Recent Aeroelastic Enhancements in OpenFAST

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The OpenFAST Multiphysics Engineering Tool

- **OpenFAST** is DOE/NREL’s premier open-source wind turbine multi-physics engineering tool.
- **FAST** underwent a major restructuring, w/ a new modularization framework (v8).
- Not only is the framework supporting expanded functionality, but it is facilitating establishment of an open-source code-development community for multi-physics engineering models (OpenFAST).
Timeline of Recent Aeroelastic Enhancements

- **2012**
  - Original BeamDyn development

- **2013**
  - First release of FAST v8

- **2014**
  - Validation against Siemens data

- **2015**
  - AeroDyn overhaul

- **2016**
  - Begin collaboration w/ Envision Energy

- **2017**
  - Last release of FAST v8

- **2018**
  - First release of OpenFAST

- **2019**
Outline

• The OpenFAST Multiphysics Engineering Tool
• Timeline of Recent Aeroelastic Enhancements
• **Overview of BeamDyn & AeroDyn**
• Siemens Verification & Validation Collaboration
• NREL-Envision Collaboration
• Outlook
ElastoDyn Versus BeamDyn

- Previous beam model in FAST (v7 & ElastoDyn module of v8):
  - Euler-Bernoulli beam
  - Straight & isotropic
  - Bending only
  - Assumed-mode method
  - Some geometric nonlinearity

- New BeamDyn module:
  - Geometrically exact beam theory (GEBT)
  - Legendre spectral finite element (LSFE)
  - Both statics & dynamics
  - Time integration via generalized-α
BeamDyn Overview

- Full 6×6 cross-sectional mass & stiffness
  - Stiffness-proportional damping
- Curved/swept reference axis (spline based)
- Nonlinear geometrically exact large deflection
- Analyze blade w/ single LSFE
- Both Gauss & Trapezoidal-Rule spatial integration

**BeamDyn** Analysis of NREL 5-MW Blade w/ 49 Cross-Sectional Stations
AeroDyn Overview

• Actuator-line physics:
  o Static (BEM) or dynamic wake (DBEMT)
  o Static or unsteady airfoil aerodynamics (UA) (Beddoes-Leishman)
  o Tower drag & influence on wind

• Recent overhaul (v15)
  o Fixed underlying problems w/ original theoretical treatments
  o Introduced improved skewed-wake, dynamic wake, & UA
  o Enabled modeling of highly flexible & curved/swept blades
  o Supported features of FAST modularization framework
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Verification & Validation of FAST Against Siemens Data

- **FAST w/ BeamDyn** was verified against **BHawC** & validated against data through collaboration w/ Siemens:
  - 3-way code-to-code & code-to-data comparison

- Siemens 2.3-MW 108-m diameter turbine (SWT-2.3-108) @ NREL:
  - Upwind 3-bladed rotor
  - Aeroelastically tailored blades w/ bend-twist coupling
  - Variable speed & collective pitch
**Instrumentation & Measurements**

- **Instrumentation:**
  - Strain-gages @ blade root, main shaft, tower top, & tower bottom
  - FiberBragg strain sensors along blade
  - Blade surface pressure taps, pitot tubes (not used)
  - Rotor speed & electrical power
  - Inflow data recorded from 135-m met. tower located ~2.5D upstream
  - Data recorded @ 100 Hz & packaged into 10-min time series

- **Measurements:**
  - Large amount of data collected from 2013-2015
  - Total of 1141 10-min datasets under normal operation utilized, covering a range of inflow wind speeds & turbulence intensities (guided by IEC 61400-13)
Verification & Validation Results
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NREL-Envision Collaboration Overview

NREL & Envision Energy collaborate to advance **OpenFAST**

**BeamDyn**
- Fixed several bugs
- Eliminated need to compile in double precision
- Introduce preconditioning in **BeamDyn** to reduce start-up transients & allow for larger time steps
- Extensive cleanup of source code

\[ \approx 15 \times \text{speed up of OpenFAST w/ BeamDyn simulations} \]

**AeroDyn**
- Fixed several bugs
- Drastically improved robustness of BEMT algorithm
- Completed DBEMT to replace generalized dynamic wake (GDW) model of older versions of **AeroDyn**
Full-System Linearization Including BeamDyn

- New functionality enables linearization of full-system OpenFAST models w/ BeamDyn for land-based wind turbines for parked or operating rotors

- Key development steps:
  - Linearization of BeamDyn module to derive Jacobians of state & output equations w.r.t. states & inputs
  - Linearization of module-to-module input-output coupling relationships (including generalization of linearization implementation)
  - Full-system matrix assembly
  - Rewrote MBC3 post-processor
  - Verification for sample cases:
    - Fixed-free & free-free beams
    - Campbell diagram of NREL 5-MW wind turbine
Full-System Linearization Including BeamDyn – Results

Fixed-fixed

ElastoDyn Free-free BeamDyn

Mode Analytical Lineariz’n BD Summary File

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Free-Free Beam (Hz):

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Outlook

• Engineering models required to address design challenges so that wind turbines are:
  o Innovative
  o Optimized
  o Reliable
  o Cost-effective

• Improved models are needed for:
  o Upscaling to larger sizes
  o Novel architectures & controls
  o Coupling to offshore platforms
  o Design at the wind-plant level
  o System-wide optimization

\[\text{Thomsen (2013)}\]

\[\text{SWT-6.0-154 w/ Airbus A380}\]

\[\text{Horns Rev Wind Farm}\]
Carpe Ventum!

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