Overview of the AeroDyn Aerodynamics Module

NREL Wind Turbine Modeling Workshop

April 17, 2013

JEMA – Tokyo, Japan

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Outline

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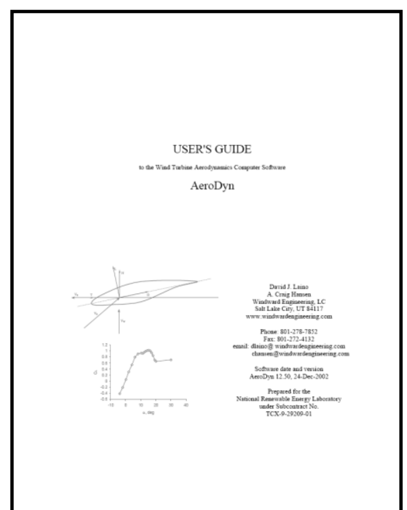
Overview

AeroDyn – What Is It?

- Wind turbine aerodynamics routines:
  - Not stand alone
  - Coupled to **FAST**, **MSC.ADAMS**, **SIMPACK**, **MotionSolve**, **FEDEM**, etc. for aero-elastic simulation
- Developed by Windward Engineering (Craig Hansen, et al) & NREL
- Latest version:
  - v13.00.02a-bjj (February 2013)
  - Newer in progress
- User's Guide:
  - Laino & Hansen (2002)
- Theory Manual:
  - Moriarty & Hansen (2005)



USER'S GUIDE

to the Wind Turbine Aerodynamics Computer Software

AeroDyn

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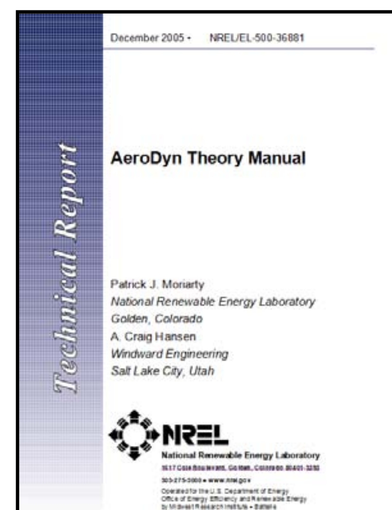
Software date and version
AeroDyn 12.50, 24-Dec-2002

Prepared for the
National Renewable Energy Laboratory
under Subcontract No.
TCX-9-29209-01



December 2005 • NREL/EL-500-36881

Technical Report

AeroDyn Theory Manual

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National Renewable Energy Laboratory
Golden, Colorado
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Windward Engineering
Salt Lake City, Utah

National Renewable Energy Laboratory

Overview
Inputs

- Local airfoil position, orientation, & velocity from structural code
- Wind flow field from **InflowWind**:
  - Full-field turbulence (**TurbSim, GH Bladed, WaSP Engineering**)
  - Uniform, but time-varying
  - Measured
  - User-defined
- Tower shadow properties
- 2-D/3-D airfoil properties:
  - C_l, C_d, C_m (vs. AoA & Re) & dynamic stall parameters
  - **AirfoilPrep**
- User aerodynamics settings:
  - Quasi-steady or dynamic wake
  - Steady or unsteady airfoil aerodynamics

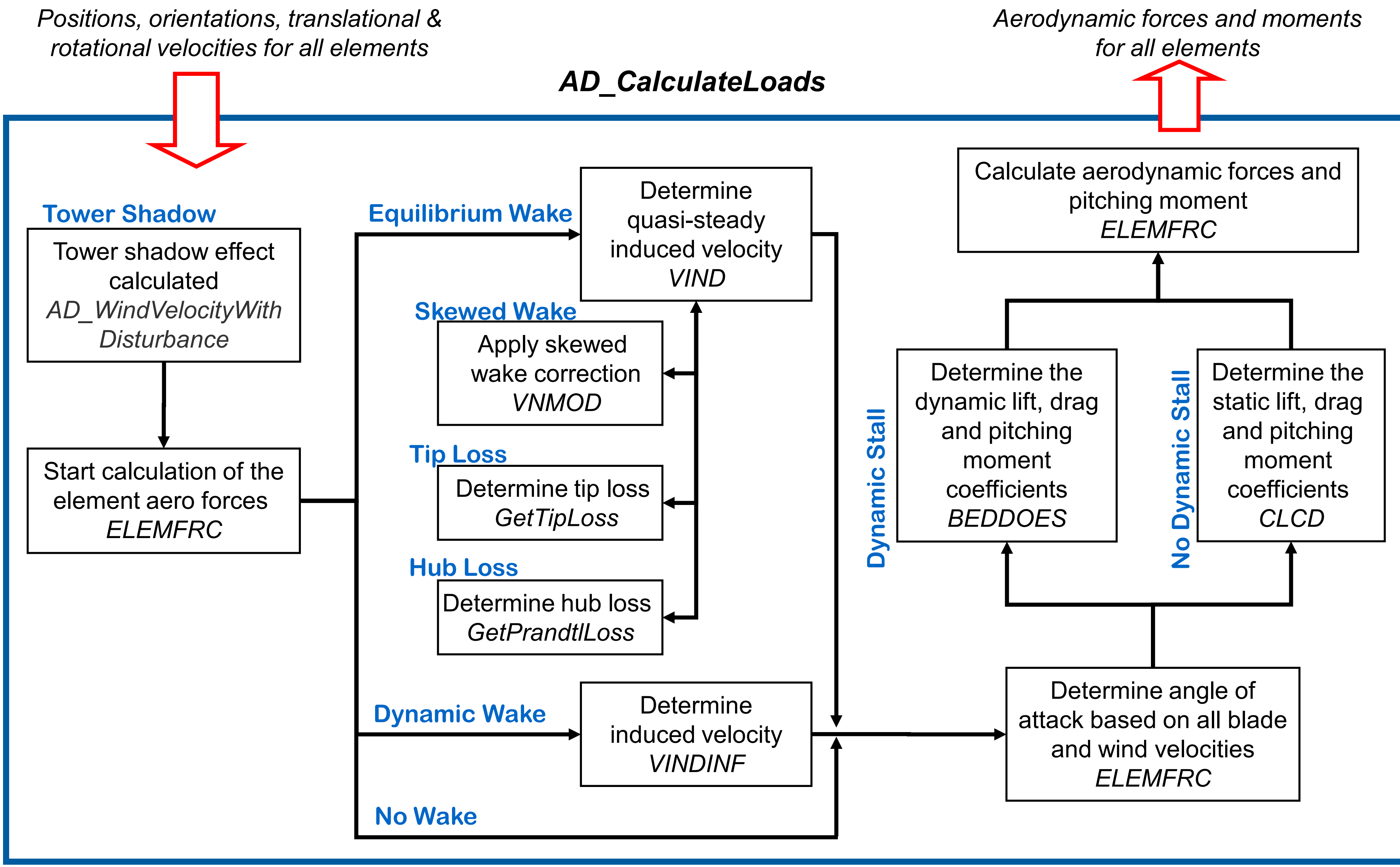
Overview

Outputs

- All elements calculated by a single call to **AeroDyn**
- Elemental loads sent back to structural code:
  - Forces & moments
- Element quantities to output file:
  - Each time step for any or all elements
  - Local wind speed
  - AoA, C_l, C_d, C_n , C_t, C_m
  - Local dynamic pressure, pitch angle
  - Induction factors – axial & tangential
  - Tangential & normal forces & pitching moments
  - Local Reynolds number

Overview

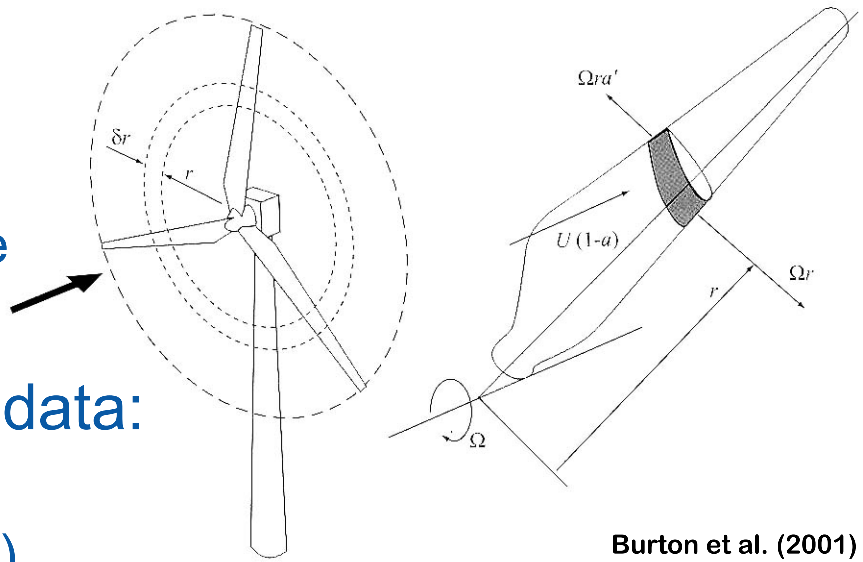
Flowchart



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
  - Requires iteration
- Blade-element loads from airfoil data:
  - Drag terms can be used in induced velocity calculation (undocumented)



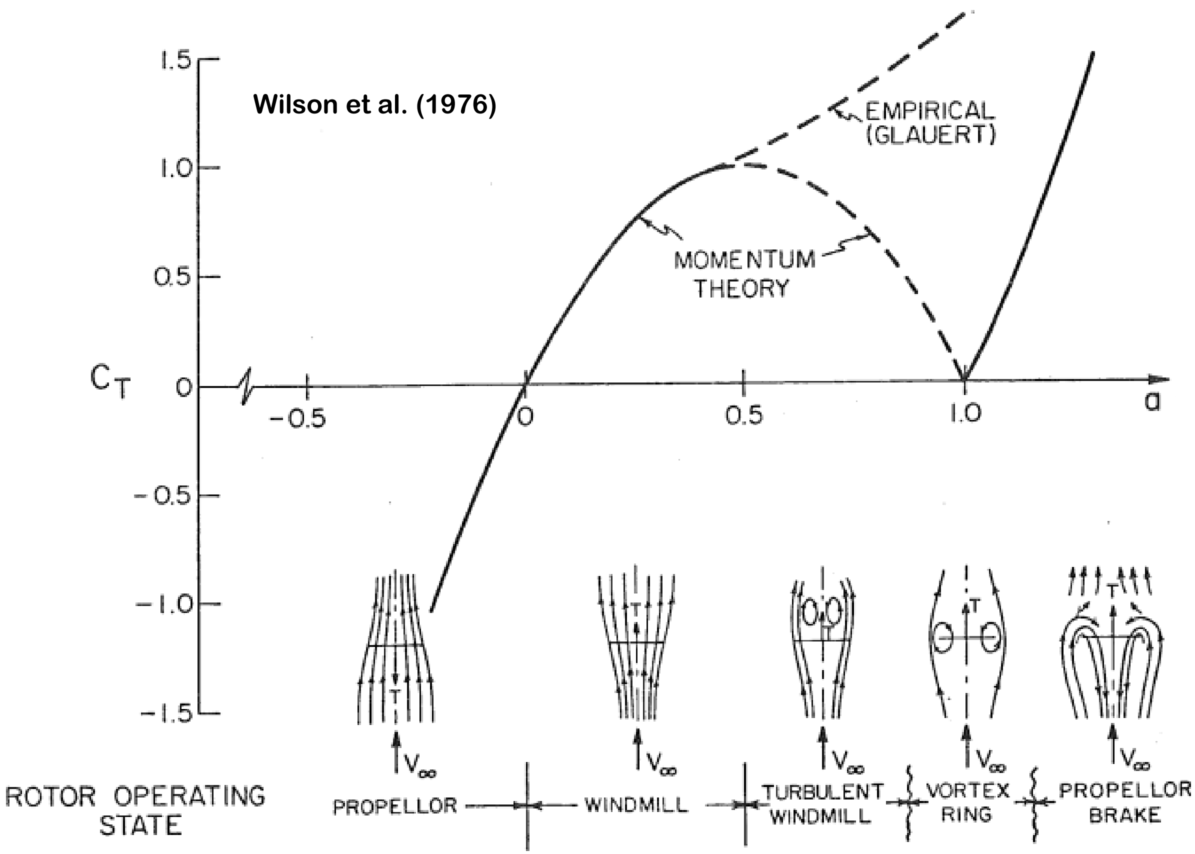
Burton et al. (2001)

- 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

Wake Modeling

BEM – Glauert Correction

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

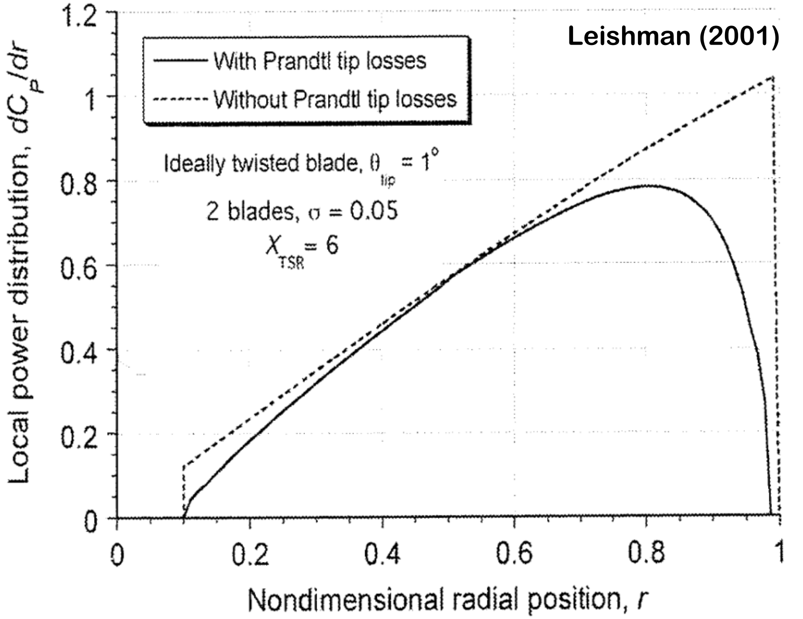


Rotor Operating States

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

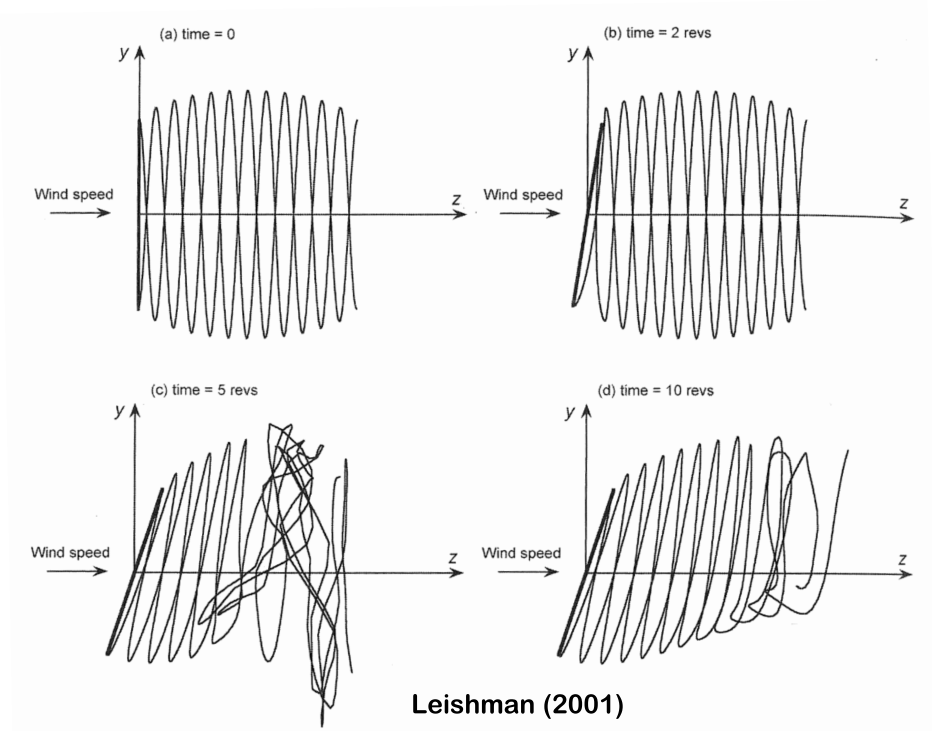


Local Power Coefficient with & without Tip Loss

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)

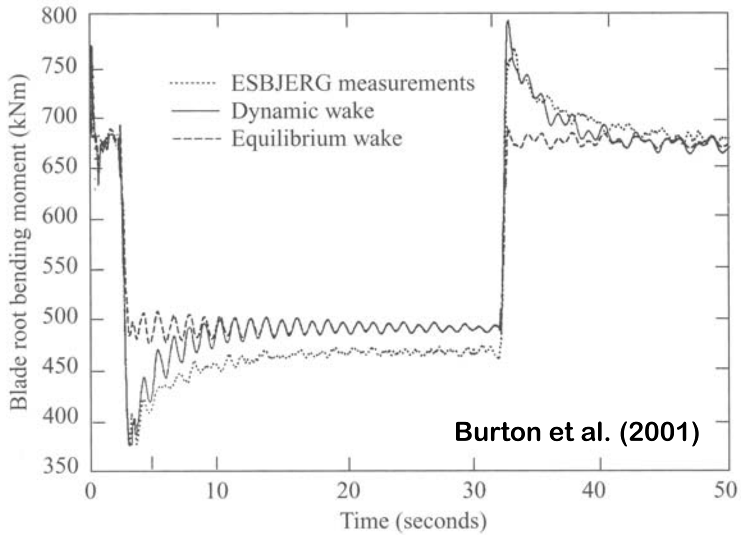


Free-Vortex Wake Calculation of a 30° Yawing Event

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



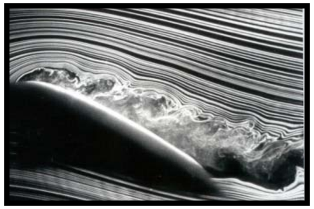
Blade Loading During Rapid Pitch Events

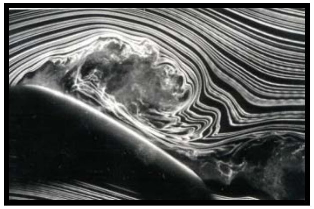
Wake Modeling

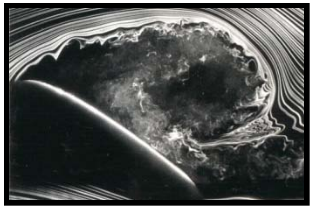
GDW – Limitations

- 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

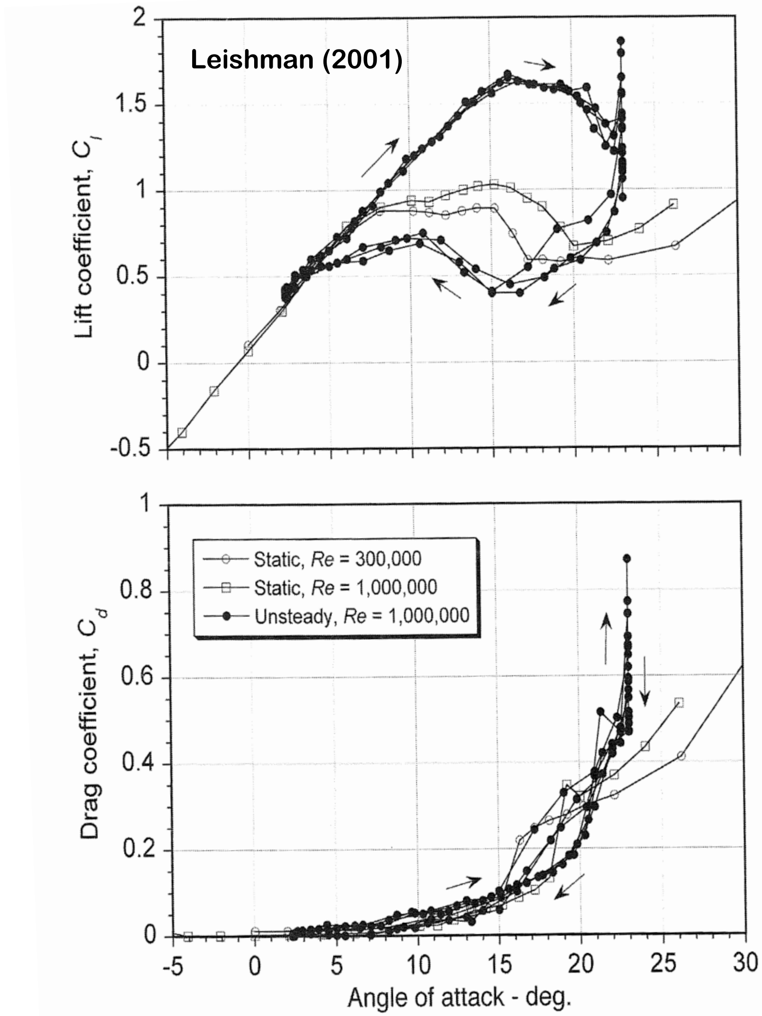
Unsteady Airfoil Aerodynamics







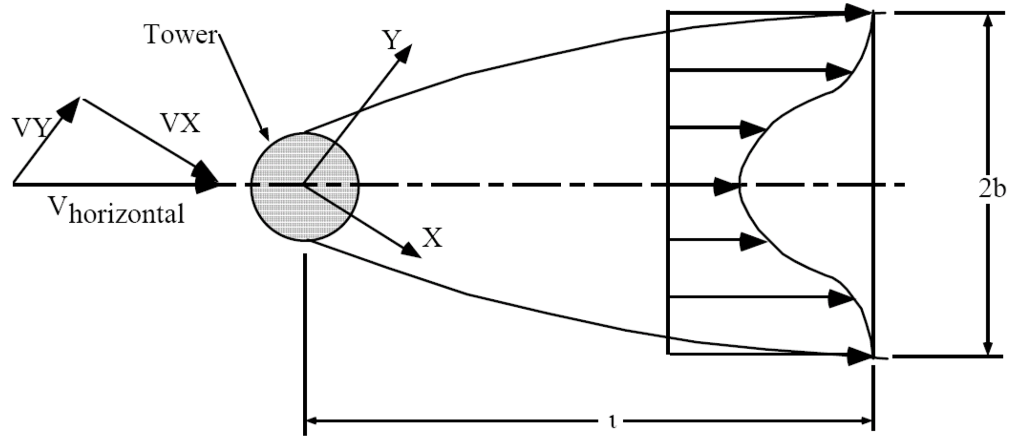
- Dynamically stalled flow field:
  - Static stall dynamically exceeded
  - C_n, C_t, C_m transiently amplified
  - Flow hysteresis
  - Produced by even slight yaw & turbulence
- Beddoes-Leishman model (1989):
  - A semi-empirical model
  - 3 submodels:
    - Unsteady attached flow
    - Trailing-edge flow separation
    - Dynamic stall & vorticity advection
  - Semi-empirical airfoil-dependent parameters derived from static data
- **AeroDyn** adds after induction calculations



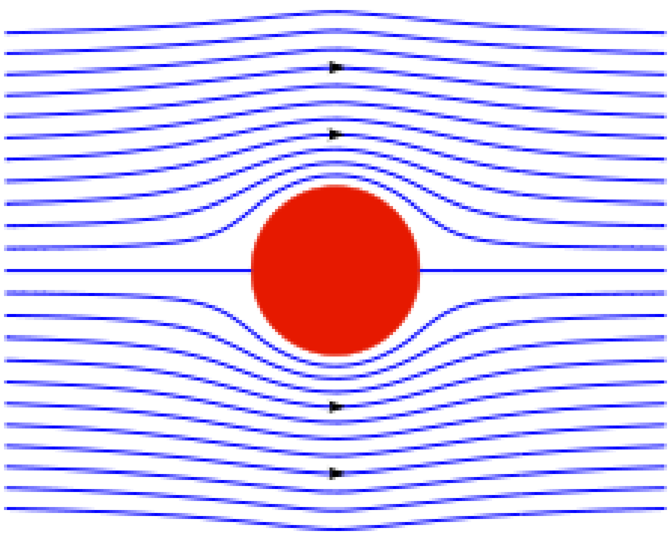
Dynamic Stall of S809 Airfoil

Tower Shadow

- Downwind tower shadow model:
  - Simple parabolic shape
  - Inputs:
    - Reference point
    - Velocity deficit
    - Wake width

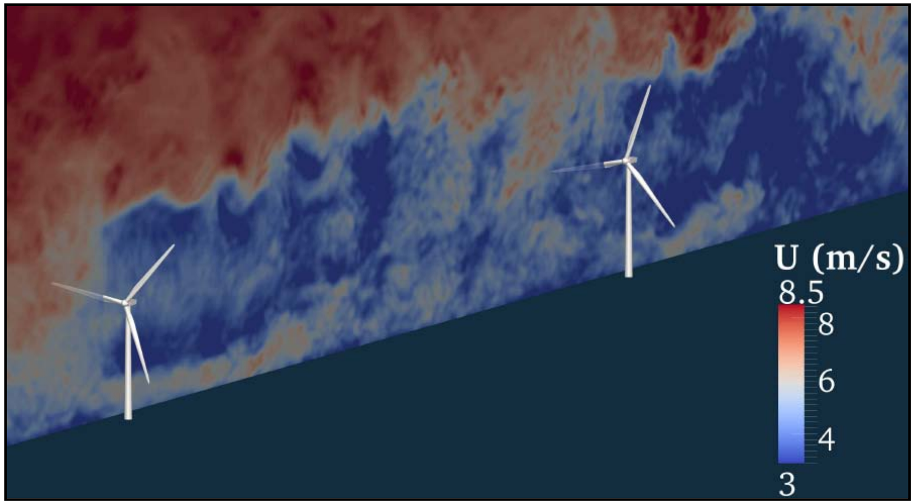


- Upwind tower-influence model:
  - Based on the potential flow solution around a cylinder
  - Included as an undocumented feature



Recent Work

- Changes in v13.00.02a-bjj:
  - Split **InflowWind** as a separate module
- Converted **AeroDyn** to new modular framework (for **FAST** v8)
- Interfaced **FAST/AeroDyn** to **OpenFOAM** for array modeling:
  - **SOWFA – S**imulator for **O**ffshore **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



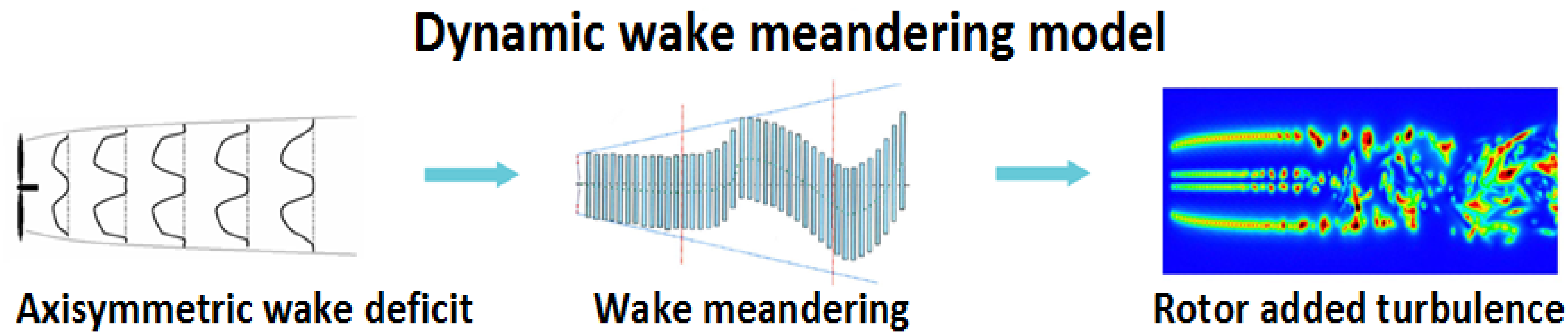
Example SOWFA Simulation

Current & Planned Work

- BEM:
  - Improved high induction model
  - Include updated algorithm with improved convergence
  - Wrap BEM iteration around all (wake, correction, dynamic-stall) calculations
  - Simplified dynamic wake (time-filtered BEM)
- GDW:
  - Initialize with single BEM solution
  - Resolve the numerical instability at low wind speeds
  - Improve for variable rotor speed
  - Include an inflow velocity filter based on the work of Peters & He
  - Add option to choose number & type of flow states
  - 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 influence & loading:
  - Improve tower-influence model based on current position of tower
  - Add tower-loading model
- Wake & array effects:
  - Couple **OpenFOAM** with **WRF** (**SOWFA**)
  - Add a Dynamic Wake Meandering (DWM) model (with UMass)



Future Opportunities

- Wake:
  - Hub & tip loss corrections for BEM – e.g. Goldstein, Shen et al
  - Coned rotor corrections for BEM – e.g. Mikkelson, Crawford
  - Vortex wake methods (prescribed & free)
  - Frozen wake for linearization
  - Wake tracking

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 standalone aeroacoustics module (to replace **FAST**'s noise module)
- Nacelle & hub influence & loading
- Improved tail-fin aerodynamics
- Implement new physics for hydro-kinetic turbines
- Extend aerodynamics model for VAWTs

Questions?

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