Overview of the AeroDyn Aerodynamics Module

NREL Wind Turbine Modeling Workshop

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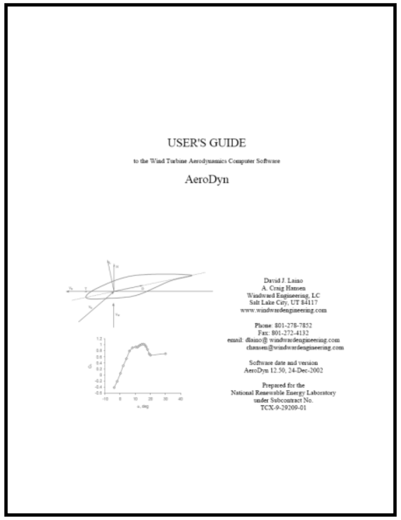
Introduction & Background

AeroDyn – What Is It?

- Aerodynamics module for horizontal-axis wind turbines:
  - Coupled to **FAST**, **MSC.ADAMS**, **SIMPACK**, **MotionSolve**, **FEDEM**, etc. for aero-elastic simulation
- Originally developed by Windward Engineering (Craig Hansen, et al); now NREL
- Latest version:
  - v14.02.01c-bjj (July 2014)
  - Newer in progress
- User's Guide:
  - Laino & Hansen (2002) & Addendums (2013)
- Theory Manual:
  - Moriarty & Hansen (2005)


USER'S GUIDE
to the Wind Turbine Aerodynamics Computer Software
AeroDyn

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Software date and version
AeroDyn 12.50, 24-Dec-2002

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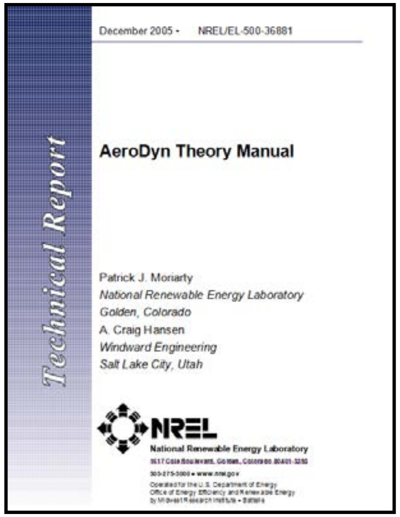
December 2005 • NREL/EL-500-36881

Technical Report

AeroDyn Theory Manual

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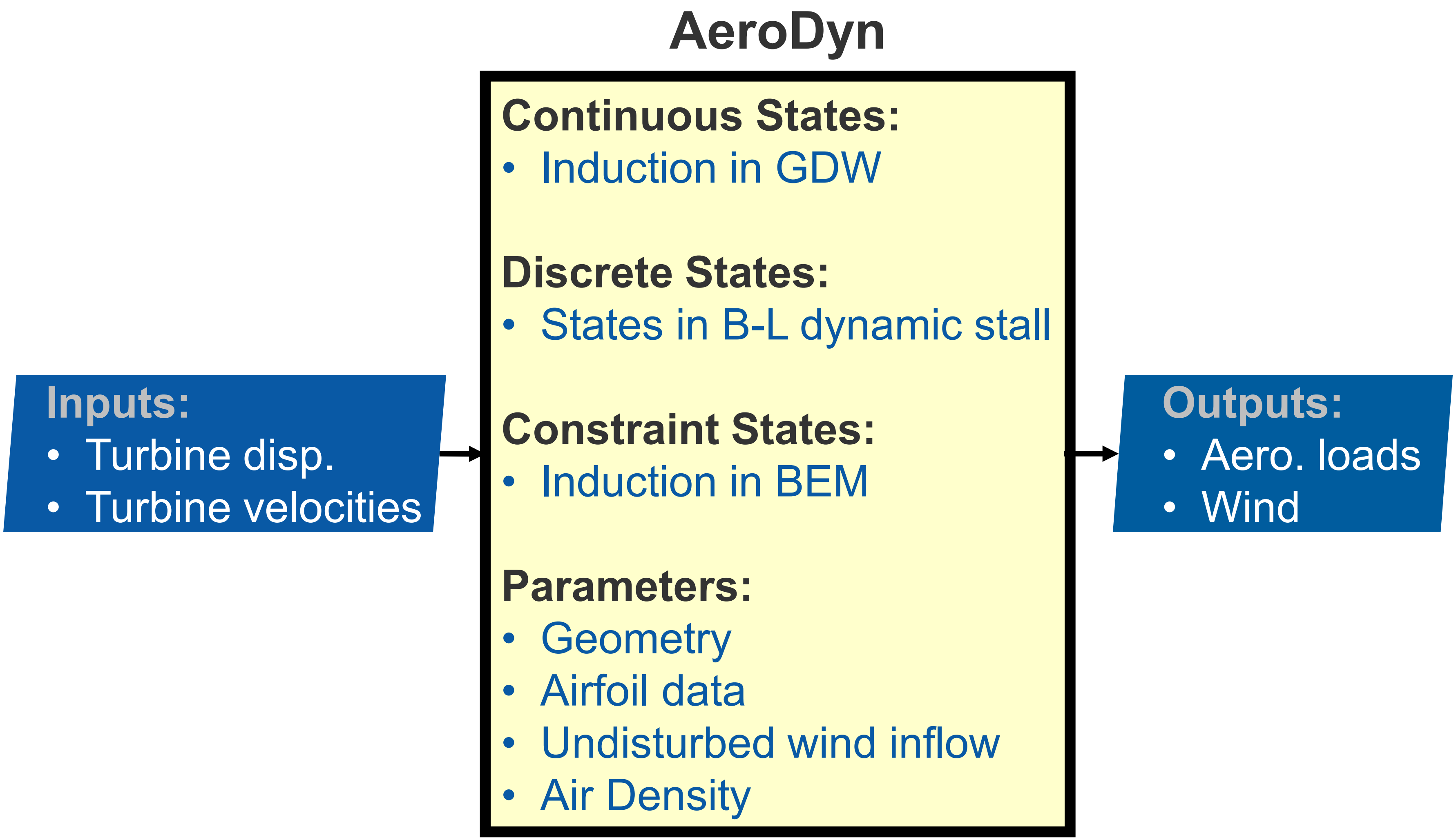
Windward Engineering
Salt Lake City, Utah

National Renewable Energy Laboratory

Introduction & Background

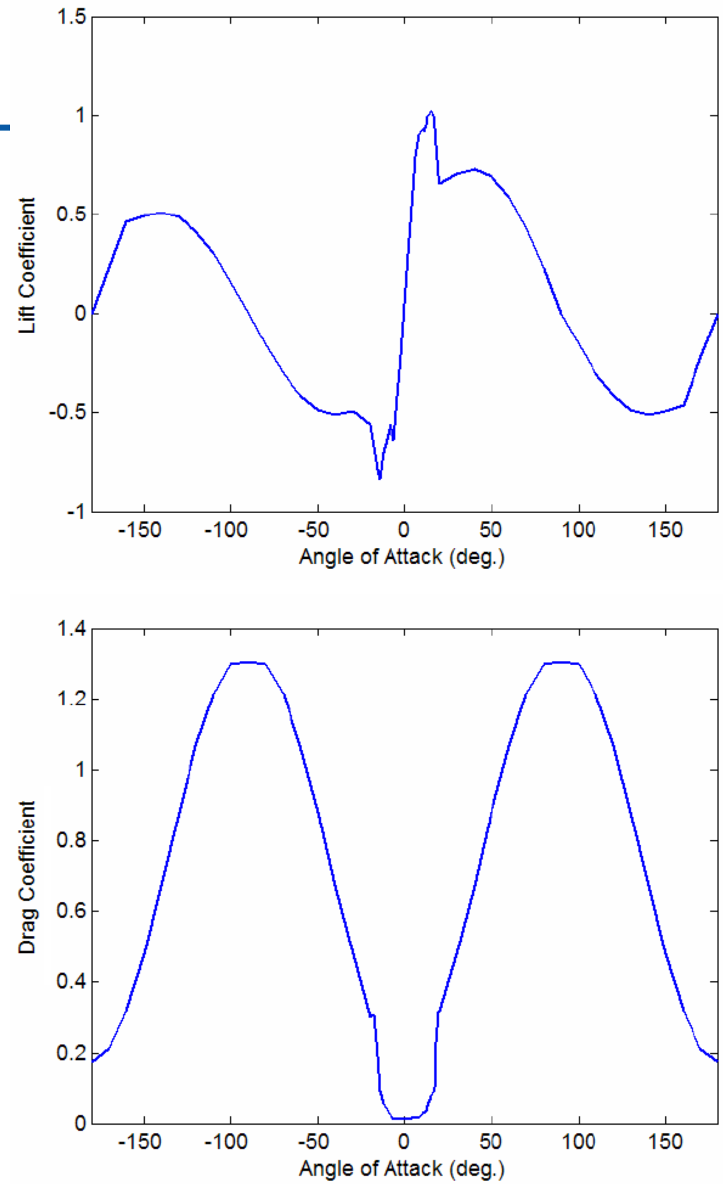
Inputs, Outputs, States, & Parameters



Introduction & Background

User Inputs

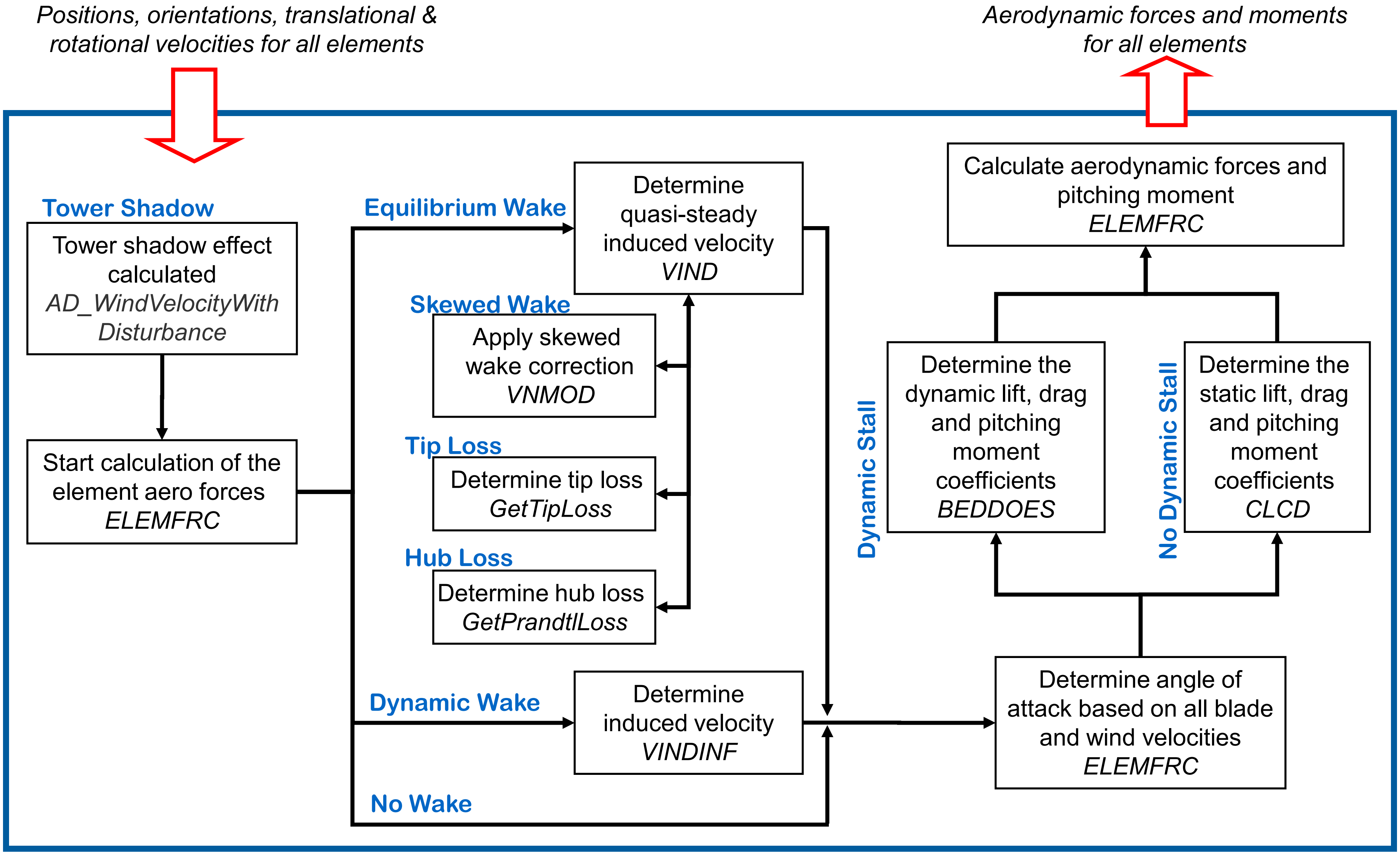
- Undisturbed wind inflow from **InflowWind** submodule:
  - Uniform, but time-varying
  - Full-field turbulence
  - User-defined
- Aerodynamic submodel selection:
  - Quasi-steady, dynamic, or no wake
  - Steady or unsteady airfoil aerodynamics, including dynamic stall
- 2-D/3-D airfoil properties:
  - C_L, C_D, C_M (vs. AoA & Re) & dynamic-stall parameters
  - **AirfoilPrep**
- Tower influence & drag load properties



S809 Airfoil Data @ Re=750M

Introduction & Background

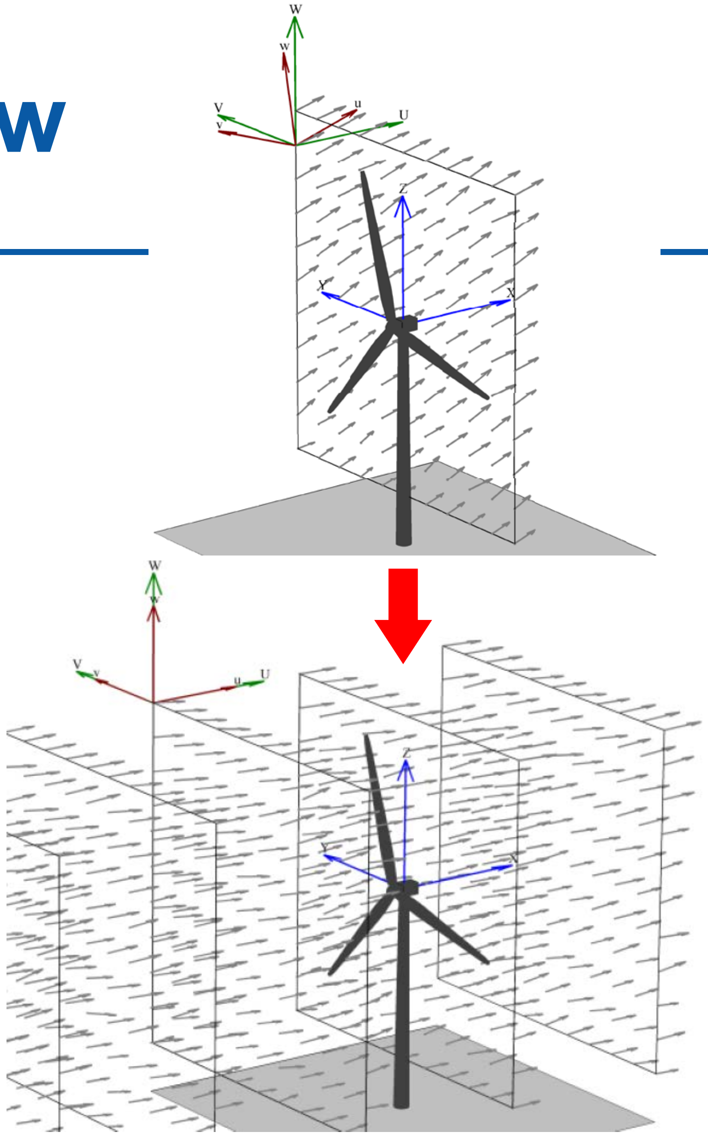
Flowchart



Undisturbed Wind Inflow

- Undisturbed wind inflow is set by **AeroDyn**'s **InflowWind** submodule, supporting:
  - Uniform, but time-varying
  - Full-field (FF) turbulence (**TurbSim**, **Bladed**, **WAsP Engineering***)
  - User-defined*
- FF turbulence approximations:
  - Taylor's frozen turbulence hypothesis used to march FF grids along the $+X$ axis of the inertia frame at mean hub-height wind speed
  - Requires wind stationarity
  - Mistreatment of horizontal or vertical mean flow angles:
    - Use nacelle-yaw instead of wind direction to model yaw error
    - Use only small vertical mean flow angles

Available in **FAST v7, but not yet in v8*

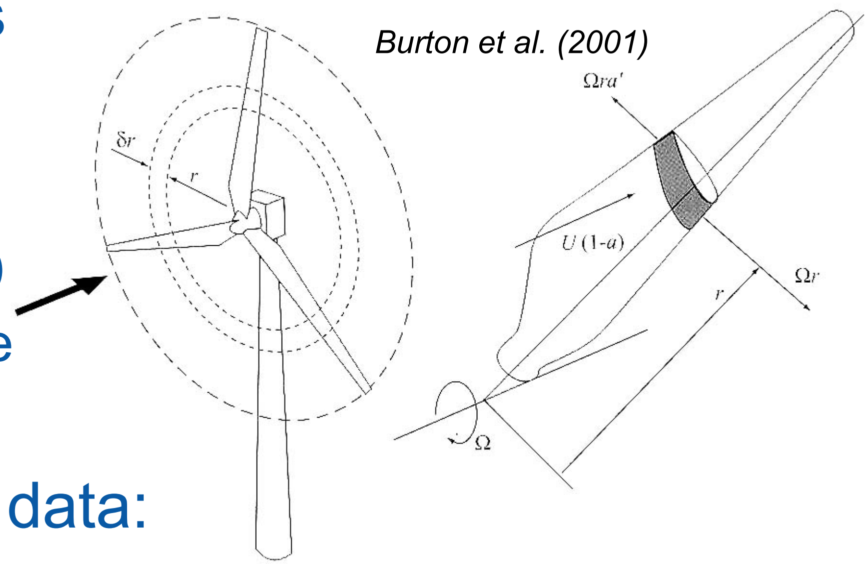


*FF Turbulence as Treated by **TurbSim** (Top) and **AeroDyn** (Bottom) with Taylor's Frozen Turbulence Hypothesis*

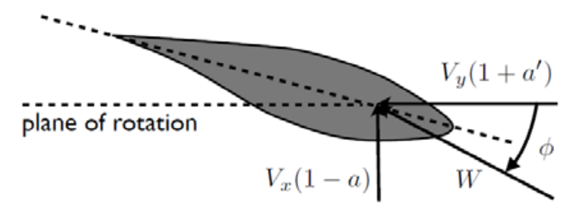
Wake Modeling

Blade-Element / Momentum (BEM)

- Blades discretized into elements
- Momentum balance in annuli:
  - Linear → axial induction (*a*)
  - Angular → tangential induction (*a'*)
  - Implemented per element per blade
  - Nonlinear solve requires iteration
- Blade-element loads from airfoil data:
  - Drag terms can optionally be used in induction calculation
- Limitations to theory:
  - No interaction between annuli (2-D only) (3D effects from **AirfoilPrep**)
  - Instantaneous reaction of wake to loading changes
  - Needs corrections for high induction, tip & hub losses, & skewed flow
  - Despite these, BEM is applied in many conditions



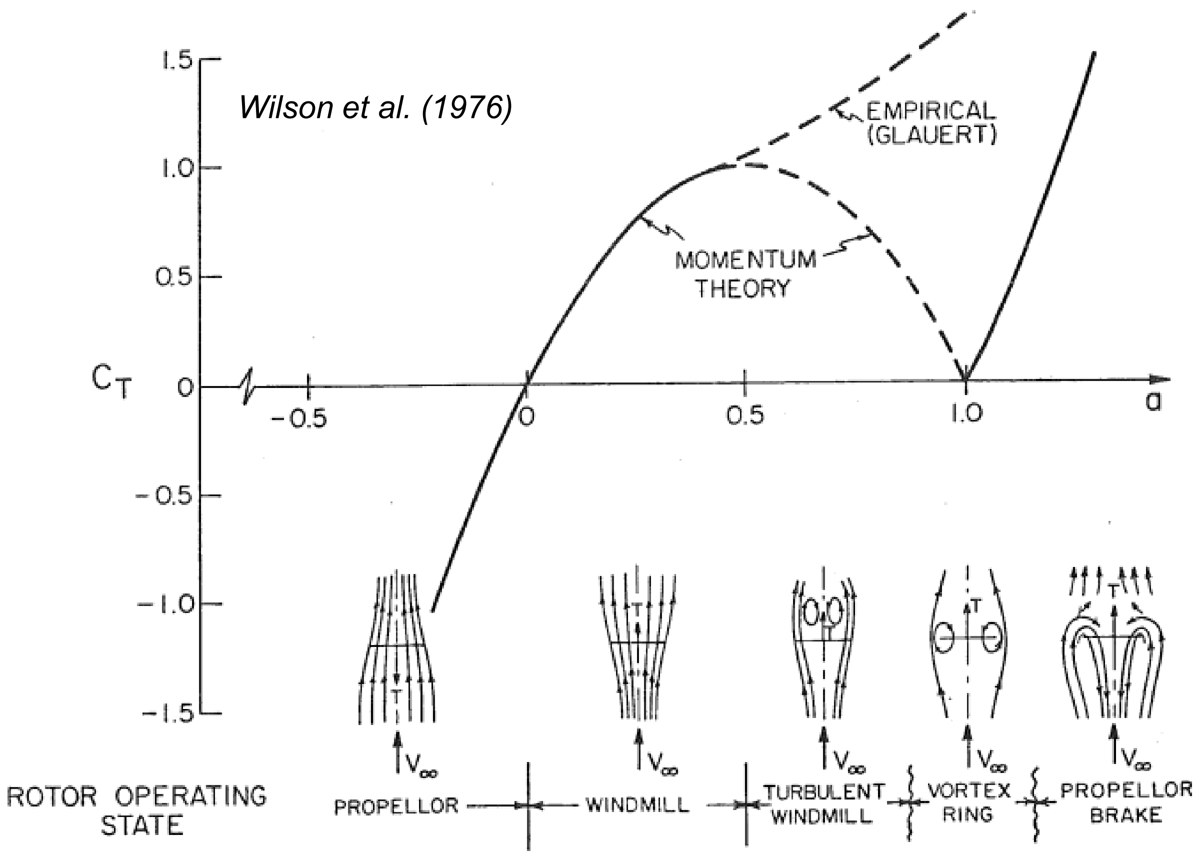
Burton et al. (2001)



Wake Modeling

BEM – Glauert Correction

- Momentum balance invalid for high induction (*a* > ~0.4):
  - Glauert correction implemented

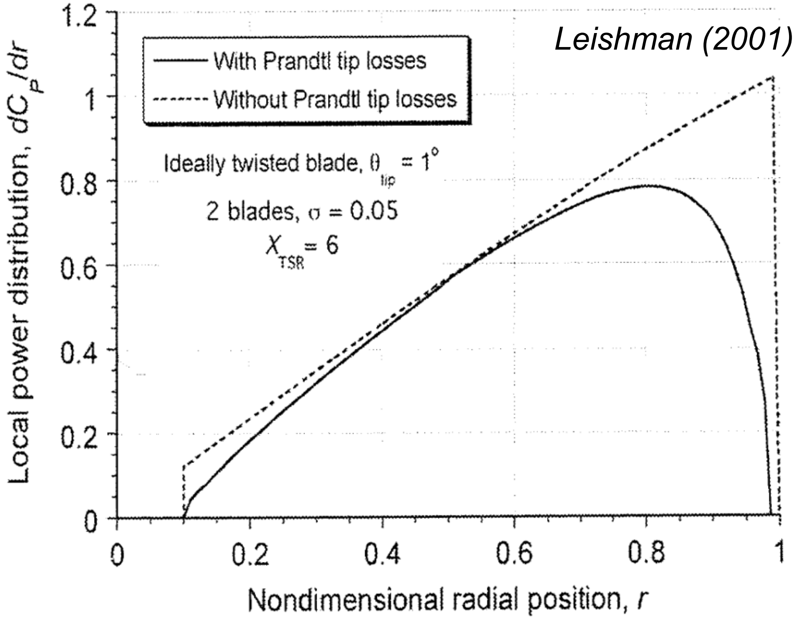


Wake States

Wake Modeling

BEM – Tip & Hub losses

- Blade tip-loss correction:
  - Models loss of lift at the blade tip:
    - Important for finite number of blades
  - Prandtl model
  - Xu & Sankar (2002):
    - Empirical correction to Prandtl using CFD of NREL Phase VI (may not apply to other turbines)
- Blade root-loss correction:
  - Prandtl model only

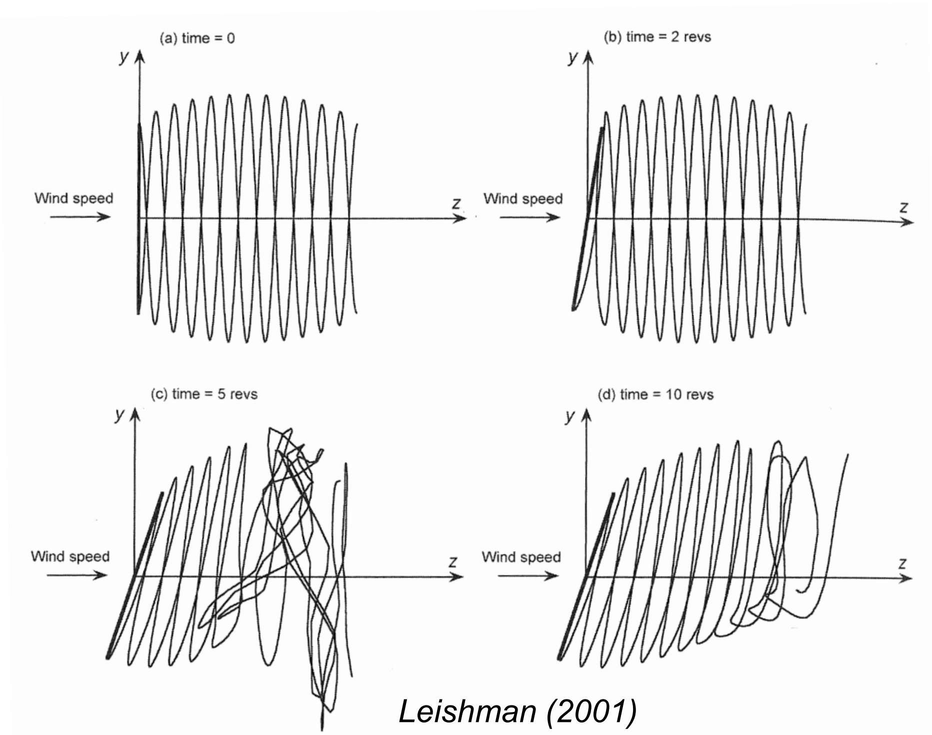


Local Power Coefficient with & without Tip Loss

Wake Modeling

BEM – Skewed Wake

- Rotor yaw error or tilt leads to crossflow & nonaxisymmetric wake
- Skewed wake corrections derive a local *a* from the rotor-averaged *a* based on the local azimuth & radial position
- **AeroDyn** applies the correction to the local *a* after induction iteration
- **AeroDyn** model bases coefficients on Pitt & Peters (1981) & Coleman (1945)

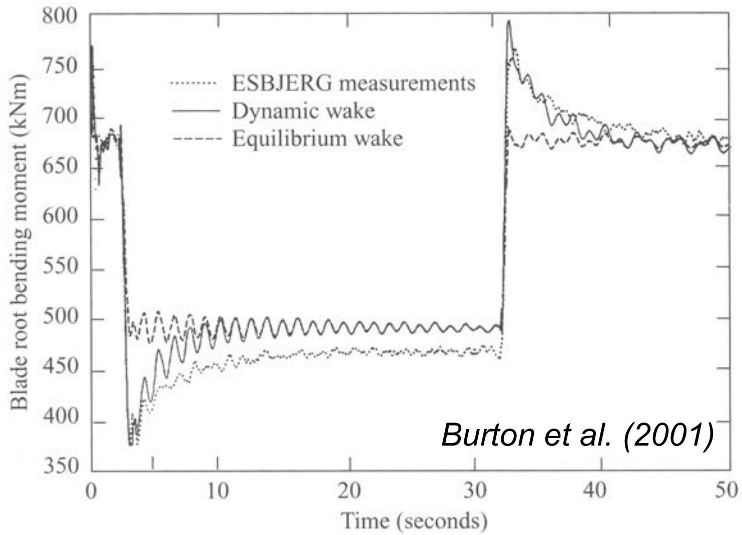


Free-Vortex Wake Calculation of a 30°-Yawing Event

Wake Modeling

Generalized Dynamic Wake (GDW)

- Transient loading leads to a dynamic wake:
  - Gusts
  - Pitch control
  - Skewing flow
- GDW models the time- & spatial-varying induction across the rotor
- **AeroDyn** GDW model based on Peters, Boyd, & He (1989):
  - Induced flow at the rotor expressed as Fourier series in the radial & azimuthal directions:
    - 10 flow states considered
  - ODEs relating induced flow to rotor loading in state-space form
  - Time-integration using ABM4 scheme:
    - Initialized with 1 s of BEM
  - Tip losses & skewed wake automatically modeled with enough states

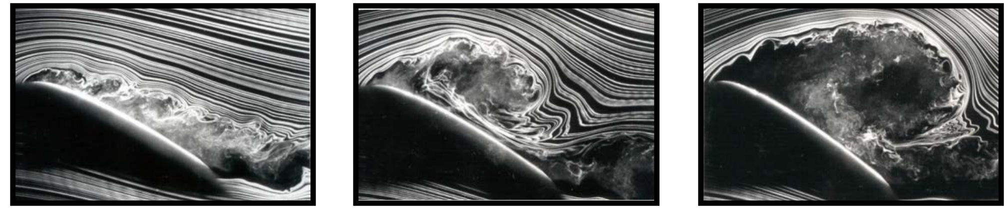


Blade Loading During Rapid Pitch Events

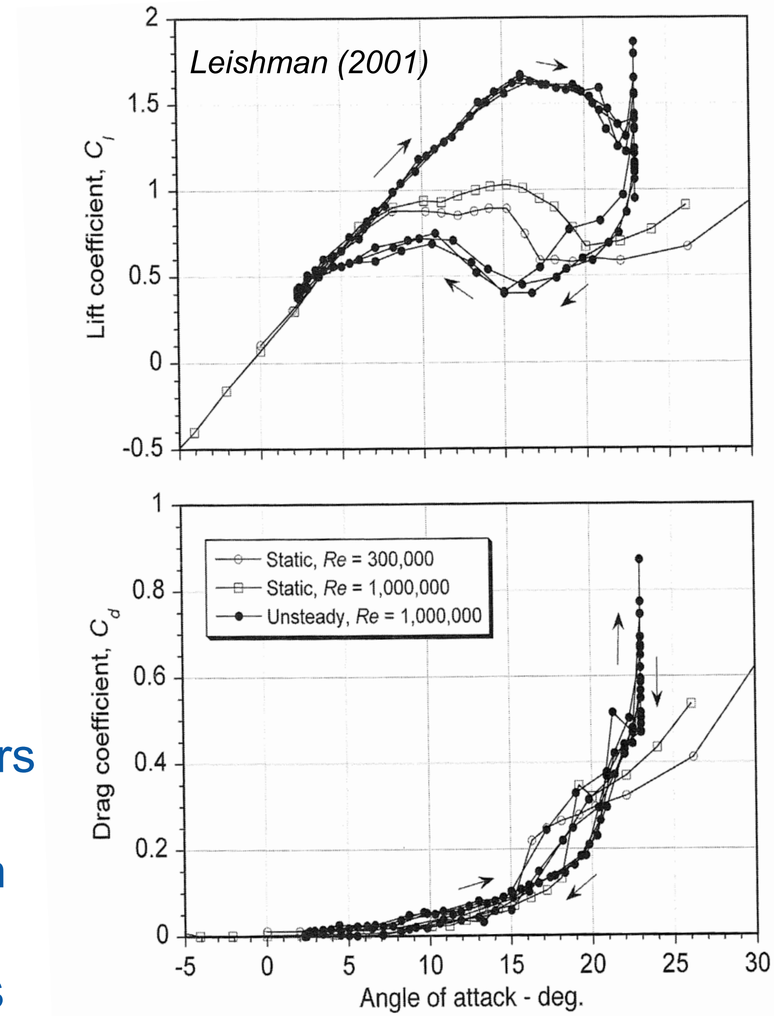
Wake Modeling
GDW – Limitations

- Limitations to GDW theory:
  - Uniform inflow (i.e. no or very low turbulence)
  - Constant rotor speed
  - Induced velocity << mean wind speed:
    - Unstable below rated power
    - Automatically disabled below 8 m/s
  - No tangential induction:
    - Uses BEM
  - 33 flow states needed to accurately model tip losses
  - Like BEM, GDW uses airfoil data
  - Despite these, recommend use whenever possible

Unsteady Airfoil Aerodynamics



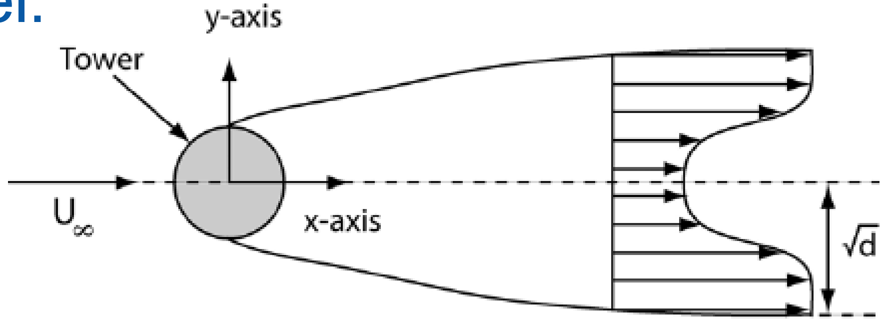
- Dynamically stalled flow field:
  - Static stall dynamically exceeded
  - C_N, C_T, C_M transiently amplified
  - Flow hysteresis
  - Produced by even slight yaw & turbulence
- Beddoes-Leishman model (1989):
  - A semi-empirical model
  - 3 submodels:
    - Unsteady attached flow
    - Trailing-edge flow separation
    - Dynamic stall & vorticity advection
  - Semi-empirical airfoil-dependent parameters derived from static data
  - Applicable for operational conditions, not in deep stall
- **AeroDyn** adds after induction calculations



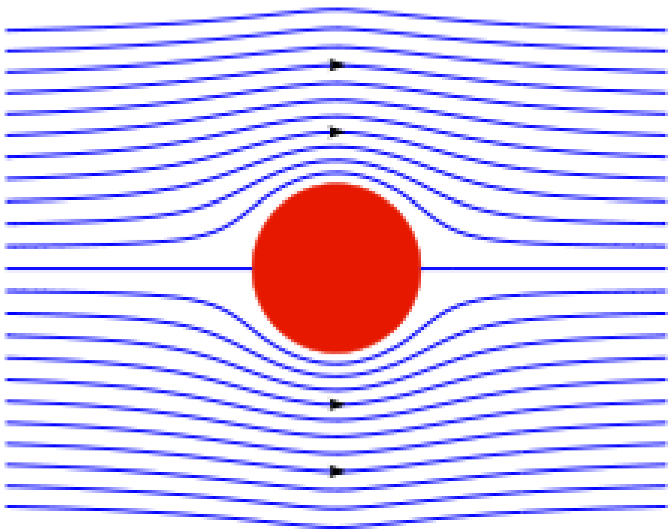
Dynamic Stall of S809 Airfoil

Tower Influence & Drag Load

- Downwind tower-shadow model:
  - Augments undisturbed wind
  - Simple user-tailored shape from:
    - Reference point
    - Velocity deficit
    - Wake width
- Upwind tower-influence model:
  - Augments undisturbed wind
  - Based on the potential flow solution around a cylinder
  - Doesn't move with the tower
- Tower drag model:
  - Drag load @ each tower node proportional to square of undisturbed relative wind speed



Tower Shadow



Potential Flow Around a Cylinder

Aerodynamic Features of FAST v8 Compared to v7

- This workshop will apply **FAST** v8
- All new features are being added to the new framework
- Until all features of v7 are included in v8, both will be supported

FAST Features	**v7.02**	**v8.08**
• Quasi-steady or dynamic wake	✓	✓
• Steady or unsteady airfoil aerodynamics	✓	✓
• Tower shadow for downwind rotors	✓	✓
• Tower influence for upwind rotors	✓	✓
• Tower drag loading		✓
• Tail-fin aerodynamic loading	✓	
• "Hub-height", TurbSim, and Bladed wind file formats	✓	✓
• Other wind formats	✓	
• Aeroacoustics (noise)	✓	

Modeling Guidance

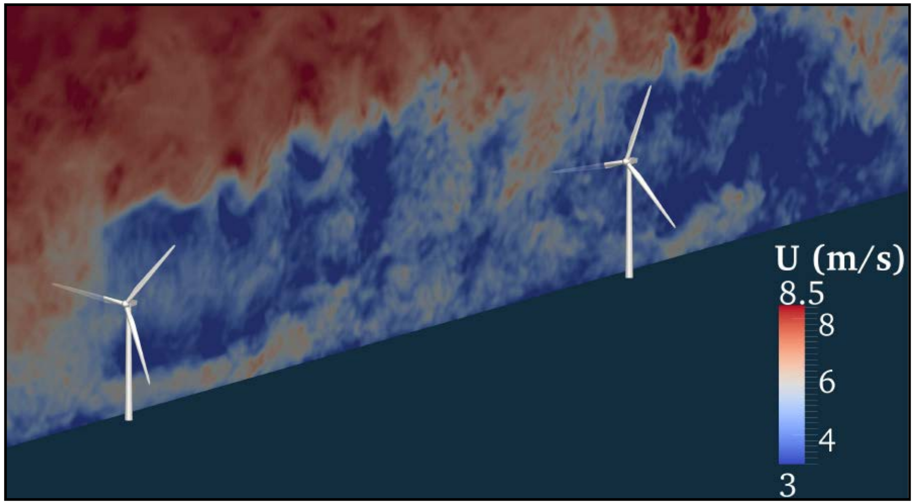
- Time step:
  - `DTAero` = 200 azimuth steps per revolution
- Blade & tower discretization:
  - `TwrNodes` ~ 20 (in **ElastoDyn**)
  - Tower discretization in **ElastoDyn** is currently used by **AeroDyn**
  - `BldNodes` ~ 20
  - Blade discretization in **AeroDyn** is currently used by **ElastoDyn**:
    - Nodes are located at centers of elements
- Airfoil data must often be “tuned” to match measurements

Modeling Guidance (cont)

- To model an operational rotor set:
  - Below rated:
    - `StallMod` = `BEDDOES` – Enable dynamic stall
    - `InfModel` = `EQUIL` – Enable BEM
  - Above rated:
    - `StallMod` = `BEDDOES` – Enable dynamic stall
    - `InfModel` = `DYNIN` – Enable GDW
- To model an idling/parked rotor set:
  - `StallMod` = `STEADY` – Disable dynamic stall
  - `IndModel` = `NONE` – Disable wake
- When using FF turbulence, use nacelle-yaw instead of wind direction to model yaw error & use small vertical mean flow angle

Recent Work

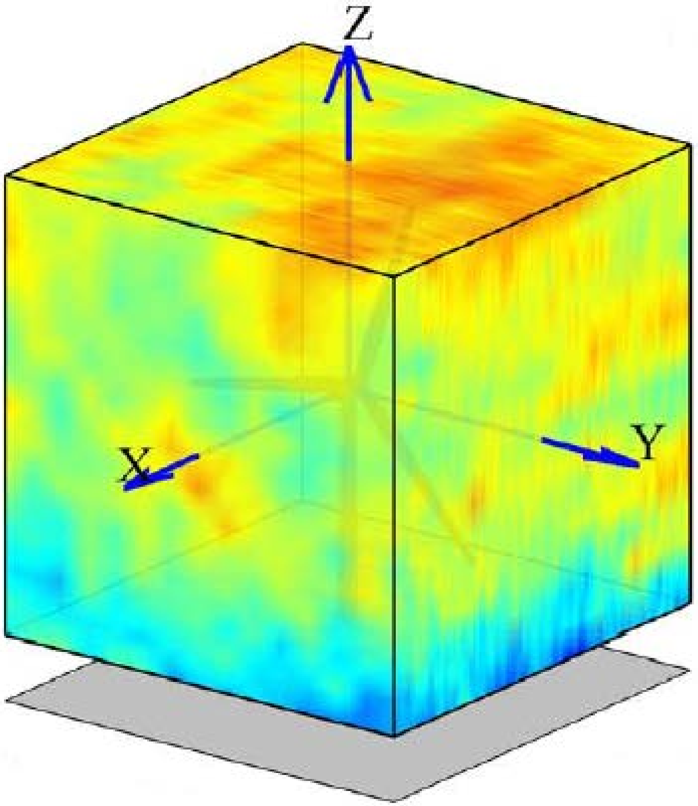
- Changes in v14.02:
  - Converted **AeroDyn** to new **FAST** framework (for v8)
  - Added tower drag loading
- Interfaced **FAST/AeroDyn** to **OpenFOAM** for array modeling:
  - **SOWFA – S**imulator f**O**r **W**ind **F**arm **A**pplications
  - **OpenFOAM** is a free, open-source, parallel, finite-volume, CFD toolbox
  - **OpenFOAM** computes inflow wind, wake, & array effects:
    - Replaces **TurbSim** & **AeroDyn**'s wake calculation
  - **AeroDyn** returns blade aero. forces to **OpenFOAM** & **FAST**:
    - Body forces applied to CFD flow field using actuator-line approach
  - Capable of multiple turbines with aero-elastics



*Example **SOWFA** Simulation*

Current & Planned Work

- **InflowWind**:
  - Convert from an **AeroDyn** submodule to a core **FAST** module, with separate input files & source code
  - Support simple steady uniform wind inputs
  - Support **WAsP Engineering*** FF turbulence format
  - Support arbitrary mean wind direction for FF turbulence formats
  - Support **TurbSim** coherent turbulence files*
  - Support user-defined wind option*
  - Add more wind outputs (multiple locations)



Full-Field Turbulence

Available in **FAST v7, but not yet in v8*

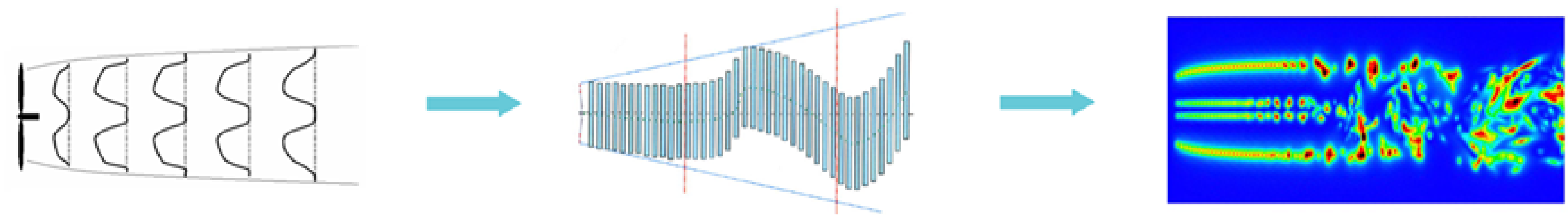
Current & Planned Work (cont)

- BEM:
  - Include updated algorithm with improved convergence (Ning)
  - Improve skewed-wake model
  - Wrap BEM iteration around all (wake, correction, dynamic-stall) calculations
  - Simplified dynamic wake (Oye's time-filtered BEM)
  - Improve support for curved & swept blades
- GDW:
  - Initialize with single BEM solution
  - Resolve the numerical instability at low wind speeds
  - Improve for variable rotor speed
  - Add option to choose number & type of flow states
  - Include an inflow velocity filter (Peters & He)
  - Include wake curvature term
  - Revise algorithms per recommendation of Peters

Current & Planned Work (cont)

- Unsteady airfoil aerodynamics:
  - Add option to choose submodels
  - Revise algorithms per recommendation of Leishman
- Tower, nacelle, & hub influence & loading:
  - Improve tower-influence model based on current position of tower
  - Add nacelle & hub drag loading based on an airfoil table
- Wake & array effects:
  - Couple **OpenFOAM** with **WRF** (**SOWFA**)
  - Add a Dynamic Wake Meandering (DWM) model (with UMass)

Dynamic wake meandering model



Axisymmetric wake deficit — Wake meandering — Rotor added turbulence

Future Opportunities

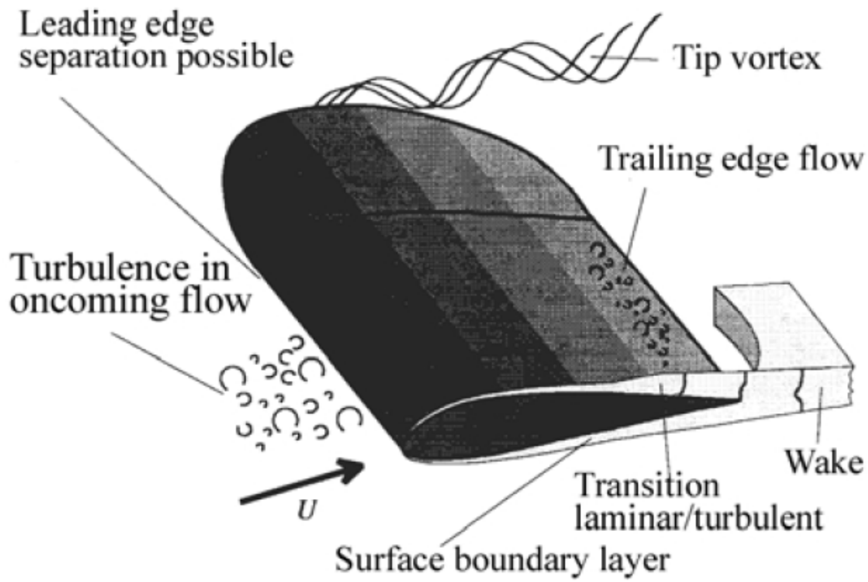
- Wake:
  - Hub & tip loss corrections for BEM – e.g. Goldstein, Shen et al
  - Coned rotor corrections for BEM – e.g. Mikkelson, Crawford
  - Frozen wake for linearization
  - Free-wake vortex method

NASA-Ames Test of UAE Phase IV

- Airfoil aerodynamics:
  - Automate rotational augmentation calculation (as an alternative to **AirfoilPrep**)
  - Automate interpolation of airfoil data from input to analysis nodes
  - Unsteady – e.g. Galbraith et al, Munduate et al, ONERA
  - Unsteady models for active flow-control devices
  - Linearized dynamic stall – e.g. Hansen et al

Future Opportunities (cont)

- Develop improved empirically & CFD-derived corrections to engineering models (e.g. hub & tip loss, stall delay, precuved & preswept blades, highly coned rotors, winglets)
- Interface **FAST** with the ECN-developed **AWSM** free-wake vortex code
- Interface **FAST** with the DTU Wind-developed **HAWC2** aerodynamics module
- Develop an aeroacoustics module (to replace **FAST** v7's noise module)
- Improved tail-fin aerodynamics
- Implement new physics for hydro-kinetic turbines



Aerodynamic Noise Sources

Wagner et al. (1996)

Questions?

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