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: AeroDyn overhaul
- 2015: Validation against Siemens data
- 2016: Begin collaboration w/ Envision Energy
- 2017: First release of OpenFAST
- 2018: Last release of FAST v8
- 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):
  o Euler-Bernoulli beam
  o Straight & isotropic
  o Bending only
  o Assumed-mode method
  o Some geometric nonlinearity

• New BeamDyn module:
  o Geometrically exact beam theory (GEBT)
  o Legendre spectral finite element (LSFE)
  o Both statics & dynamics
  o 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

Blade Loading During Rapid Pitch Events

Dynamic Stall of S809 Airfoil

Leishman (2001)

Burton et al. (2001)
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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:
  o 3-way code-to-code & code-to-data comparison

• Siemens 2.3-MW 108-m diameter turbine (SWT-2.3-108) @ NREL:
  o Upwind 3-bladed rotor
  o Aeroelastically tailored blades w/ bend-twist coupling
  o 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
  \( \approx 15 \times \) 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

Mode Analytical Linearization BD Summary File

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Fixed-Free Beam (Hz):
1  0.5842    0.5776    0.5776
2  0.5842    0.5776    0.5776
3  3.6607    3.6060    3.6060
4  3.6607    3.6060    3.6060
5  10.2512   10.0173   10.0173
6  10.2512   10.0173   10.0173

Free-Free Beam (Hz):
1  3.7171    3.4070
2  3.7171    3.4070
3  10.2465   9.6849
4  10.2465   9.6849
5  20.0873   19.8438
6  20.0873   19.8438
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

SWT-6.0-154 w/ Airbus A380

Horns Rev Wind Farm
Carpe Ventum!

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