NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Overview of the AeroDyn Aerodynamics Module

Design Codes Workshop

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MIT – Cambridge, MA

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Outline

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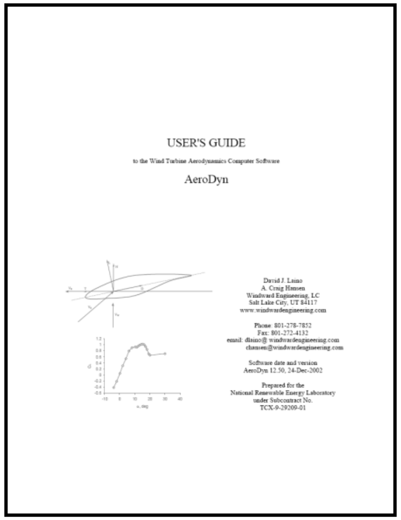
Overview

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:
  - 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

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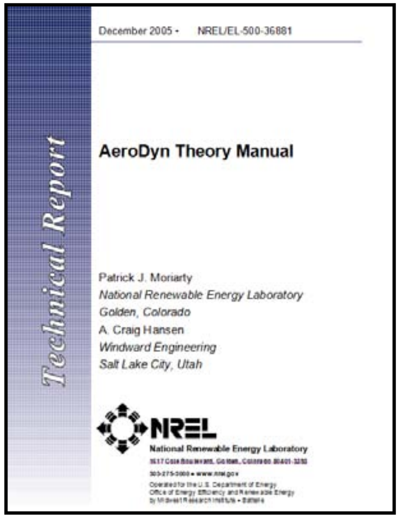

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Technical Report

AeroDyn Theory Manual

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Windward Engineering
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Overview
Inputs

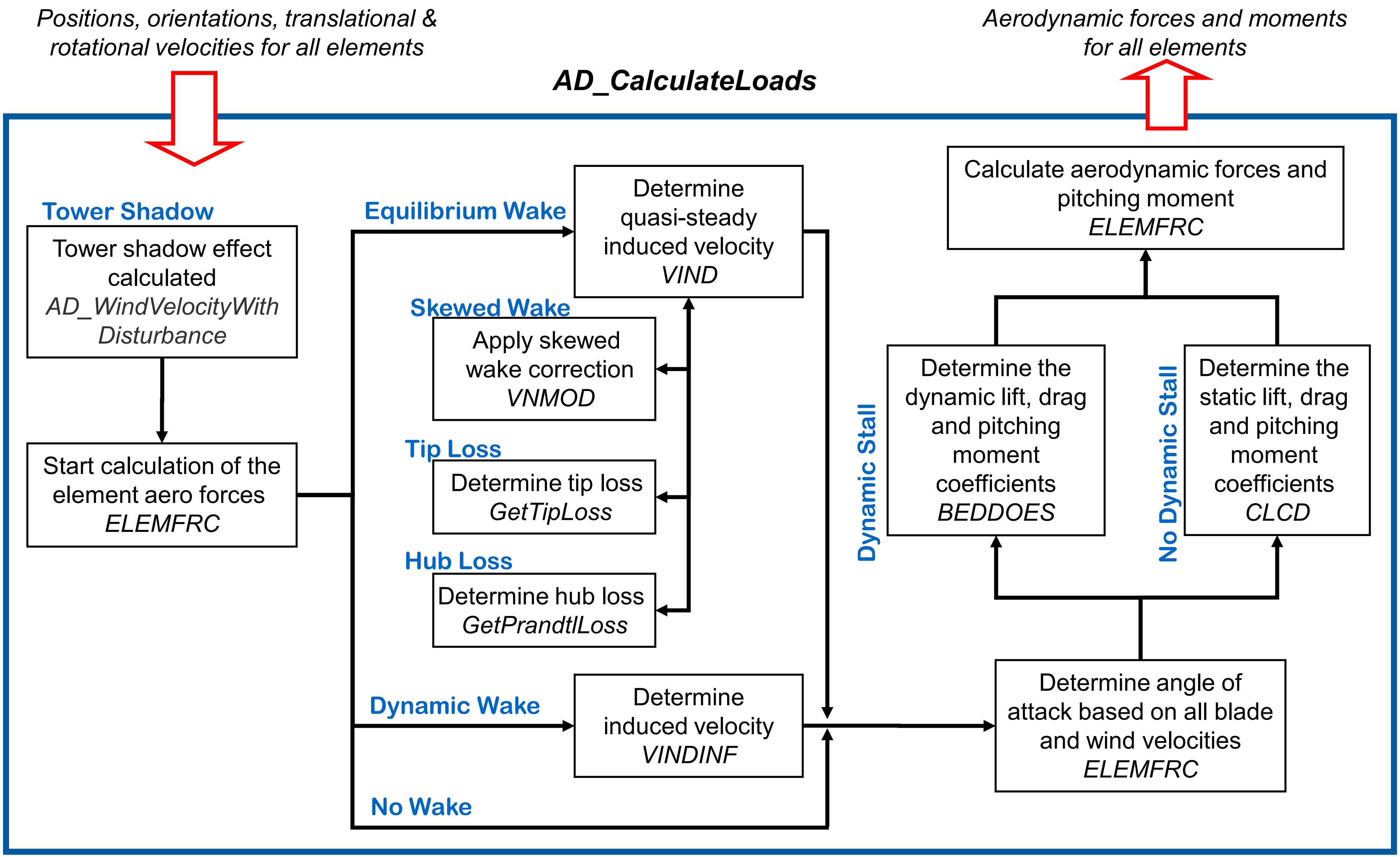
- Local airfoil position & motion from dynamics routines
- Wind flow field:
  - Full field turbulence (**TurbSim**)
  - Uniform, but time-varying
  - Measured
  - User-defined
- Tower shadow properties
- 2-D/3-D airfoil properties:
  - C_l, C_d, C_m (vs. α & Re) & dynamic stall constants (6)
  - **AirfoilPrep**
- 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
  - α, 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

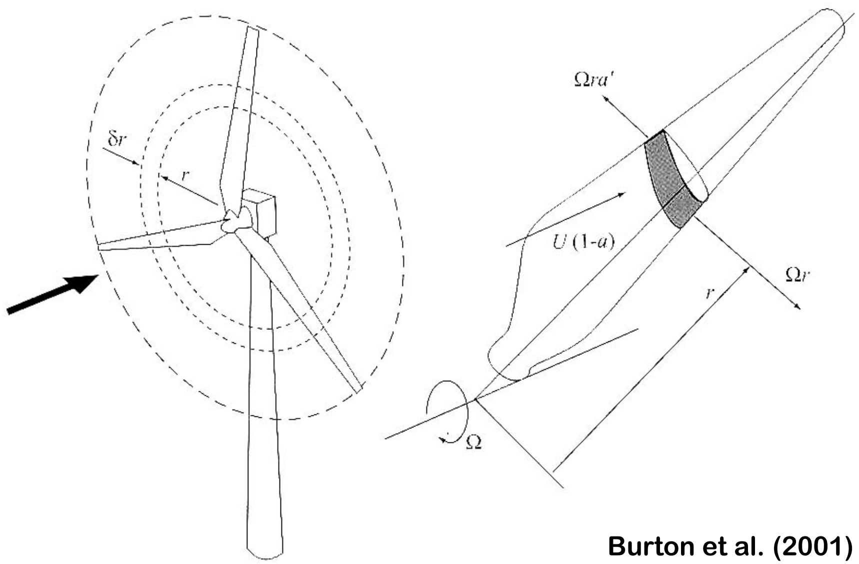
Overview
Flowchart



Wake Modeling

Blade Element Momentum (BEM)

- Blades broken into N elements
- Rotor plane broken into N annuli
- Momentum balance in annuli:
  - Done per element per blade
- Airfoil data used
- Drag terms can be used in calculation 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 > ~0.4 (Glauert correction implemented)
  - Despite these, BEM is applied in many conditions



Burton et al. (2001)

Wake Modeling

BEM – Tip & Hub losses

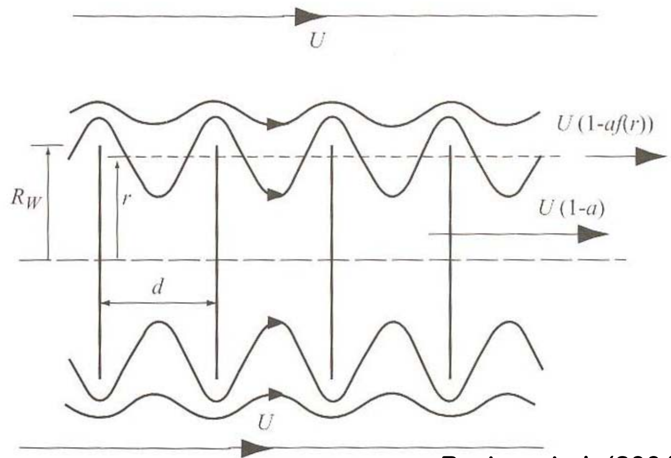
- Tip loss correction:
  - Prandtl (1919) / Glauert (1935):
    - Non-expanding wake
    - Large error < 3 blades
    - "Linearized" version

$$dT = 4\pi r \rho V^2 (1-a) a F dr$$

$$dQ = 4\pi r^3 \rho V \Omega (1-a) a' F dr$$

  - Xu & Sankar (2002):
    - Empirical correction to Prandtl using CFD of NREL Phase VI
- Blade root loss:
  - Prandtl only

$$F = \frac{2}{\pi}\cos^{-1}\left(e^{-\frac{N}{2}\frac{r-R}{r}\frac{\sqrt{1+\lambda^2}}{\lambda}}\right)$$



Burton et al. (2001)

Wake Modeling

BEM – Skewed wake

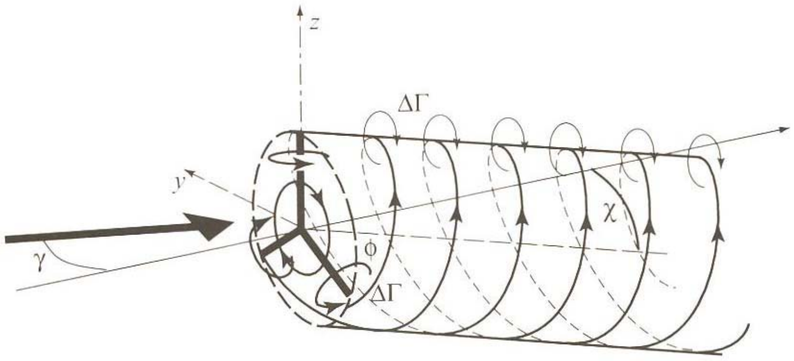
- Skewed wake correction:
  - Coleman (1945):

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

  - **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'



Burton et al. (2001)

Wake Modeling

Generalized Dynamic Wake (GDW)

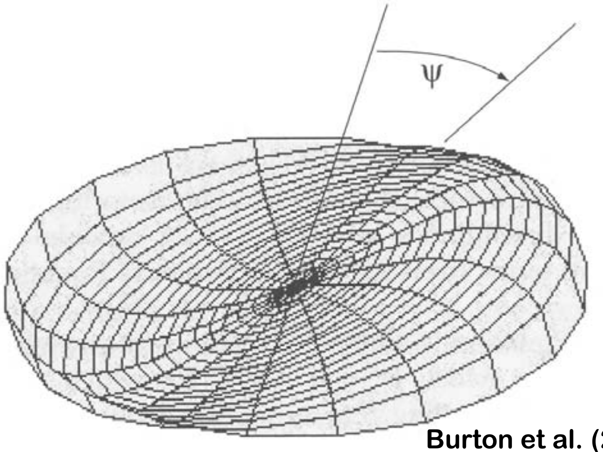
- Peters, Boyd, & He (1989):
  - Kinner's (1937) solution to Laplace's equation for pressure distribution:

$$p(\nu,\eta,\psi)=\sum_{m=0}^{\infty}\sum_{n=m+1,m+3,\cdots}^{\infty}\hat{P}_n^m(\nu)\hat{Q}_n^m(i\eta)\left[\tau_n^m(\hat{t})\cos(m\psi)+\tau_n^m(\hat{t})\sin(m\psi)\right]$$

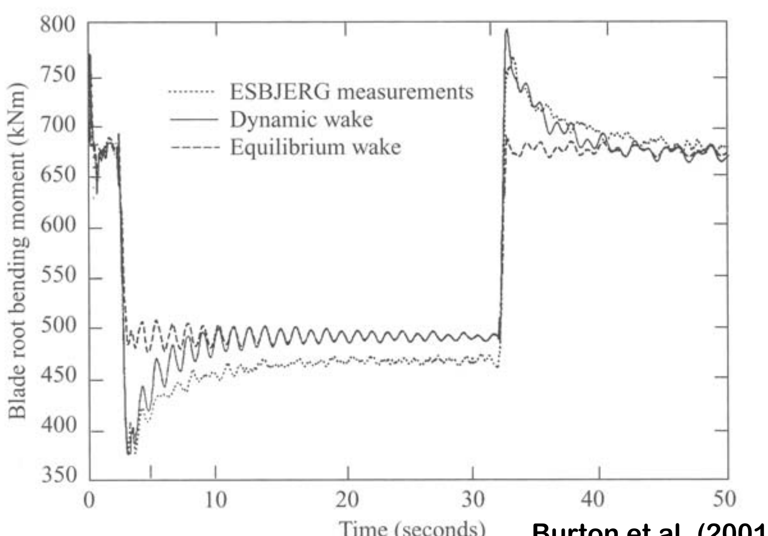
  - Unsteady Euler equations used to calculate induced velocities:

$$M\left[\frac{dw}{d\hat{t}}\right]+L^{-1}[w]=p$$

  - 10 flows states or harmonics modeled (4% error for light loading)
  - Finite number of blades
  - Unsteady wake response
  - Tip losses & skewed wake automatically modeled



Burton et al. (2001)

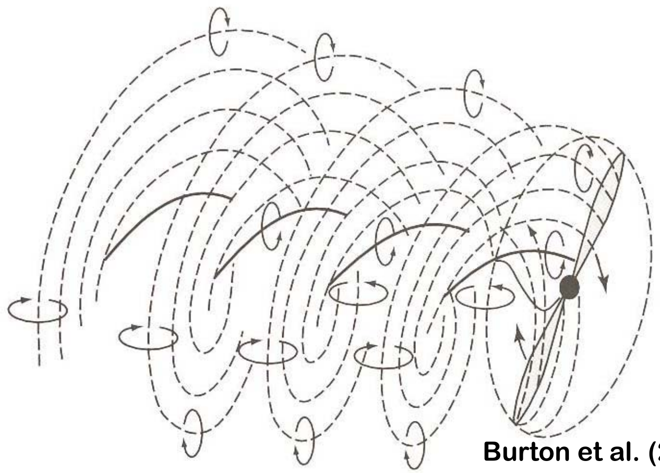


Burton et al. (2001)

Wake Modeling

GDW – Limitations

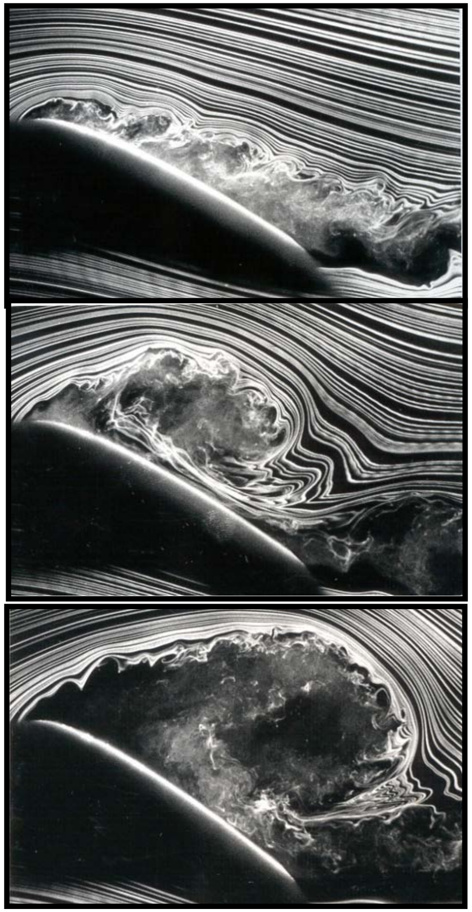
- Steady & uniform inflow (i.e. no or very low turbulence)
- Induced velocity << mean wind speed:
  - Unstable below 8 m/s
- No tangential induction:
  - Uses BEM
- 33 states needed to accurately model tip losses
- Despite these, recommend use whenever possible



Burton et al. (2001)

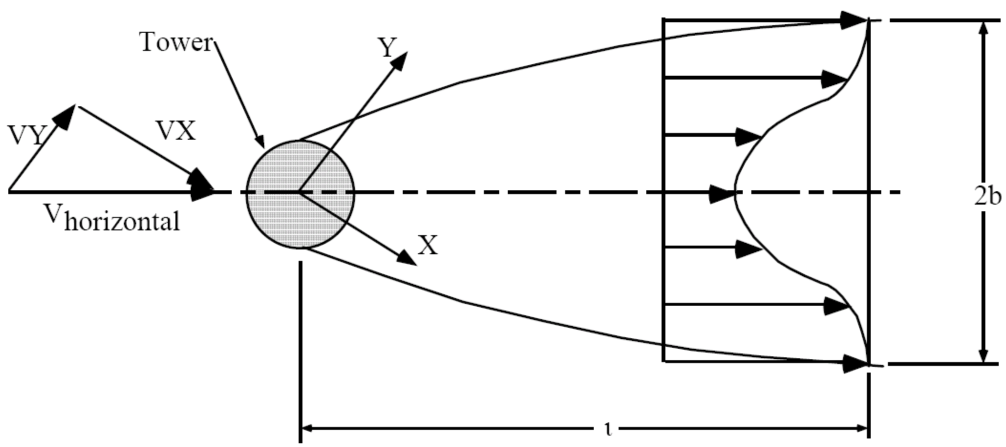
Dynamic Stall

- 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

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
- Can read **TurbSim**'s binary full-field ".bts" & tower ".twr" files
- Linked with **NWTC Subroutine Library**
- Uses metric system only (option for English units has been removed)

Overhaul

Current & Planned Work – Theory / Structure

- Wind inflow module – Add ability to read in **WaSP Engineering** output (e.g., Mann turbulence)
- 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

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:
  - 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

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Questions?

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