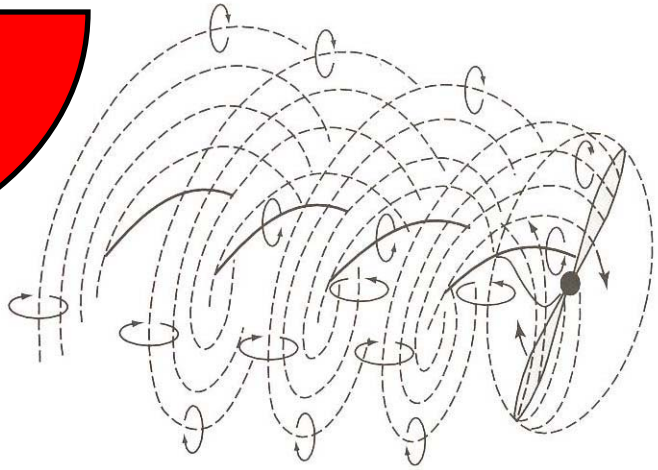
Coupled Flow Field



Blade
- Rotational effects
- Dynamic stall

Wake
- Trailed vorticity
- Shed vorticity

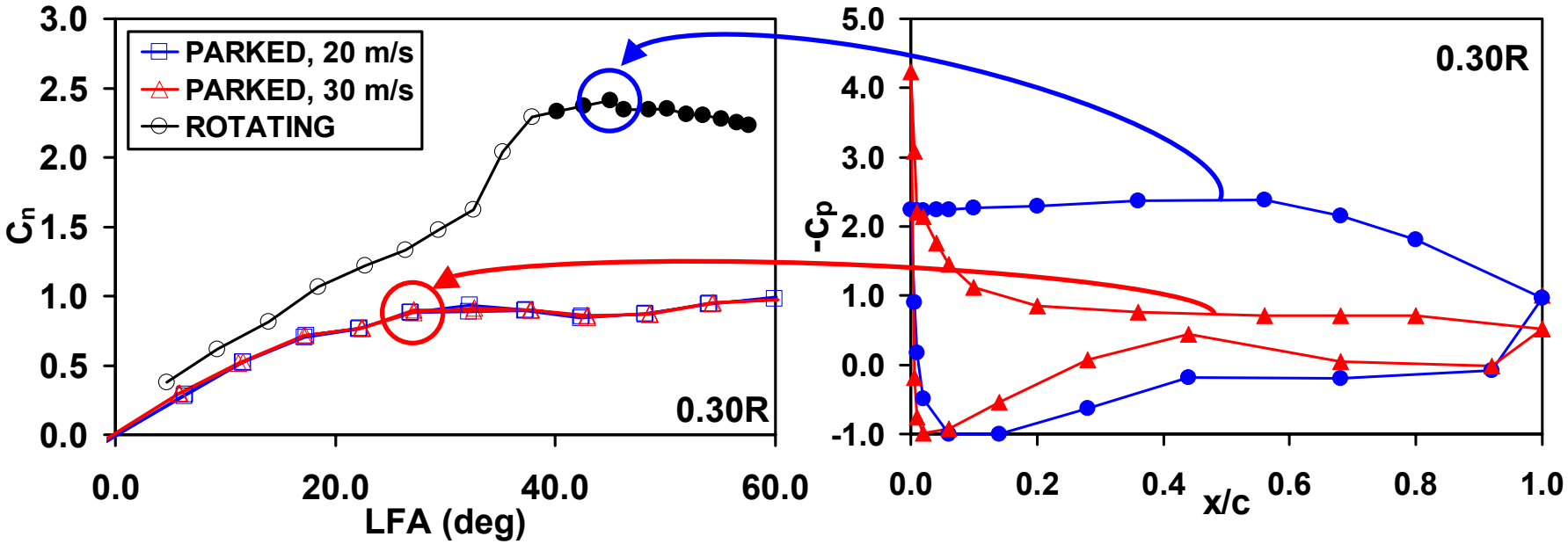




Rotational Augmentation

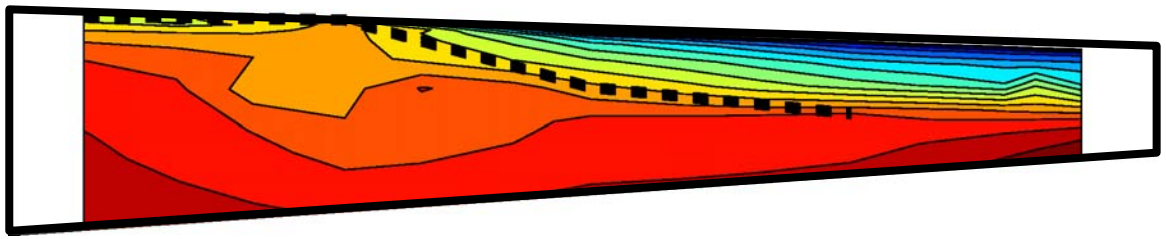
Axisymmetric Operation

Rotation Delays and Modifies Stall

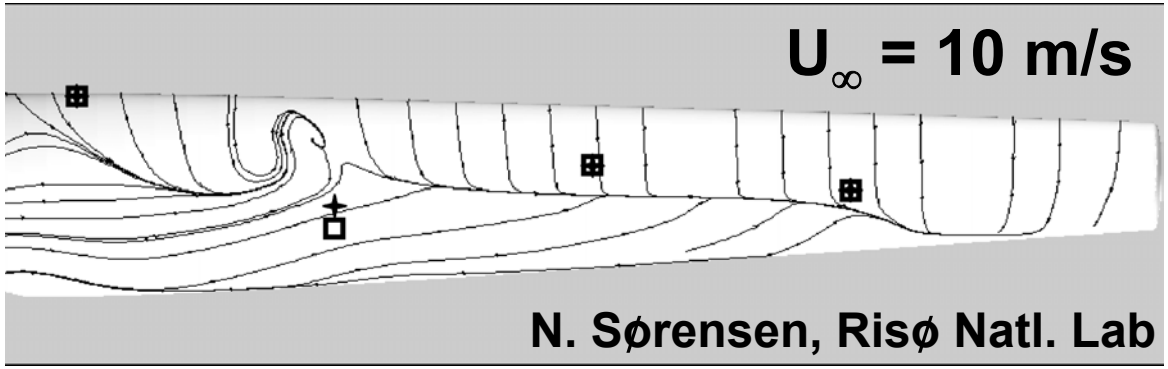


- Rotating vs. parked
  - C_n amplified
  - c_p augmented
- Aerodynamics
  - Little hysteresis
  - Re independent
  - Sweep effect minor

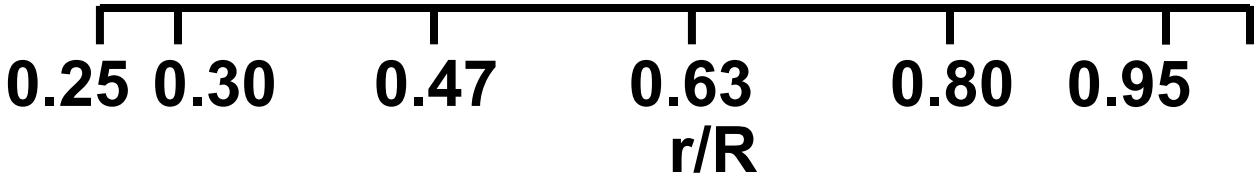
Separated, 3-D Flow Field



Measured surface pressure



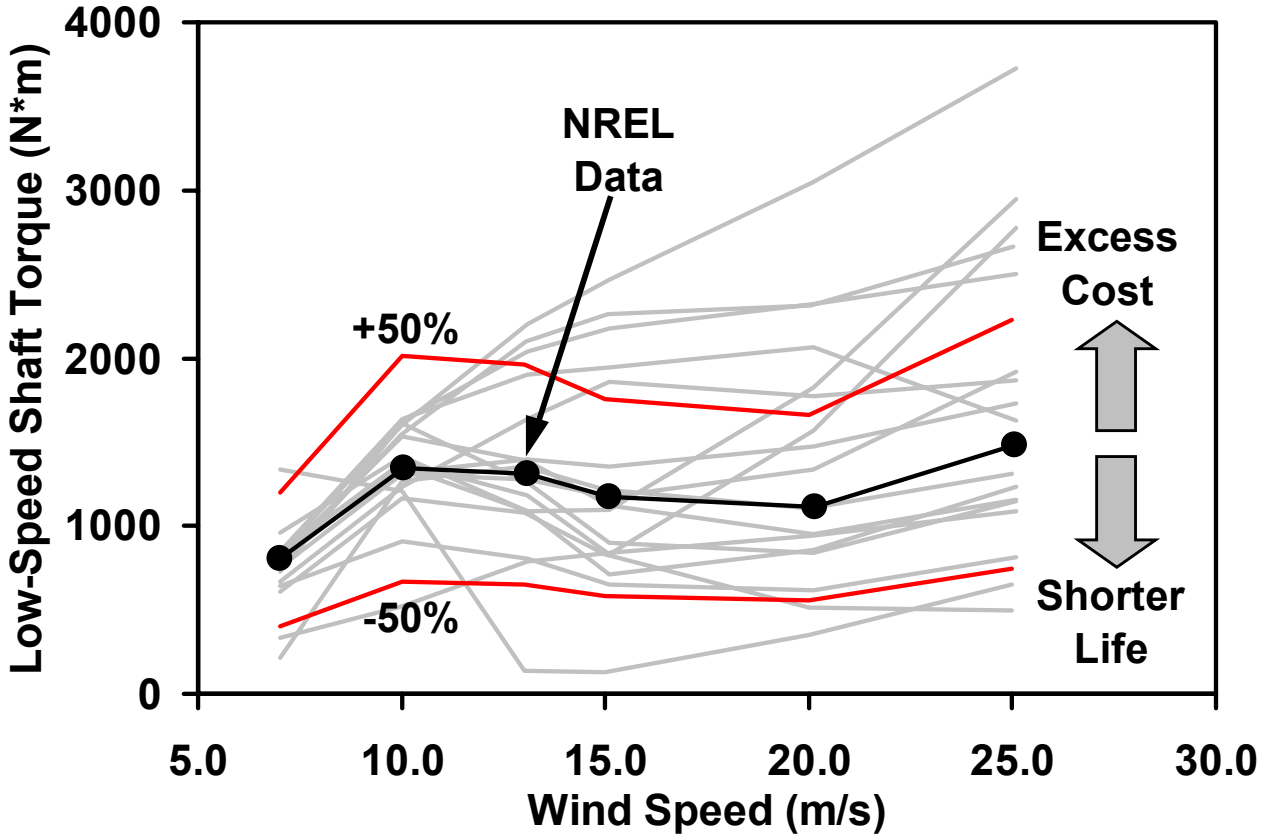
Computed shear topology



Rotational Augmentation Modeling

- Models for BEMT codes
  - 2-D airfoil → 3-D blade
  - Navier-Stokes reduced via OM (Snel)
  - Model derived from solution (Selig & Du)
  - Tuning required
- Computational prediction
  - First principles based
  - Turbulence, transition modeling
  - Full N-S, hybrid model, DES

Rotational Modeling Accuracy

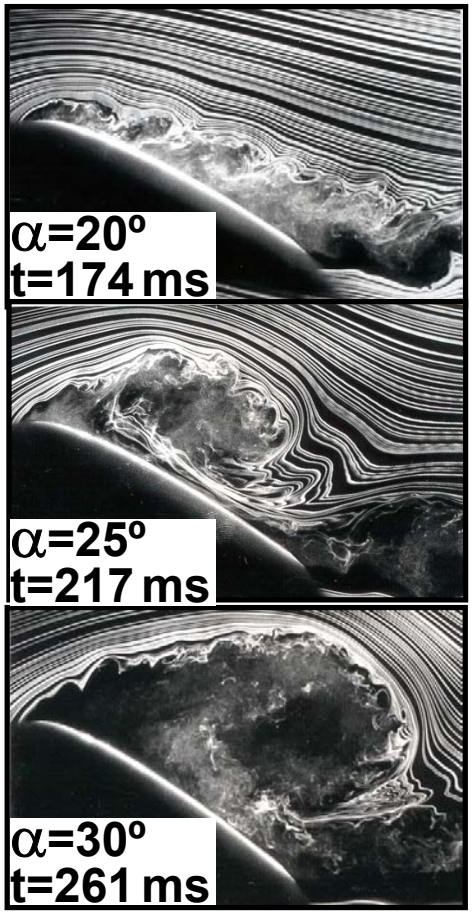


- Low wind speed predictions more accurate than high
- Overall, significant deviations, no consistent pattern

Dynamic Stall

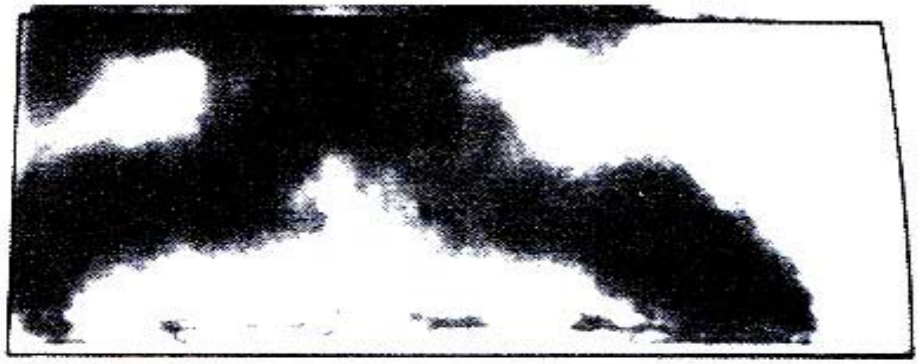
Yawed Operation

Dynamic Stall - Powerful & Complex

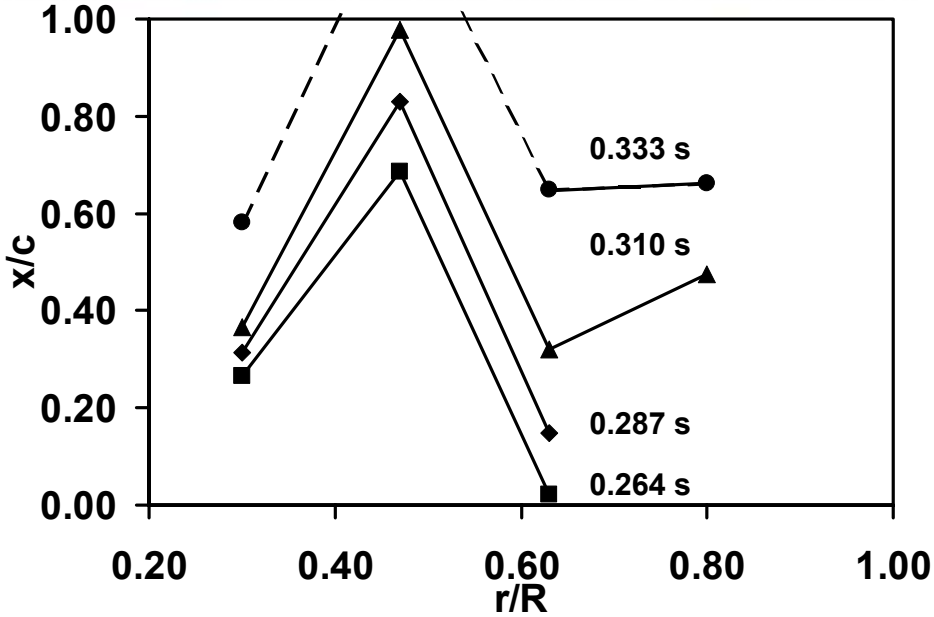


- **Dynamically stalled flow field**
  - Static stall dynamically exceeded
  - Vortex dominates flow field
  - C_n, C_t, C_m transiently amplified
- **Difficult to measure and model**
  - Gradients in space and time
  - Broad scale range
  - Nonlinear physics
- **Produced by even slight yaw**

3-D Structure Compounds Complexity



Rectangular wing, constant rate pitching

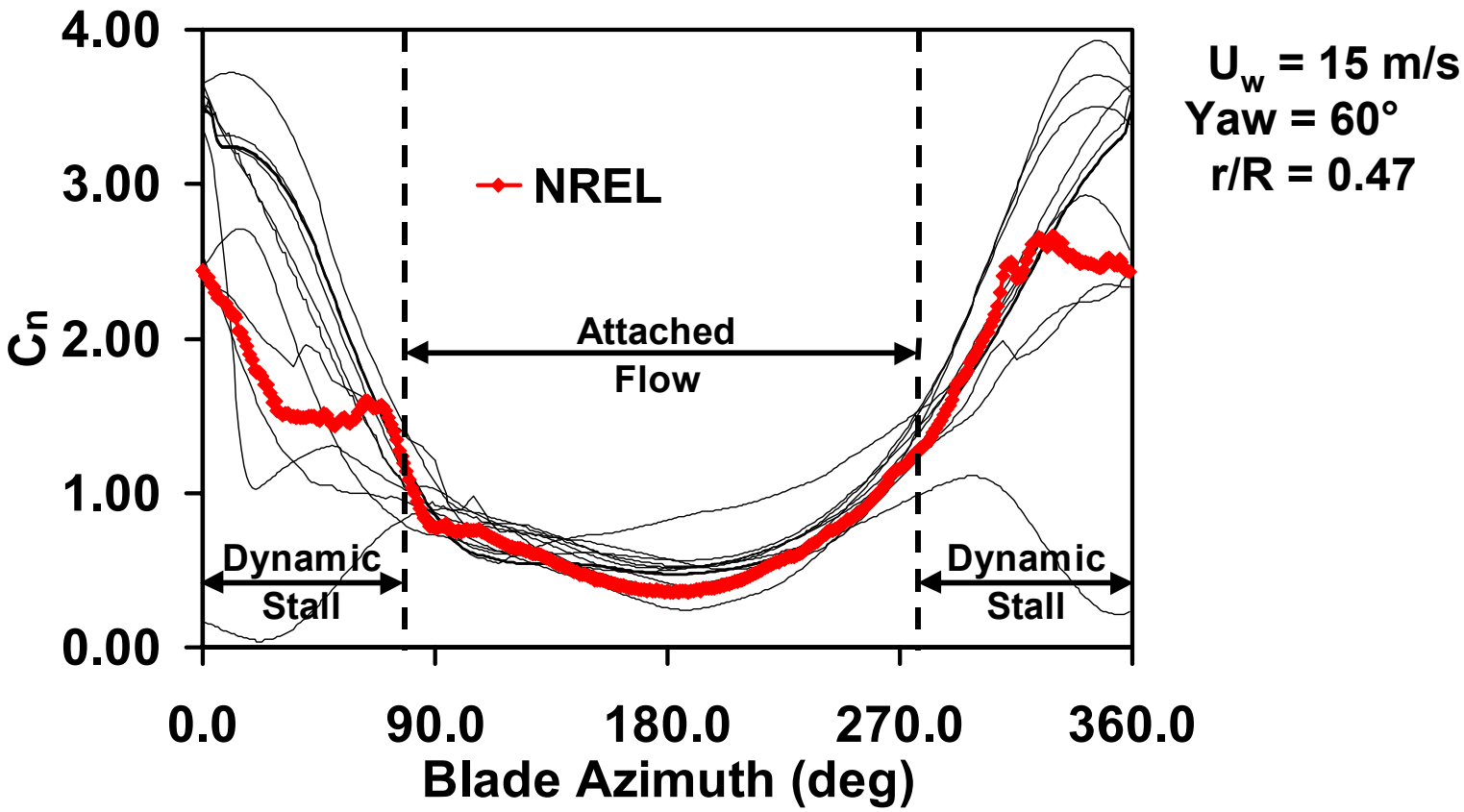


Tapered blade, rotating while yawed

Dynamic Stall Modeling

- ONERA, Johnson, … , Leishman-Beddoes
- Leishman-Beddoes model
  - Attached flow – linear indicial model
  - Trailing edge separation – Kirchoff method
  - Vortex – initiation, convection, shedding
  - All but 4 input parameters from static data
- Computational modeling
  - First principles based
  - Turbulence model applicability
  - RANS, DES

Dynamic Stall Modeling Accuracy

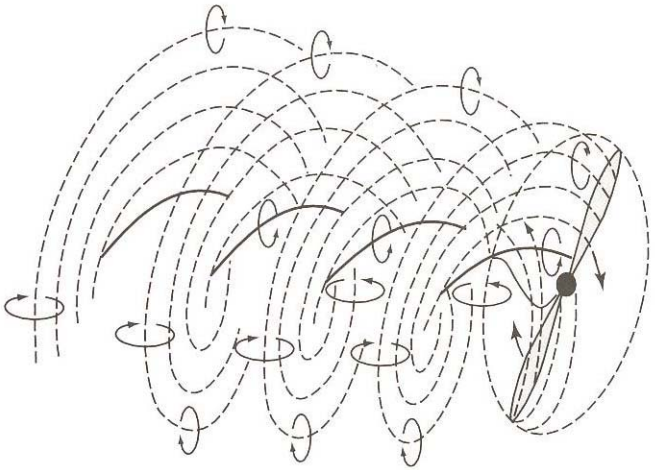


- Attached flow predictions agree with measured data
- Dynamic stall predictions deviate from measured data

Turbine Wake

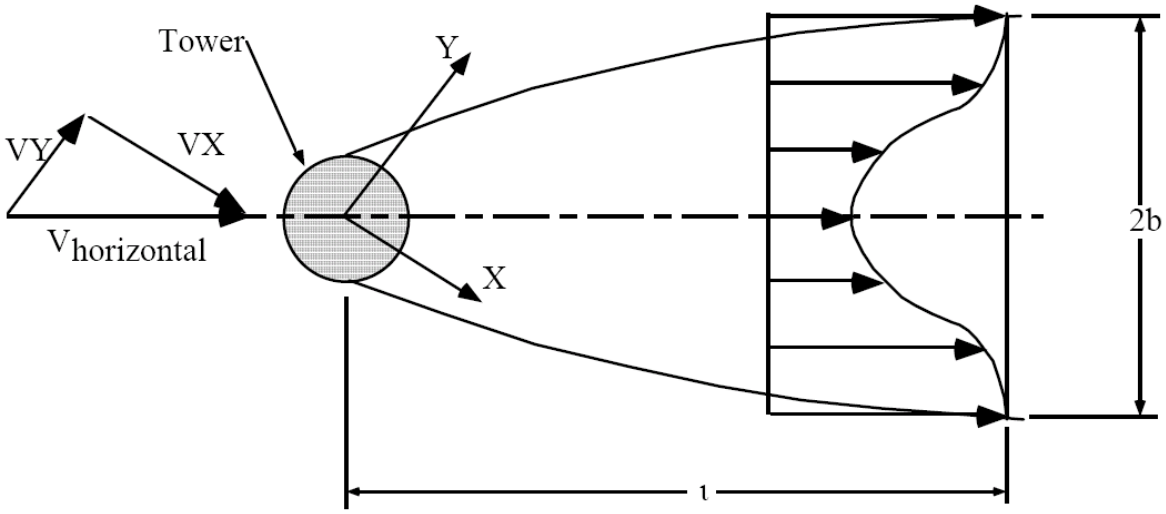
Wake Dynamics and Modeling

- Wake flow field
  - Tip and hub vortices
  - Trailed vorticity
  - Dynamic stall vortices
- Wake modeling
  - Equilibrium wake
  - Dynamic wake
  - Generalized dynamic wake
- Wake computation
  - Free wake
  - CFD



Tower Wake

- Simple parabolic shape
  - Reference point
  - Velocity deficit
  - Wake width



Summary

- Present
  - Significant uncertainties
  - Incremental approach
  - Constrained evolution
- Future
  - Greater accuracy, reliability
  - Aggressive design
  - Accelerated innovation