Partitioned Nonlinear Structural Analysis of Wind Turbines using BeamDyn

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Background

- Previous beam model used in FAST (v7.0 and ElastoDyn module of v8.0)
  - Euler-Bernoulli beam model with shortening effect
  - Two degree-of-freedoms (No torsion, shear, and axial DoFs)
  - Assumed-mode method (Two bending modes in one direction)
- Beam models used in other wind turbine tools
  - Multibody-formulation
  - Linear beam models
  - Constraints introduced between linear beams to describe large deflections and rotations
  - Finite element method
- Partitioned Analysis
  - FAST modularization framework
  - Tight coupling
  - Loose coupling

Objective

- Objective: create efficient high-fidelity beam models for wind turbine blade analysis
  - Based on Geometrically Exact Beam Theory (GEBT)
  - Advanced numerical techniques for implementation
  - Achieve the speed of computational design without significant loss of accuracy comparing to the ultimate accuracy obtained by 3D nonlinear FEA
  - Compatible with the FAST modularization framework
  - Verification and Validation

NWTC static and dynamic blade tests showing typical large, elastic deflections.

Approach

- Implementation
  - Geometrically Exact Beam Theory (GEBT)

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    - Mixed implementation (Yu and Blair, 2012; Wang et al., 2013)
  - Legendre Spectral Finite Element (LSFE) (Patera, 1984)

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    - Successfully applied to simulation of fluid dynamics, geophysics, elastodynamics
    - Limited usage in structural dynamics
  - FAST Modularization Framework (Jonkman, 2013; Sprague et al., 2015)
    - Loose coupling
    - Predictor-correction
- BeamDyn, an alternative of ElastoDyn in FAST for blades

GEBT

- Governing Equation

$$\dot{\underline{h}} - \underline{F}' = \underline{f}$$

$$\dot{\underline{g}} + \dot{\tilde{u}}\underline{h} - \underline{M}' - (\tilde{x}_0' + \tilde{u}')\underline{F} = \underline{m}$$

- Constitutive Equation

$$\begin{Bmatrix} \underline{h} \\ \underline{g} \end{Bmatrix} = \underline{\underline{\mathcal{M}}} \begin{Bmatrix} \dot{\underline{u}} \\ \underline{\omega} \end{Bmatrix}$$

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- Strain Measures

$$\begin{Bmatrix} \underline{\epsilon} \\ \underline{\kappa} \end{Bmatrix} = \begin{Bmatrix} \underline{x}_0' + \underline{u}' - (\underline{\underline{R}}\,\underline{\underline{R}}_0)\bar{\imath}_1 \\ \underline{k} \end{Bmatrix}$$

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- Geometrically exact: deformed beam geometry is represented exactly

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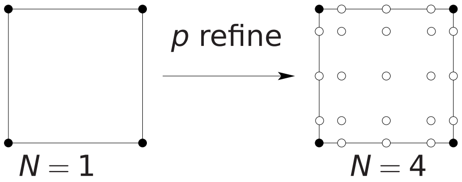
- Geometrically exact: deformed beam geometry is represented exactly
- Small strains

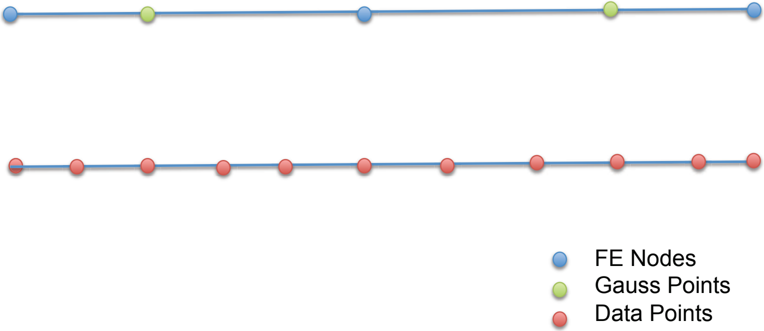
Legendre Spectral Finite Elements

- LSFE methods combine the geometric flexibility of the FE method with the accuracy of global spectral methods.
  - Solution improved through increased basis polynomial order (*p*-refinement)
  - LSFEs employ Lagrangian interpolant shape functions with nodes at Gauss-Lobatto-Legendre (GLL) points
  - *Exponential* convergence rates for sufficiently smooth solutions



Numerical Integration

- FE Node, Integration Point, and Data Point

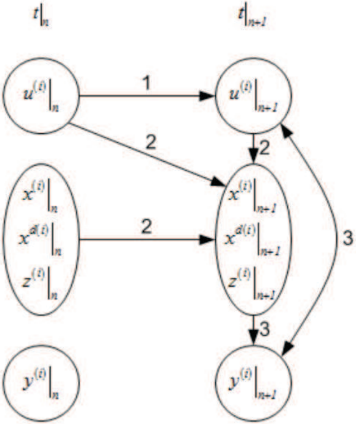


- Gauss Integration
- Trapezoidal-Rule Integration

$$\int_a^b f(x)dx \approx \frac{1}{2}\sum_{k=1}^{N}(x_{k+1} - x_k)\left[f(x_{k+1}) + f(x_k)\right]$$

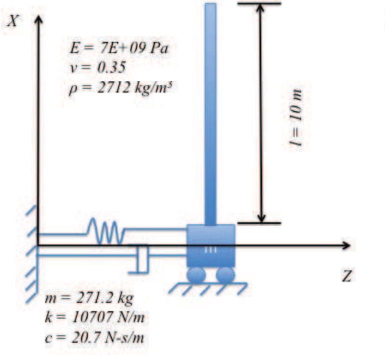
Partitioned Analysis

- Module Coupling Algorithm
  1. Prediction by extrapolating based on known values.
  2. Update states.
  3. Global input-output solve. Range from a simple transfer of information to a full nonlinear-system solve.
  4. Correction. Either accept the current solutions or repeat 2 and 3.



Example 1: Partitioned Analysis

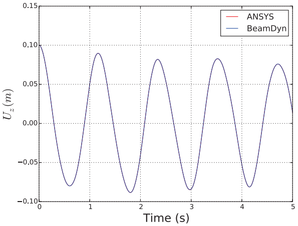
- Beam-Spring-Damper-Mass System



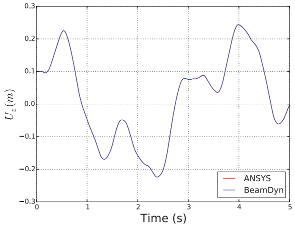
- Time integrator for SDM: Adams-Bashforth-Moulton (ABM4)
- Time integrator for beam: Generalized-α
- Initial condition solution from $U_Z = 0.1$ m.
- Benchmark: ANSYS 60 BEAM188 elements; 10^{-5}s time increment

Example 1: Partitioned Analysis

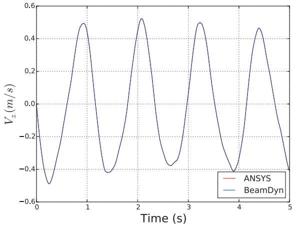
- *Root Displacement*



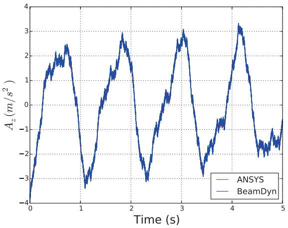
- *Tip Displacement*



- *Root Velocity*

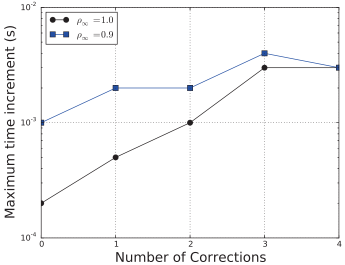


- *Root Acceleration*

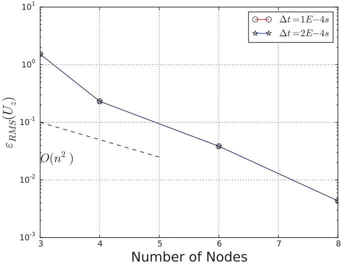


Example 1: Partitioned Analysis

- Stability



- Accuracy



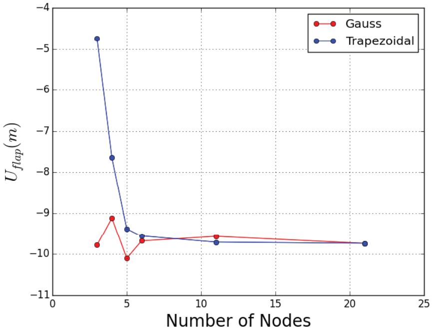
- Corrections and numerical damping help maximum allowable time step size
- RMS Error

$$\varepsilon_{RMS} = \sqrt{\frac{\sum_{k=0}^{n_{max}} [U_z^k - U_b(t^k)]^2}{\sum_{k=0}^{n_{max}} [U_b(t^k)]^2}}$$

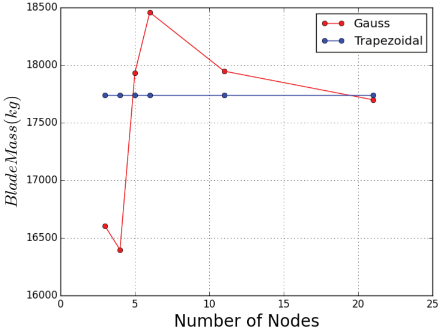
Example 2: NREL 5-MW Wind Turbine

- NREL 5-MW Wind Turbine
  - 61.5m long with initial twist
  - 49 cross-sectional stations
  - Blade modeled with a SINGLE element

Tip Displacement

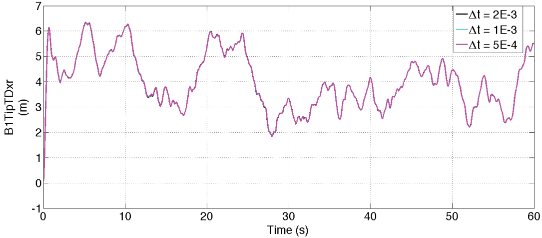


- Blade Mass

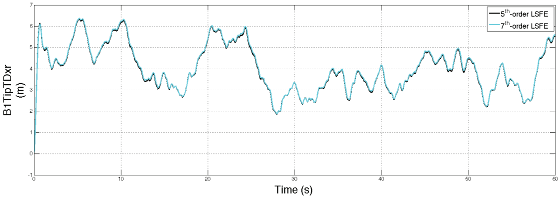


Example 2: NREL 5-MW Wind Turbine

- Time Discretization

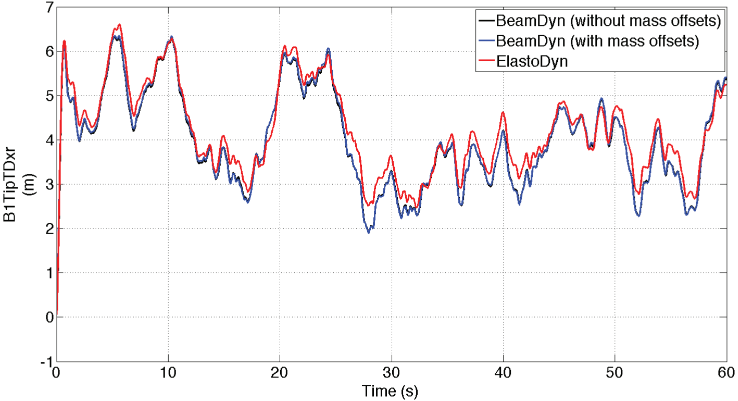


- Space Discretization



Example 2: NREL 5-MW Wind Turbine

- Aero-Servo-Elastic Coupled Analysis
- Mean Wind Speed 12 m/s^2 with Turbulence
- Test Case 26 in FAST Archive
- Tip Displacement U_{flap}



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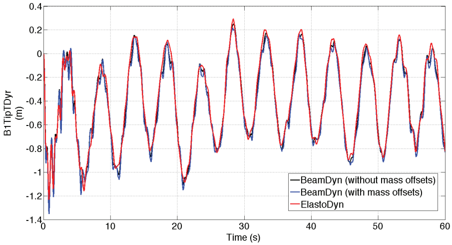
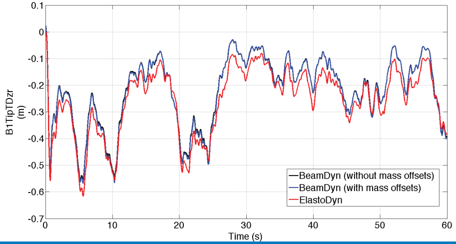
- Tip Displacement U_{edge}

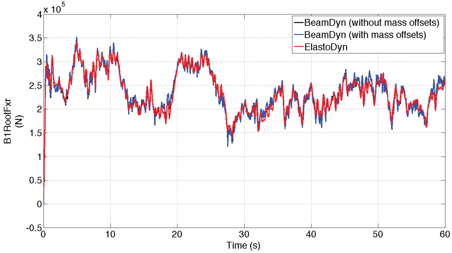


- Tip Displacement U_{axial}



Example 2: NREL 5-MW Wind Turbine

- Root Reaction Force F_{flap}



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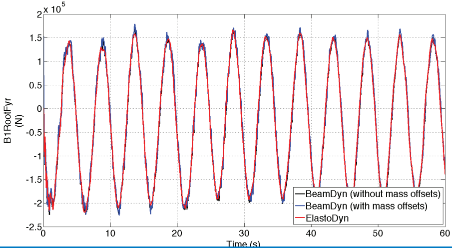
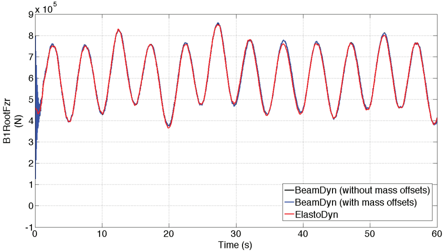
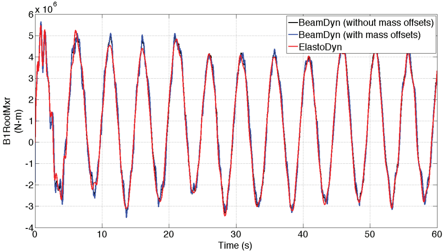


Example 2: NREL 5-MW Wind Turbine

- Root Reaction Force F_{axial}



- Root Reaction Moment M_{edge}



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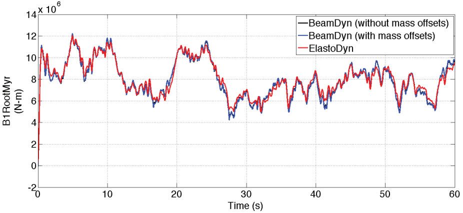
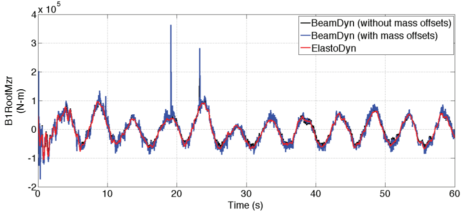


- Root Reaction Torque M_{pitch}



Summary

- Conclusion
  - Based on geometrically exact beam theory, BeamDyn is capable of dealing with geometric nonlinear beam problems with arbitrary magnitude of displacements and rotations for both static and dynamic analyses
  - Along with a preprocessor like PreComp or VABS, BeamDyn takes full elastic coupling effects into account
  - Spectral Finite Elements and new Trapezoidal-Rule quadrature have been adopted in the implementation of BeamDyn. These new techniques further improved the efficiency and accuracy.
  - BeamDyn is implemented following the programming requirements (data structures and interfaces) of the FAST modularization framework. The module coupling algorithm has been implemented and verified through numerical examples.
  - BeamDyn optionally replaces previous blade model of FAST when high-fidelity modeling of aero-elastically tailored blades is required.
  - More verification and validation results in "FAST v8 Verification and Validation for a MW-Scale Wind Turbine with Aeroelastically Tailored Blades", Guntur, S. etal.

Questions?

Acknowledgments

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