Overview of the AeroDyn Aerodynamics Module

Design Codes Workshop

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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, etc. for aero-elastic simulation

• Developed by Windward Engineering (Craig Hansen, et al) & NREL

• Latest version:
  – v13.00.00a-bjj (March 2010)
  – Newer in progress

• User’s Guide:

• Theory Manual:
  – Moriarty & Hansen (2005)
Overview

Inputs

- Local airfoil position & motion from dynamics routines
- 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. $\alpha$ & Re) & dynamic stall constants (6)
  - 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 dynamics routines:
  - Forces & moments
- Element quantities to output file:
  - Each time step for any or all elements
  - Local wind speed
  - $\alpha$, $C_l$, $C_d$, $C_n$, $C_t$, $C_m$
  - 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

**ELEMFRC**

Determine quasi-steady induced velocity $V_{IND}$

**VIND**

Apply skewed wake correction $VNMOD$

**Skewed Wake**

Determine angle of attack based on all blade and wind velocities $ELEMFRC$

**AD_CalculateLoads**

Calculate aerodynamic forces and pitching moment $ELEMFRC$

**Tip Loss**

Determine tip loss $GetTipLoss$

**Hub Loss**

Determine hub loss $GetPrandtlLoss$

**Dynamic Wake**

Determine induced velocity $V_{INDINF}$

**Tower Shadow**

Tower shadow effect calculated $AD\_WindVelocityWithDisturbance$

**Start calculation of the element aero forces** $ELEMFRC$

**Equilibrium Wake**

Determine the dynamic lift, drag and pitching moment coefficients $BEDDOES$

**Dynamic Stall**

Determine the static lift, drag and pitching moment coefficients $CLCD$

**No Dynamic Stall**

Determine angle of attack based on all blade and wind velocities $ELEMFRC$

**No Wake**

Calculate tower shadow effect $AD\_WindVelocityWithDisturbance$

**Skewed Wake**

Determine the dynamic lift, drag and pitching moment coefficients $BEDDOES$

**No Dynamic Stall**

Determine the static lift, drag and pitching moment coefficients $CLCD$
Wake Modeling
Blade Element Momentum (BEM)

- Blades broken into N elements
- Rotor plane broken into N annuli
- Momentum balance in annuli:
  - Done per blade
- Airfoil data used
- Drag terms can be used in calc. of induced velocities:
  - Axial & tangential (undocumented)
- Limitations to theory:
  - No interaction between annuli (2-D only)
  - Theory only valid for uniform circulation (uniform induction)
  - Instantaneous reaction of wake to loading changes
  - Invalid when $a > \sim 0.4$ (Glauert correction implemented)
  - Despite these, BEM is applied in many conditions

Burton et al. (2001)
Wake Modeling
BEM – Tip & Hub losses

• Tip loss correction:
  – Prandtl (1919) / Glauert (1935):
    • Non-expanding wake
    • Large error < 3 blades
    • “Linearized” version
      \[ dT = 4\pi \rho V^2 (1-a) aF dr \]
      \[ dQ = 4\pi r^3 \rho \Omega (1-a) a' F dr \]
  – Xu & Sankar (2002):
    • Empirical correction to Prandtl using CFD of NREL Phase VI

• Blade root loss:
  – Prandtl only

\[
F = \frac{2}{\pi} \cos^{-1}\left( e^{-\frac{N}{2} \frac{r-R}{r} \sqrt{1+\lambda^2}} \right)
\]
Wake Modeling
BEM – Skewed wake

• Skewed wake correction:
  – Coleman (1945):

    \[ a_{skew} = a \left[ 1 + K \frac{r}{R} \sin \psi \right] \]

  – AeroDyn:

    \[ a_{skew} = a \left[ 1 + \frac{15\pi}{32} \frac{r}{R} \sqrt{\frac{1 - \sin \gamma}{1 + \sin \gamma}} \left( \sin \delta \sin \psi + \cos \delta \cos \psi \right) \right] \]

  – Infinite number of blades
  – Non-expanding wake
  – Applied after induction iteration
  – Does not affect \( a' \)
Wake Modeling

Generalized Dynamic Wake (GDW)

- Peters, Boyd, & He (1989):
  - Kinner’s (1937) solution to Laplace’s equation for pressure distribution:
    \[
    p(v, \eta, \psi) = \sum_{m=0}^{\infty} \sum_{n=m+1,m+3,...} \hat{P}_n^m(v) \hat{Q}_n^m(i \eta) \left[ \epsilon_n^m(i) \cos(m \psi) + \epsilon_n^m(i) \sin(m \psi) \right]
    \]
  - Unsteady Euler equations used to calculate induced velocities:
    \[
    M \left[ \frac{dw}{dt} \right] + L^{-1}[w] = p
    \]
  - 10 flows states or harmonics modeled (4% error for light loading)
  - Finite number of blades
  - Unsteady wake response
  - Tip losses & skewed wake automatically modeled
Wake Modeling
GDW – Limitations

- Steady & uniform inflow (i.e. no or very low turbulence)
- Induced velocity $\ll$ mean wind speed:
  - Unstable below 8 m/s
- No tangential induction:
  - Uses BEM
- 33 states needed to accurately model tip losses
- Despite these, recommend use whenever possible

Burton et al. (2001)
Dynamic Stall

- Dynamically stalled flow field:
  - Static stall dynamically exceeded
  - $C_n$, $C_t$, $C_m$ transiently amplified
  - Produced by even slight yaw
- Beddoes-Leishman (1989):
  - Semi-empirical model
  - Six input parameters per airfoil derived from static data
  - Four time constants empirically tuned to S809 airfoil (Pierce & Hansen, 1995)
- **AeroDyn** adds after induction calculations
Tower Shadow

- **Simple parabolic shape:**
  - Reference point
  - Velocity deficit
  - Wake width
Overhaul
Reasons for Overhaul

• Trouble developing, maintaining, & using AeroDyn
• Common request from users
• Desire to have improved:
  – Functionality
  – Usability
  – Code readability
• Eliminate problems
• Make it easier to include additional aerodynamic theories
• Develop a standardized & streamlined interface to structural dynamic analysis programs
• Important because proper aerodynamic modeling is critical for accurate performance, loads, & stability analyses
Overhaul
Recent Work (Changes in v13.00.00)

• New interface between AeroDyn & structural codes has been implemented (all data exchanged in a single call per coupling step)
• Tower influence model documented in the theory manual has been implemented (as a hidden feature)
• Wind inflow has been removed from inside AeroDyn & made into a separate module
• Linked with NWTC Subroutine Library
• Uses metric system only (option for English units has been removed)
Overhaul
Recent Work (Wind Inflow Module in v13.00.00)

- All wind-inflow routines & variables are contained in a separate module with clear interface
- Can read TurbSim’s binary full-field “.bts” & tower “.twr” files
- Full-field wind files are relative to the ground, not the turbine hub-height
- Can be used outside of AeroDyn, e.g. the module has been made into a MATLAB mex function (allows easy access to the wind file data)
Overhaul
Current & Planned Work – Theory / Structure

• BEM – Include updated algorithm from WT_Perf

• GDW:
  – Initialize with single BEM solution
  – Add option to choose number & type of flow states
  – Include turbulent wake state correction
  – Include a filtered velocity based on the work of Peters & He

• Dynamic stall – Develop state-space-based version

• Tower influence & loading:
  – Improve tower-influence model based on current position of tower
  – Add tower-loading model

• Aeroacoustics – Develop standalone aeroacoustics module (to replace FAST’s noise module)

• Wind inflow module – Add ability to read in WaSP Engineering output (e.g., Mann turbulence)
Overhaul
Current & Planned Work – Theory / Structure (cont)

• General:
  – Improve modularization:
    • e.g.: Create separate modules for rotational augmentation, induction, element loading, & dynamic stall
  – Wrap BEM iteration around all (wake, correction, dynamic-stall) calculations
  – Implement model-specific time-integration schemes
  – Add option to automate rotational augmentation calculation (replace AirfoilPrep)
  – Add option to interpolate airfoil data from input stations to analysis nodes
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.: Mikkelson (2001) & Crawford (2006)
• Dynamic stall:
• Linearization of wake & dynamic stall:
  – Frozen BEM & GDW
• Vortex wake methods (prescribed & free)
• 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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