

Overview of the AeroDyn Aerodynamics Module



**NREL Wind Turbine
Modeling Workshop**

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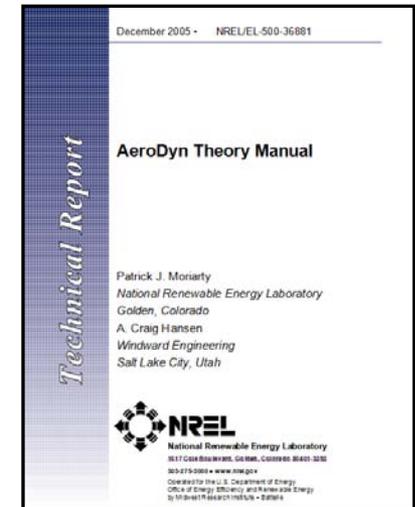
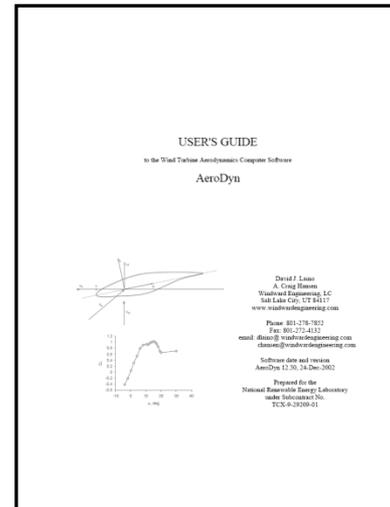
Outline

- Overview:
 - AeroDyn – What Is It?
 - Inputs
 - Outputs
 - Flowchart
- Wake Modeling:
 - Blade-Element / Momentum (BEM):
 - Glauert Correction
 - Tip & Hub Losses
 - Skewed Wake
 - Generalized Dynamic Wake (GDW)
- Dynamic Stall
- Tower Shadow
- Recent Work
- Overhaul:
 - Current & Planned Work
 - Future Opportunities

Overview

AeroDyn – What Is It?

- Wind turbine aerodynamics routines:
 - Not stand alone
 - Coupled to **FAST**, **MSC.ADAMS**, **SIMPACT**, **MotionSolve**, **FEDEM**, etc. for aero-elastic simulation
- Developed by Windward Engineering (Craig Hansen, et al) & NREL
- Latest version:
 - v13.00.01a-bjj (February 2012)
 - Newer in progress
- User's Guide:
 - Laino & Hansen (2002)
- Theory Manual:
 - Moriarty & Hansen (2005)



Overview

Inputs

- Local airfoil position, orientation, & velocity from structural code
- Wind flow field:
 - Full-field turbulence (**TurbSim**)
 - 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:
 - Dynamic or quasi-steady wake
 - Dynamic or static stall

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

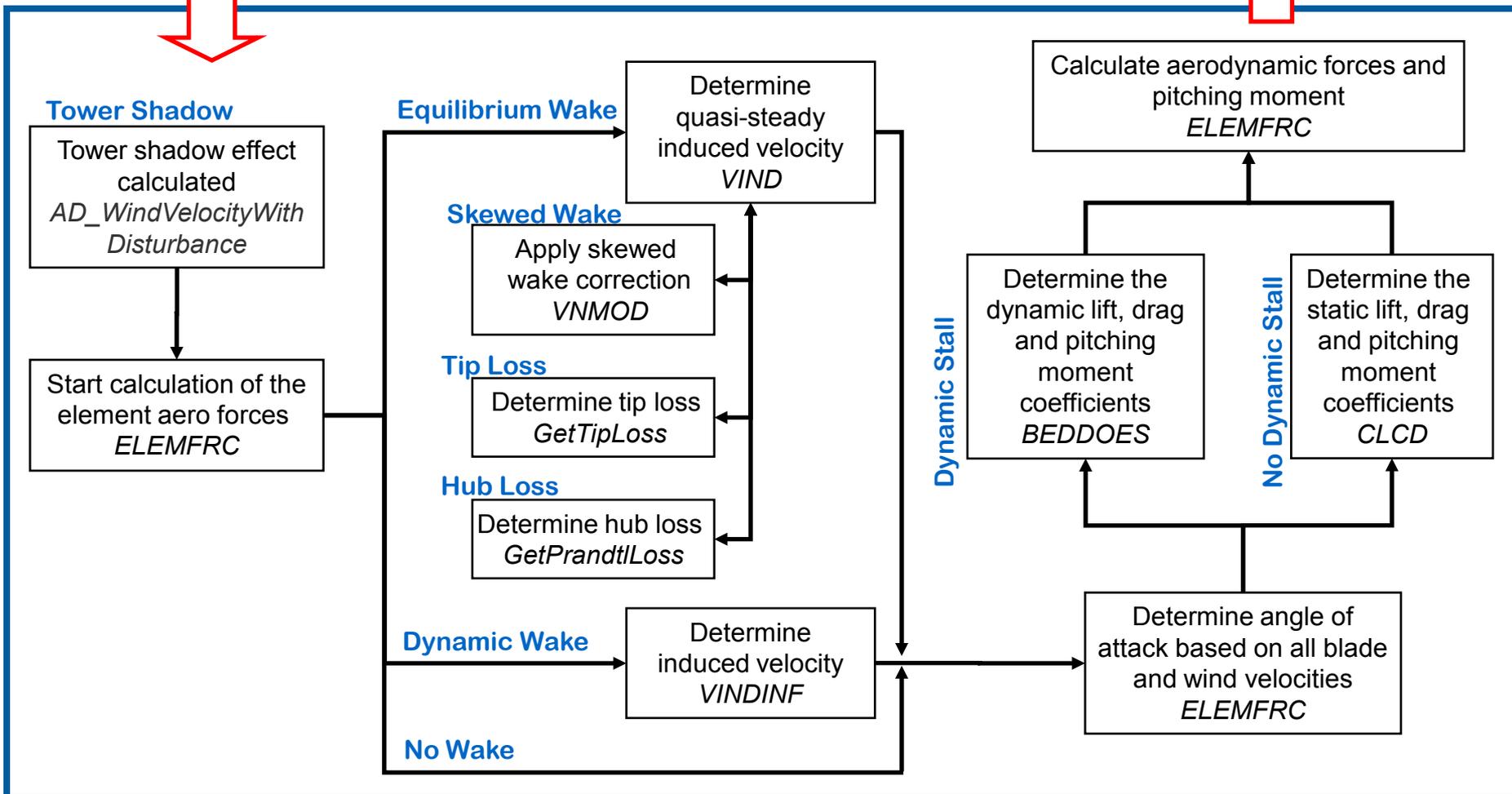
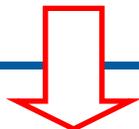
Overview

Flowchart

Positions, orientations, translational & rotational velocities for all elements

Aerodynamic forces and moments for all elements

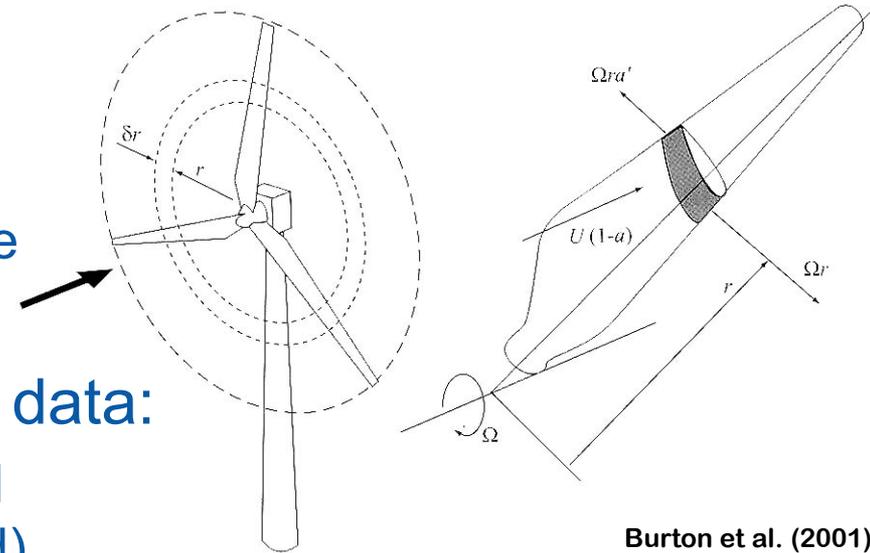
AD_CalculateLoads



Wake Modeling

Blade-Element / Momentum (BEM)

- Blades discretized into elements
- Momentum balance in annuli:
 - Linear \rightarrow axial induction (a)
 - Angular \rightarrow 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)
- 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

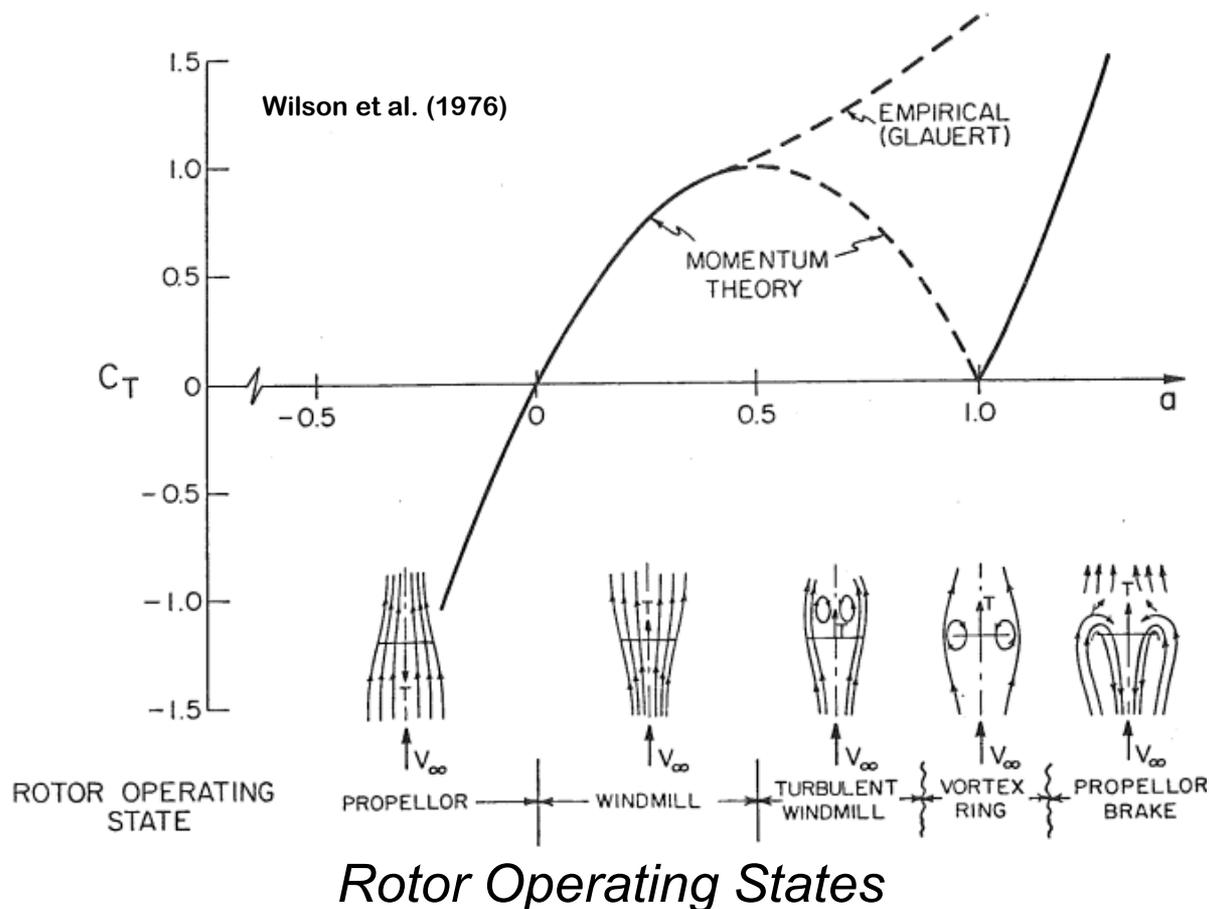


Burton et al. (2001)

Wake Modeling

BEM – Glauert Correction

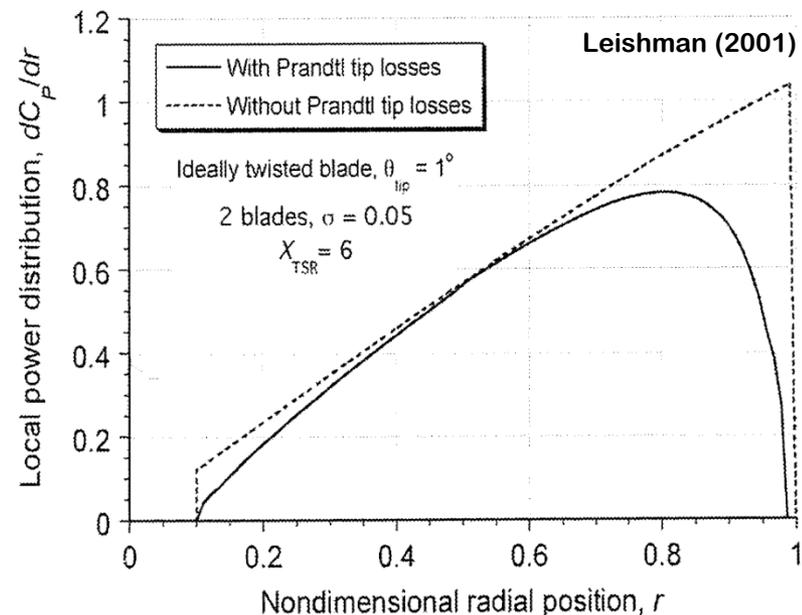
- Momentum balance invalid for high induction ($a > \sim 0.4$):
 - Glauert correction implemented



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

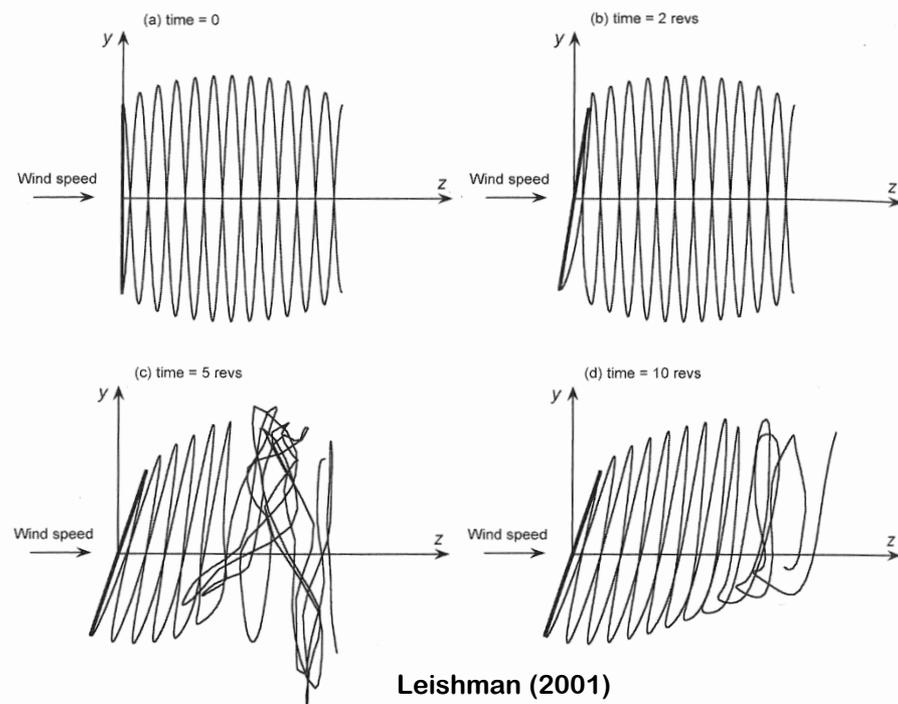


Local Power Coefficient with & without Tip Loss

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)

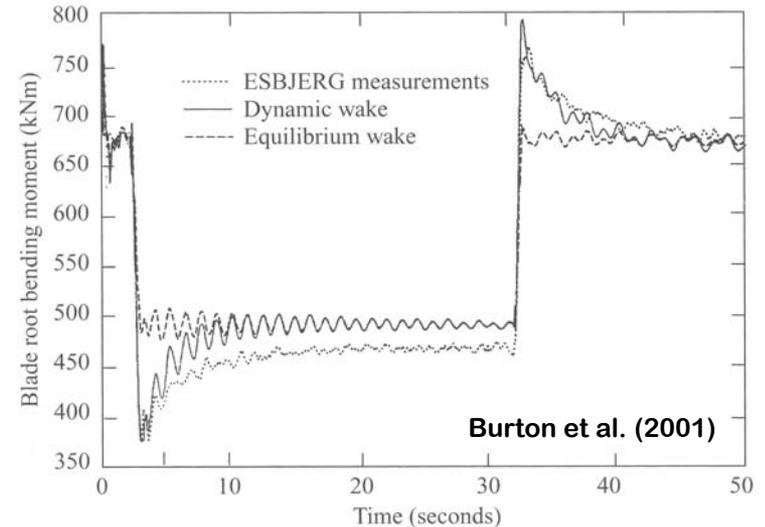


*Free-Vortex Wake Calculation
of a 30° Yawing Event*

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 4th-order ABAM scheme:
 - Initialized with 1 s of BEM
 - Tip losses & skewed wake automatically modeled with enough states



Blade Loading During Rapid Pitch Events

Wake Modeling

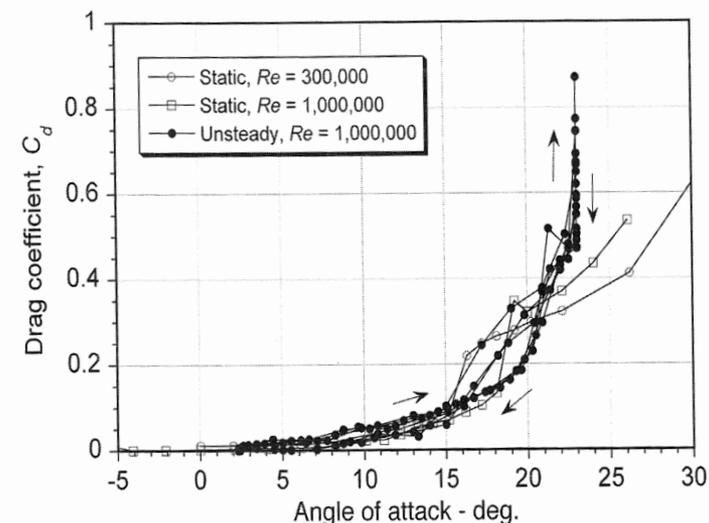
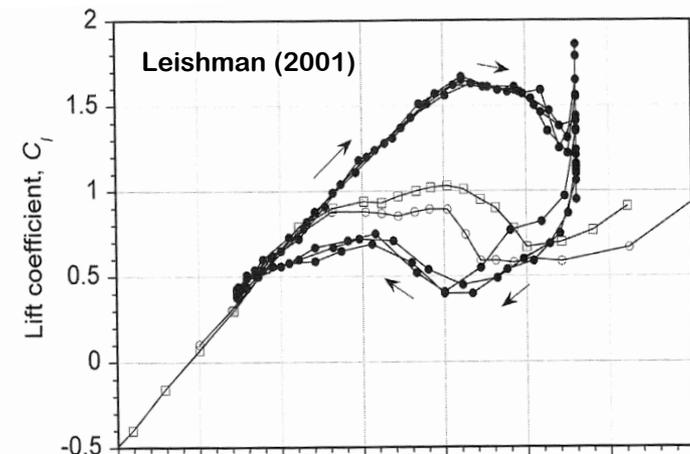
GDW – Limitations

- Limitations to GDW theory:
 - Uniform inflow (i.e. no or very low turbulence)
 - Constant rotor speed
 - Induced velocity \ll 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

Dynamic Stall



- 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

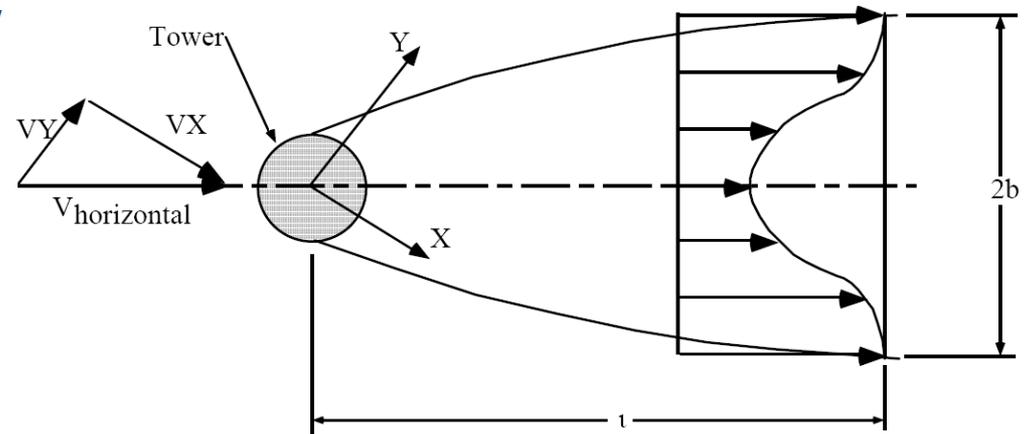


Dynamic Stall of S809 Airfoil

Tower Shadow

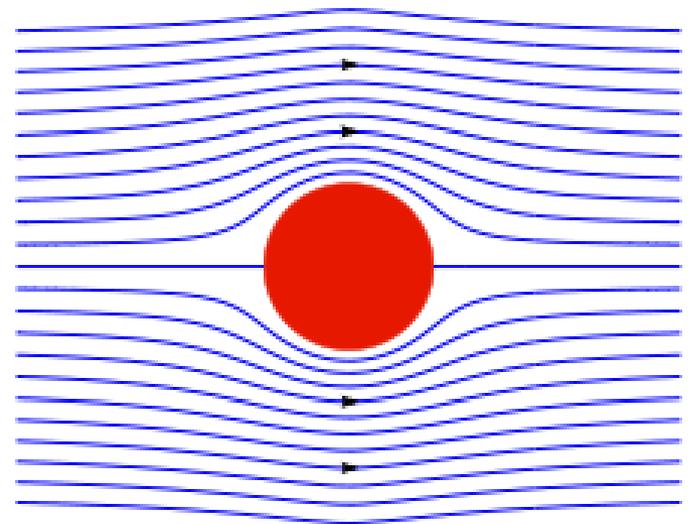
- Downwind tower shadow model:

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



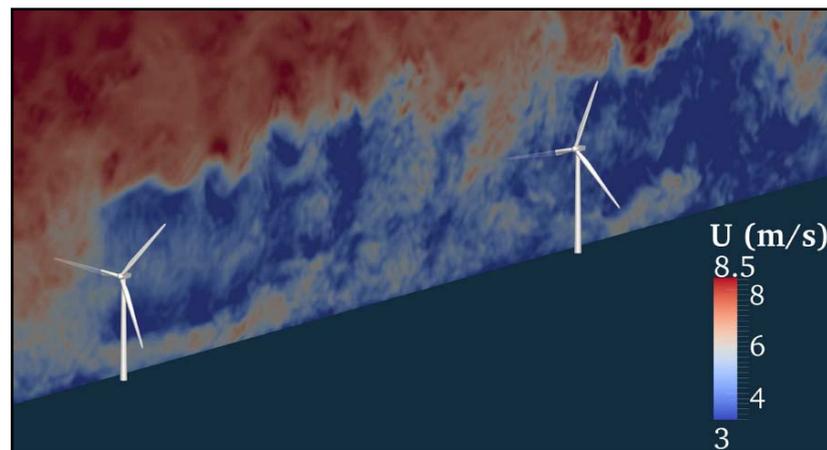
- Upwind tower-influence model:

- Based on the potential flow solution around a cylinder
- Included as an undocumented feature



Recent Work

- Changes in v13.00.01a-bjj:
 - Added ability to read-in **HAWC** wind format (e.g., Mann turbulence)
 - Several minor changes & bug fixes
- Interfaced **FAST/AeroDyn** to **OpenFOAM** for array modeling:
 - **SOWFA** – Simulator for **Offshore Wind Farm Applications**
 - **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 aerodynamic forces to **OpenFOAM** & **FAST**:
 - Body forces applied to CFD flow field using actuator line approach
 - Capable of:
 - Multiple turbines
 - Aero-elastics



Example SOWFA Simulation

Overhaul

Current & Planned Work – Theory / Structure

- BEM:
 - Include updated algorithm with improved convergence
 - Wrap BEM iteration around all (wake, correction, dynamic-stall) calculations
- GDW:
 - Initialize with single BEM solution
 - Add option to choose number & type of flow states
 - Adapt for variable rotor speed
 - Include a filtered velocity based on the work of Peters & He
 - Include turbulent wake state correction
 - Revise algorithms per recommendation of Peters
- Wake & array effects:
 - Add a Dynamic Wake Meandering (DWM) model (with UMass & DTU Wind)

Overhaul

Current & Planned Work – Theory / Structure (cont)

- Airfoil aerodynamics:
 - Add option to automate rotational augmentation calculation (as an alternative to **AirfoilPrep**)
 - Add option to interpolate airfoil data from input to analysis nodes
 - Revise dynamic-stall algorithms per recommendation of Leishman
- Tower influence & loading:
 - Improve tower-influence model based on current position of tower
 - Add tower-loading model
- General:
 - Improve modularization:
 - Create separate modules for wind inflow, airfoil aerodynamics, & induction
 - Implement model-specific time-integration schemes
 - Interface **FAST** with the ECN-developed **AWSM** free-wake vortex code
 - Interface **FAST** with the DTU Wind-developed **HAWC2** aero. module

Overhaul

Future Opportunities – Add New Models

- Hub & tip loss corrections for BEM:
 - e.g.: Shen et al (2005)
- Coned rotor corrections for BEM:
 - e.g.: Mikkelsen (2001) & Crawford (2006)
- Dynamic stall:
 - e.g.: Galbraith et al (2008), Munduate et al (2008), ONERA (1989)
- Linearization of wake & dynamic stall:
 - Frozen BEM & GDW
 - Hansen et al dynamic stall (2004)
- Vortex wake methods (prescribed & free)
- Develop standalone aeroacoustics module (to replace **FAST**'s noise module)
- Nacelle & hub influence & loading
- Influence of large & low-frequency floating platform motions on wake
- Wake tracking
- Improved tail-fin aerodynamics
- Implement new physics for hydro-kinetic turbines

Questions?



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