Recent Aeroelastic Enhancements in OpenFAST

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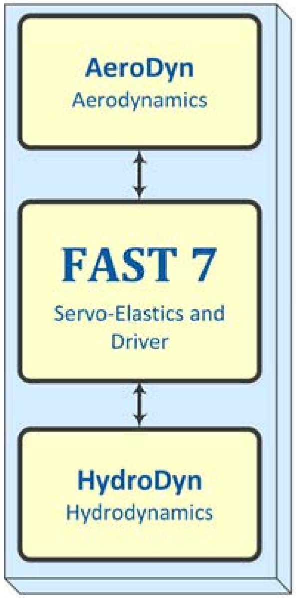
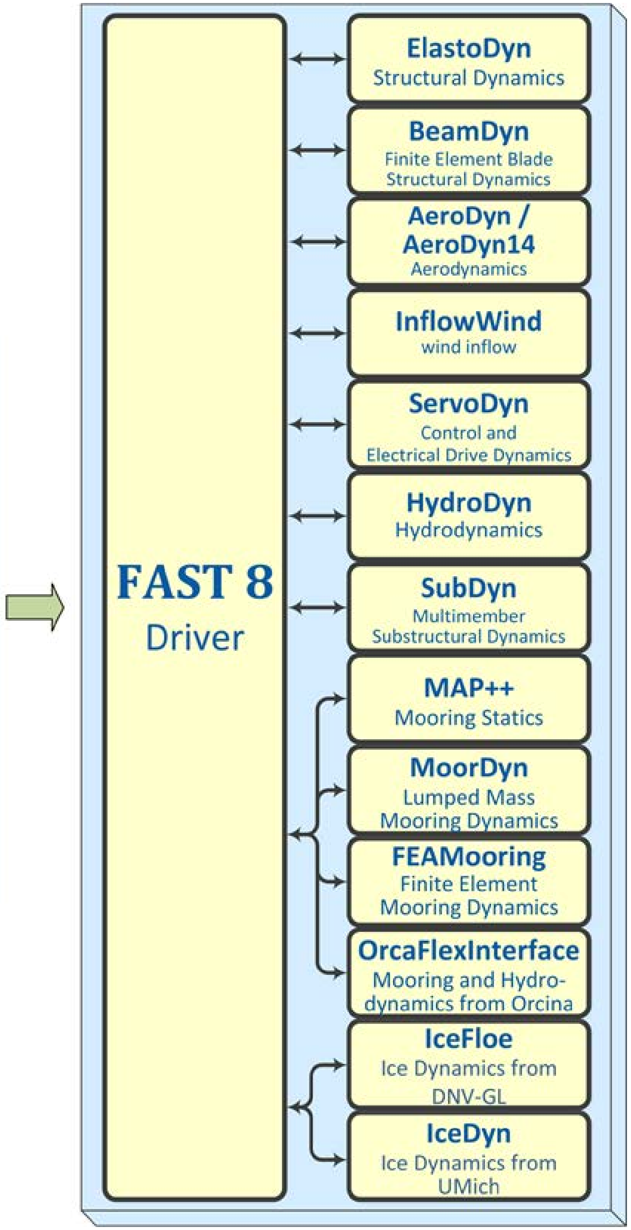
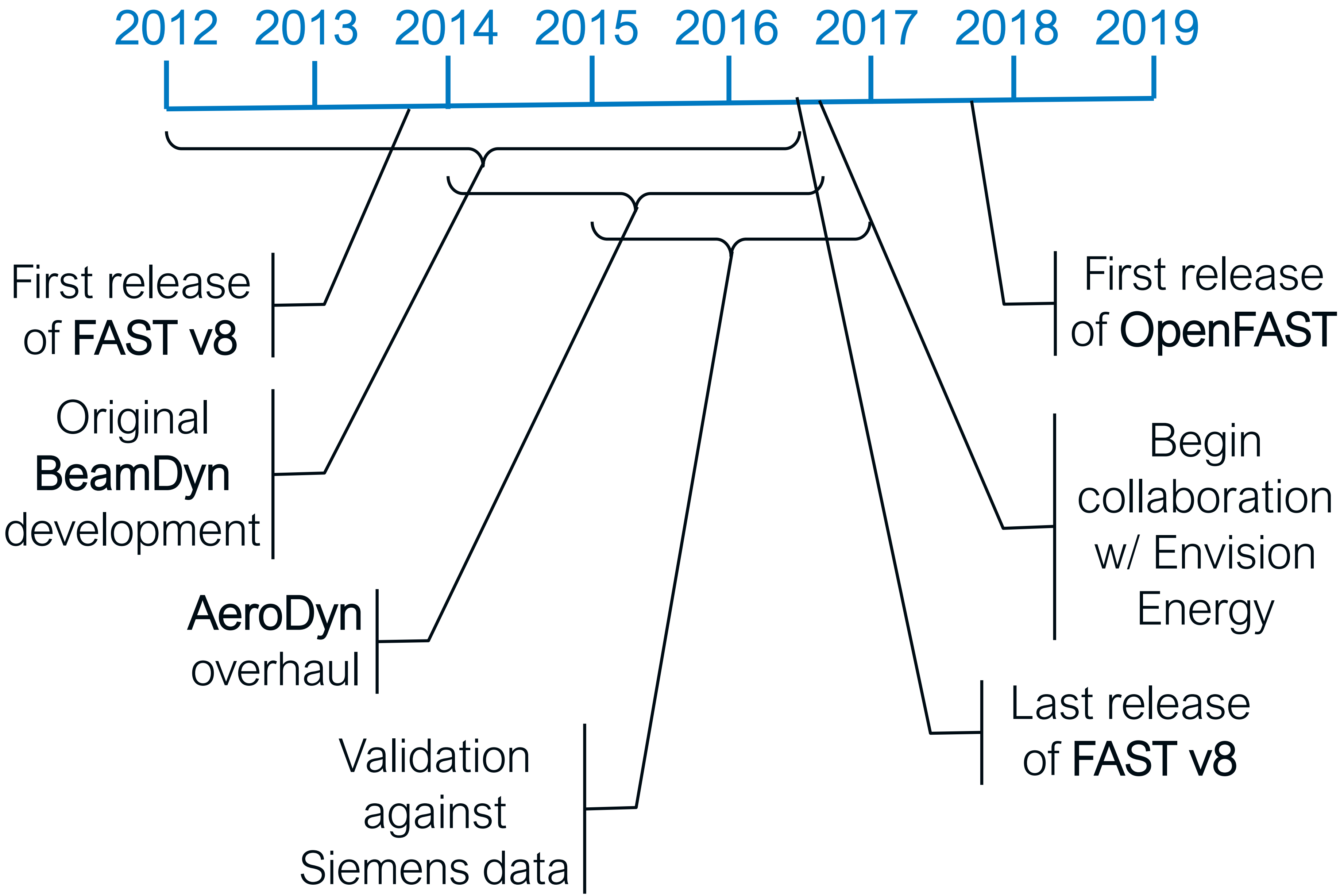
The OpenFAST Multiphysics Engineering Tool

- **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

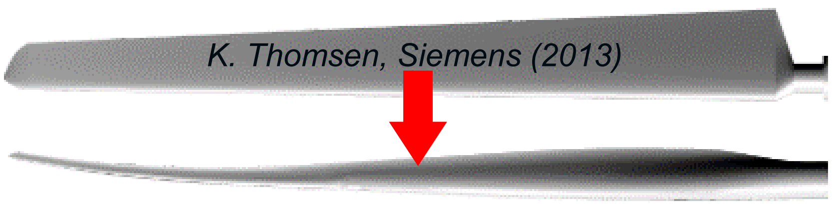


Outline

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

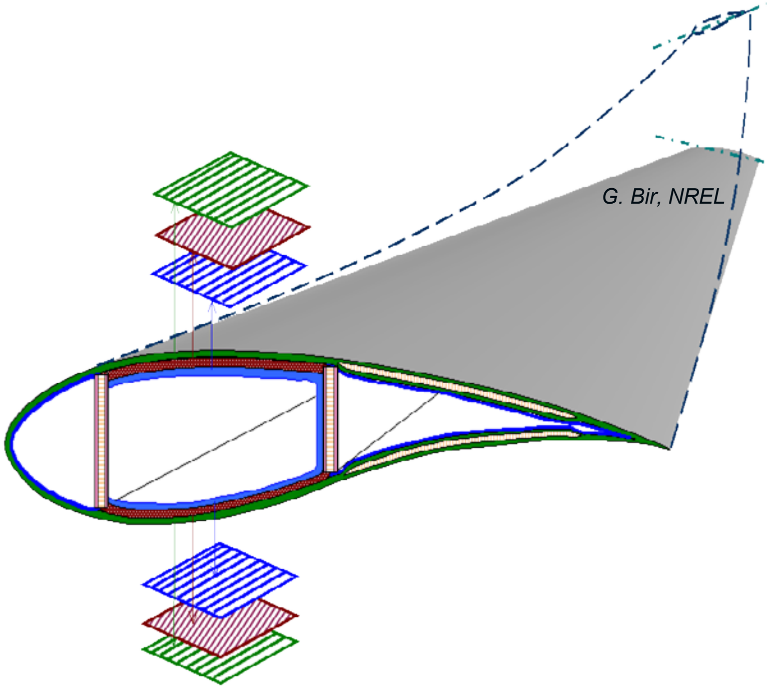
ElastoDyn Versus BeamDyn

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



Advancement in Blade Design

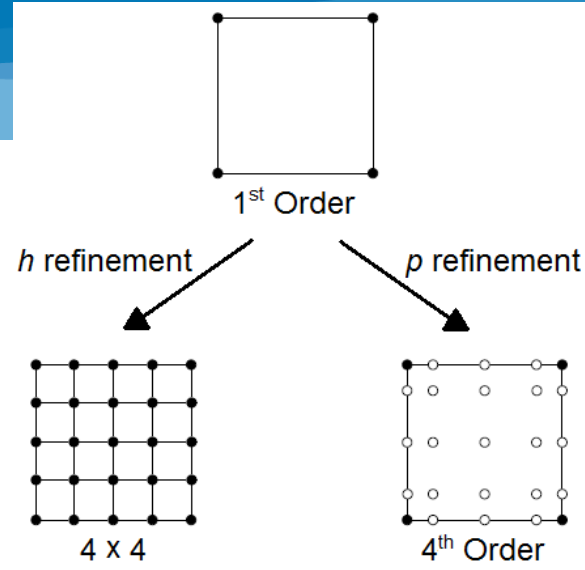
- New **BeamDyn** module:
  - Geometrically exact beam theory (GEBT)
  - Legendre spectral finite element (LSFE)
  - Both statics & dynamics
  - Time integration via generalized-α

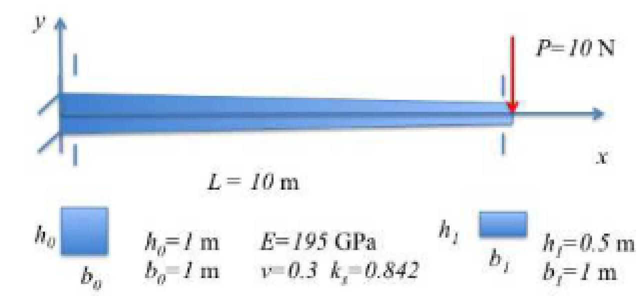


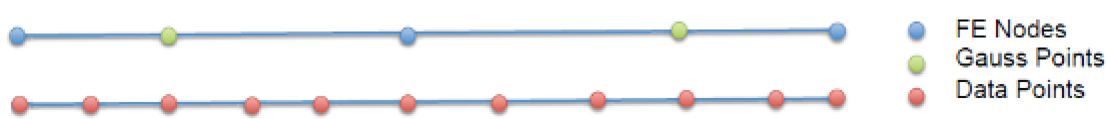
Blade Twist Induced By Anisotropic Layup

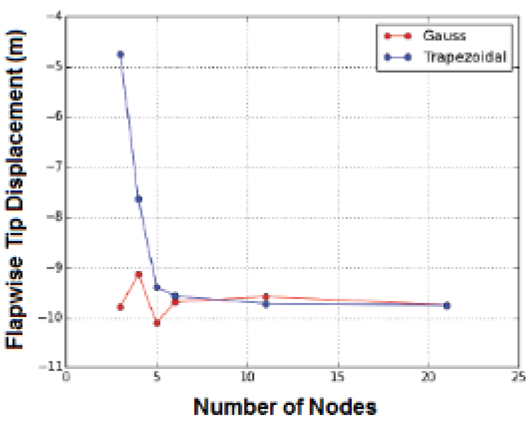
BeamDyn Overview

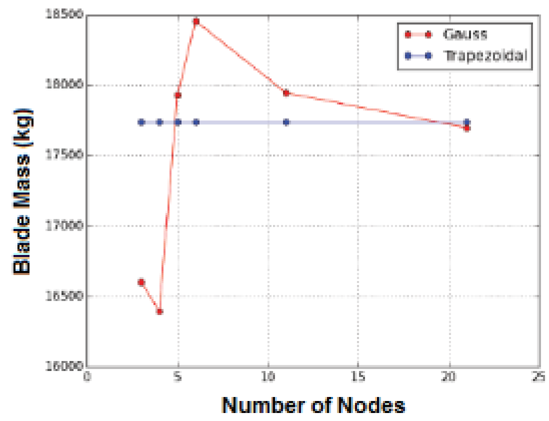
- Full 6×6 cross-sectional mass & stiffness
  - Stiffness-proportional damping
- Curved/swept reference axis (spline based)
- Nonlinear geometrically exact large deflection
- Analyze blade w/ single LSFE
- Both Gauss & Trapezoidal-Rule spatial integration

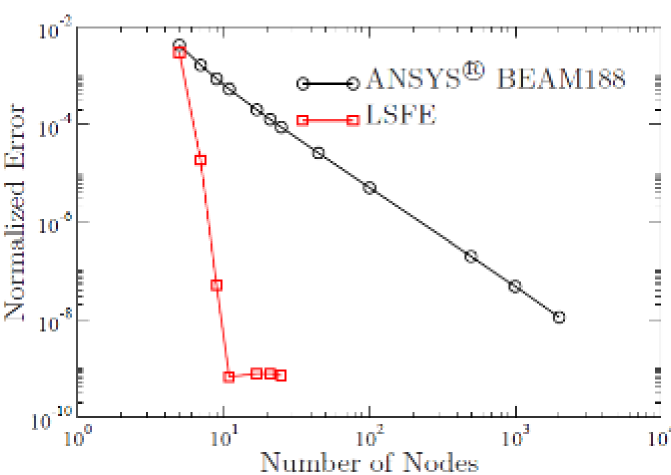










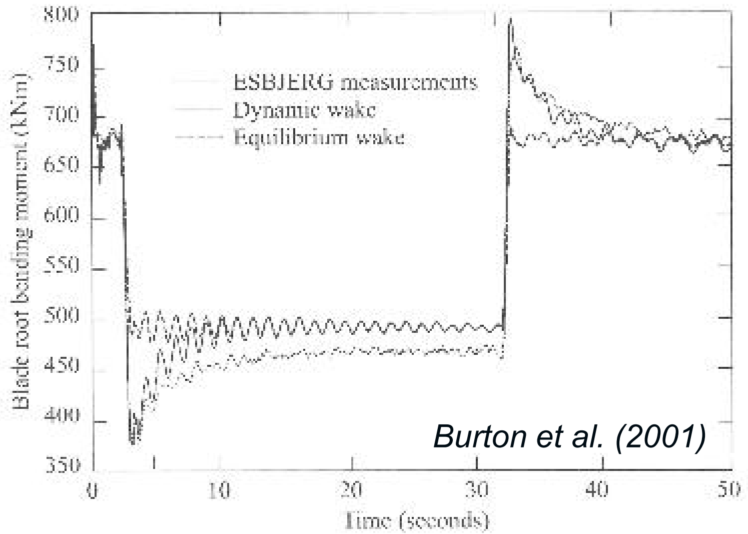


***BeamDyn** Analysis of NREL 5-MW Blade w/ 49 Cross-Sectional Stations*

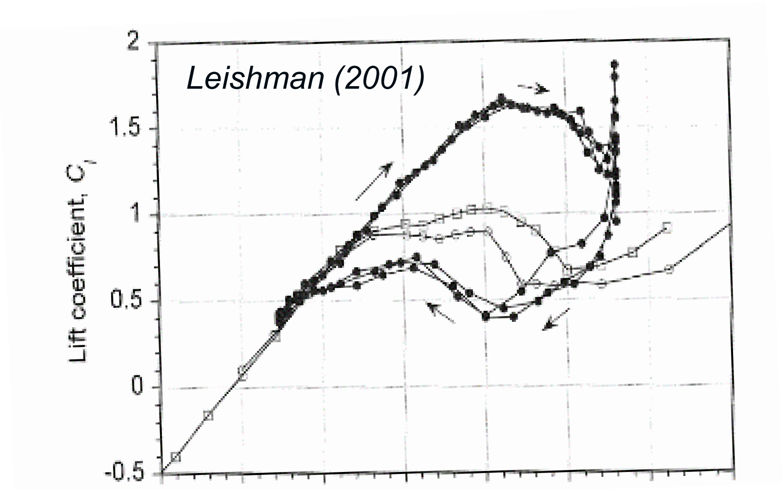
AeroDyn Overview

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

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



Blade Loading During Rapid Pitch Events



Dynamic Stall of S809 Airfoil

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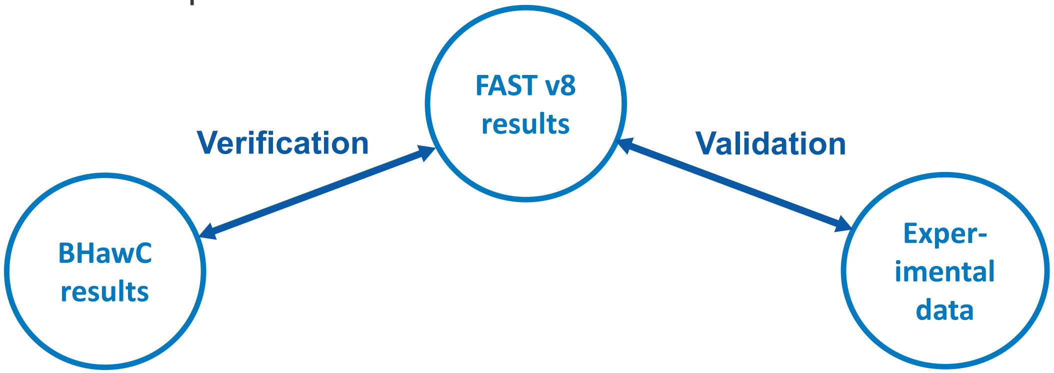
Verification & Validation of FAST Against Siemens Data

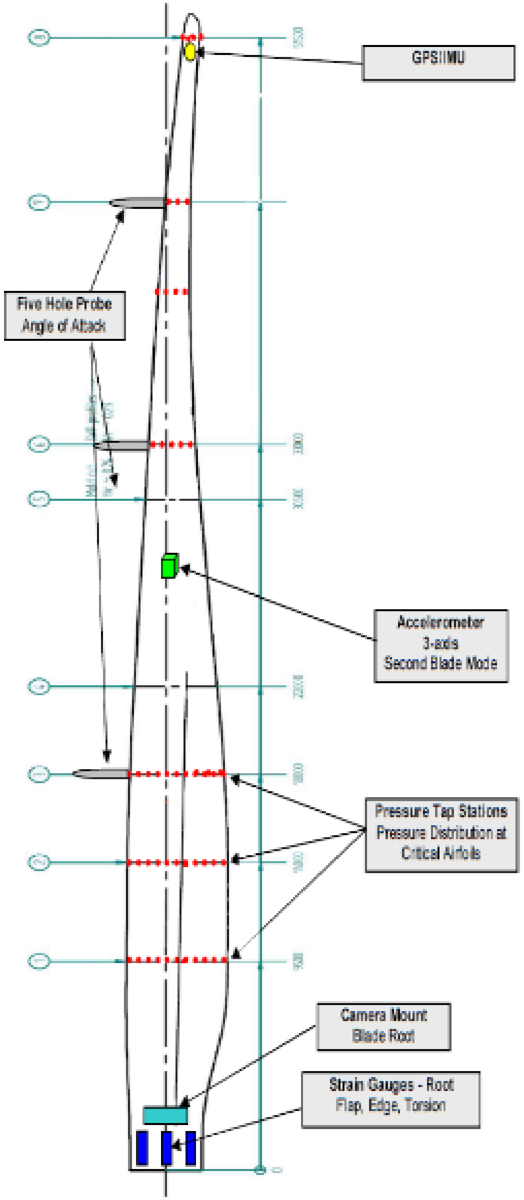
- **FAST** w/ **BeamDyn** was verified against **BHawC** & validated against data through collaboration w/ Siemens:
  - 3-way code-to-code & code-to-data comparison



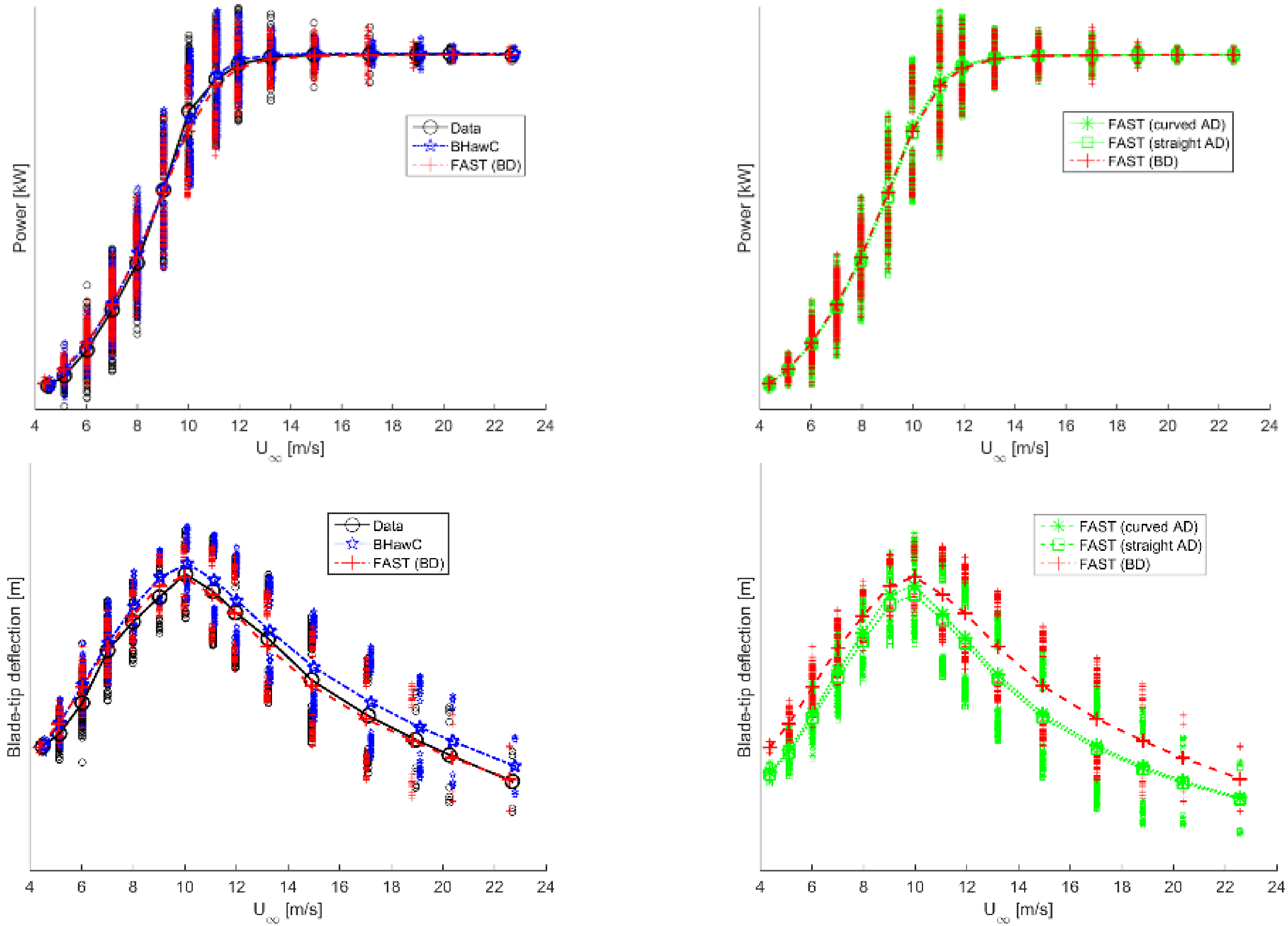
- Siemens 2.3-MW 108-m diameter turbine (SWT-2.3-108) @ NREL:
  - Upwind 3-bladed rotor
  - Aeroelastically tailored blades w/ bend-twist coupling
  - Variable speed & collective pitch

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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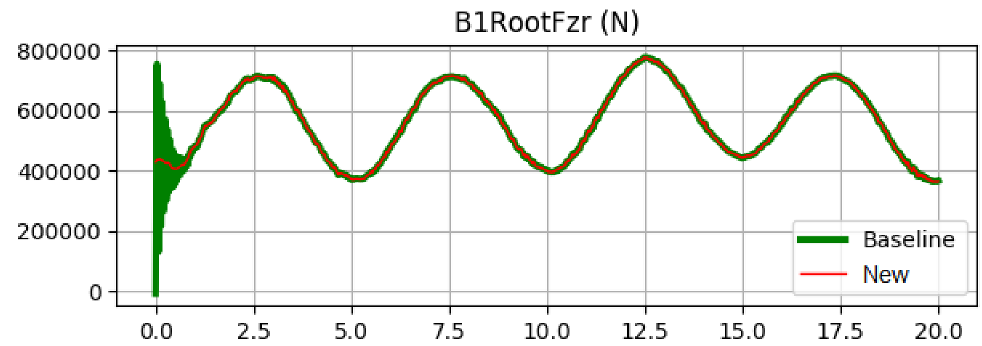
NREL-Envision Collaboration Overview

*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

➡ ≈15× 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

InflowWind (IfW)

$$\Delta y^{(IfW)} = D^{(IfW)} \Delta u^{(IfW)}$$

ServoDyn (SrvD)

$$\Delta y^{(SrvD)} = D^{(SrvD)} \Delta u^{(SrvD)}$$

ElastoDyn (ED)

$$\Delta \dot{x}^{(ED)} = A^{(ED)} \Delta x^{(ED)} + B^{(ED)} \Delta u^{(ED)}$$

$$\Delta y^{(ED)} = C^{(ED)} \Delta x^{(ED)} + D^{(ED)} \Delta u^{(ED)}$$

BeamDyn (BD)

$$\Delta \dot{x}^{(BD)} = A^{(BD)} \Delta x^{(BD)} + B^{(BD)} \Delta u^{(BD)}$$

$$\Delta y^{(BD)} = C^{(BD)} \Delta x^{(BD)} + D^{(BD)} \Delta u^{(BD)}$$

AeroDyn (AD)

$$\Delta y^{(AD)} = D^{(AD)} \Delta u^{(AD)}$$

Glue Code

$$0 = \left.\frac{\partial U}{\partial \tilde{u}}\right|_{op} \Delta u + \left.\frac{\partial U}{\partial y}\right|_{op} \Delta y$$

Full System

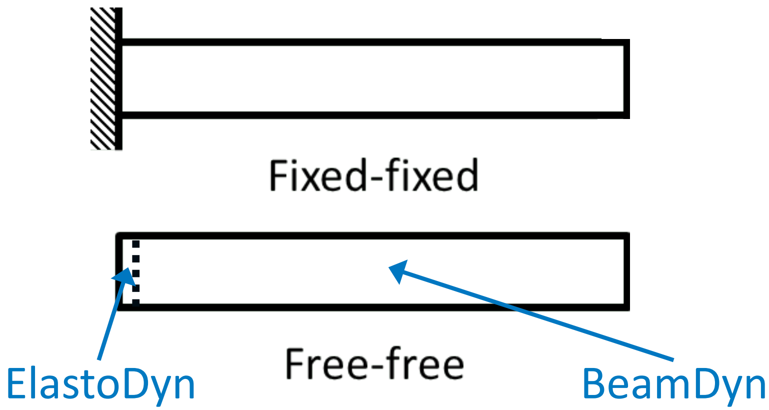
$$\Delta \dot{x} = A \Delta x + B \Delta u^{+}$$

$$\Delta y = C \Delta x + D \Delta u^{+}$$

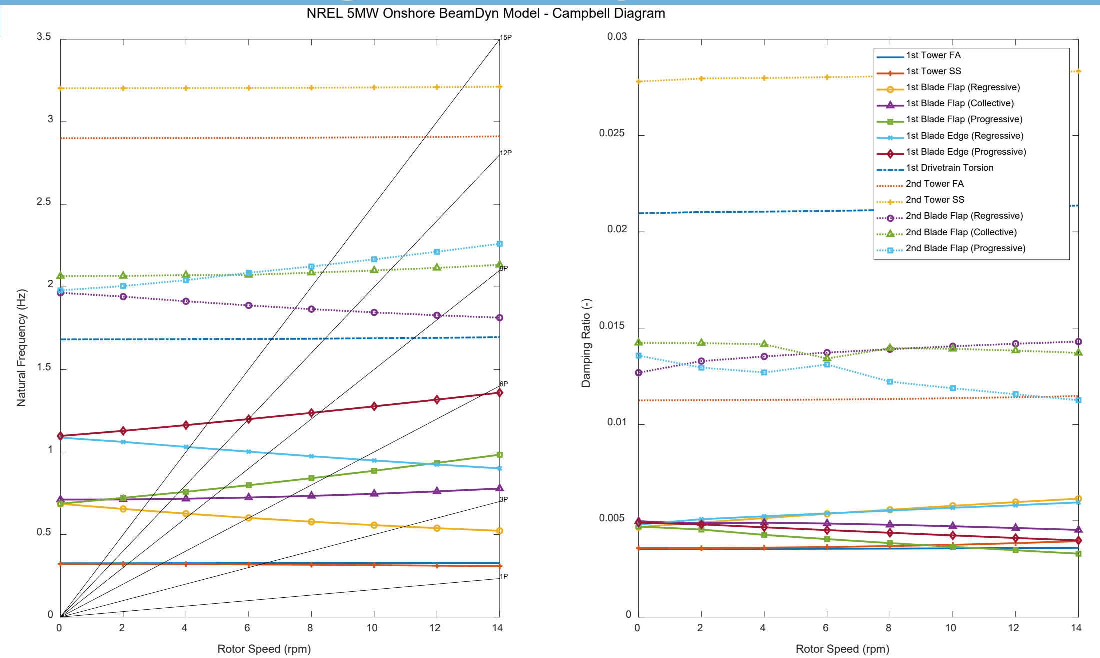
with

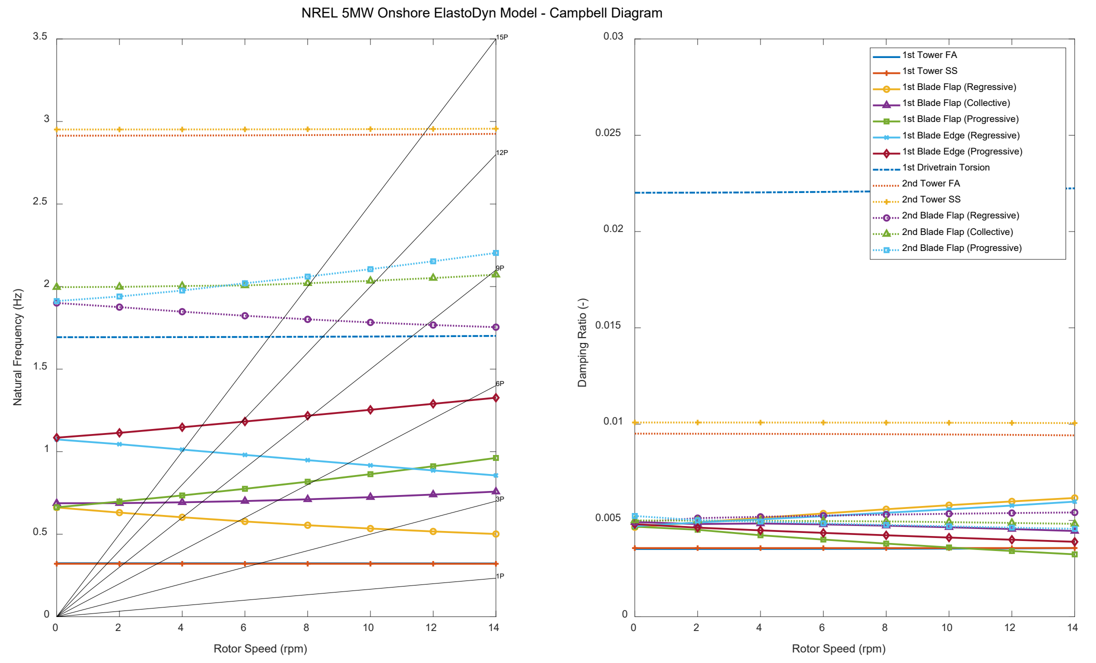
$$A = \begin{bmatrix} A^{(ED)} & 0 \\ 0 & A^{(BD)} \end{bmatrix} - \begin{bmatrix} 0 & 0 & B^{(ED)} & 0 & 0 \\ 0 & 0 & 0 & B^{(BD)} & 0 \end{bmatrix} \left[G|_{op} \right]^{-1} \left.\frac{\partial U}{\partial y}\right|_{op} \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ C^{(ED)} & 0 \\ 0 & C^{(BD)} \\ 0 & 0 \end{bmatrix} \quad etc.$$

Full-System Linearization Including BeamDyn – Results



Mode	Analytical	Lineariz'n	BD Summary File
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:
  - Innovative
  - Optimized
  - Reliable
  - Cost-effective

SWT-6.0-154 w/ Airbus A380

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

Horns Rev Wind Farm

Carpe Ventum!

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