Overview of the AeroDyn Aerodynamics Module

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• Wake Modeling:
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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:
- Theory Manual:
  - Moriarty & Hansen (2005)
Introduction & Background
Inputs, Outputs, States, & Parameters

AeroDyn

Continuous States:
• Induction in GDW

Discrete States:
• States in B-L dynamic stall

Constraint States:
• Induction in BEM

Parameters:
• Geometry
• Airfoil data
• Undisturbed wind inflow
• Air Density

Inputs:
• Turbine disp.
• Turbine velocities

Outputs:
• Aero. loads
• Wind

Introduction & Background
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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

![Graph showing lift and drag coefficients vs. angle of attack]

*S809 Airfoil Data @ Re=750M*
Introduction & Background

Flowchart

- **Tower Shadow**
  - Tower shadow effect calculated
  - `AD_WindVelocityWithDisturbance`

- **Start calculation of the element aero forces** `ELEMFRC`

- **Equilibrium Wake**
  - Determine quasi-steady induced velocity `VIND`

- **Skewed Wake**
  - Apply skewed wake correction `VNMOD`
  - **Tip Loss**
    - Determine tip loss `GetTipLoss`
  - **Hub Loss**
    - Determine hub loss `GetPrandtlLoss`

- **Dynamic Wake**
  - Determine induced velocity `VINDINF`

- **No Wake**
  - **Dynamic Stall**
    - **No Dynamic Stall**
      - Calculate aerodynamic forces and pitching moment `ELEMFRC`
      - Determine the static lift, drag and pitching moment coefficients `CLCD`
      - Determine angle of attack based on all blade and wind velocities `ELEMFRC`
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
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
  - 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
Wake Modeling
BEM – Glauert Correction

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

*Wilson et al. (1976)*

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*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
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

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

Leishman (2001)
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
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
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
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

<table>
<thead>
<tr>
<th>FAST Features</th>
<th>v7.02</th>
<th>v8.08</th>
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<tbody>
<tr>
<td>Quasi-steady or dynamic wake</td>
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<td>✓</td>
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<tr>
<td>Steady or unsteady airfoil aerodynamics</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Tower shadow for downwind rotors</td>
<td>✓</td>
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<tr>
<td>Tower influence for upwind rotors</td>
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<tr>
<td>Tower drag loading</td>
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<tr>
<td>Tail-fin aerodynamic loading</td>
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<tr>
<td>&quot;Hub-height&quot;, TurbSim, and Bladed wind file formats</td>
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<td>Other wind formats</td>
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<tr>
<td>Aeroacoustics (noise)</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Modeling Guidance

• **Time step:**
  - $\text{DTAero} = 200$ azimuth steps per revolution

• **Blade & tower discretization:**
  - $\text{TwrNodes} \sim 20$ (in *ElastoDyn*)
  - Tower discretization in *ElastoDyn* is currently used by *AeroDyn*
  - $\text{BldNodes} \sim 20$
  - 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 – Simulator for 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 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)

\(^*\)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)
Future Opportunities

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

- **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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