Partitioned Nonlinear Structural Analysis of Wind Turbines using BeamDyn

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Motivation

- Beam model currently used in FAST
  - Euler-Bernoulli beam model with shortening effect
  - Two degree-of-freedoms
  - Assumed-mode method
- 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 that
  - Based on Geometrically Exact Beam Theory (GEBT)
  - Advanced numerical technique 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.

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- 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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    - Limited usage in structural dynamics
  - FAST Modularization Framework (Jonkman, 2013)
    - Loose coupling
    - Predictor-correction
- BeamDyn, an alternative of ElastoDyn in FAST

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

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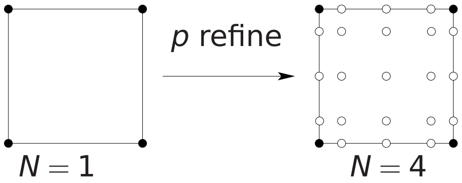
- Geometrically exact: deformed beam geometry is represented exactly
- Small strains

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
  - Gauss Integration
  - Trapezoidal-Rule Integration



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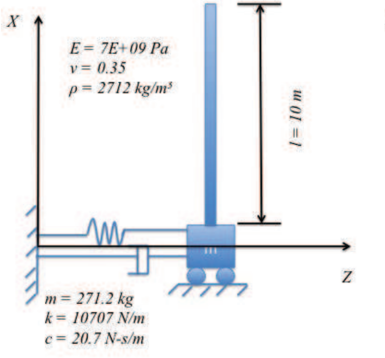
  4. Either accept the states, inputs, and outputs, or apply a correction by repeating step (2) with the inputs calculated in Step (3), and then repeating Step (3).

Example 1: Partitioned Analysis

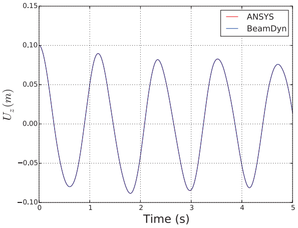
- Beam-Spring-Damper-Mass System



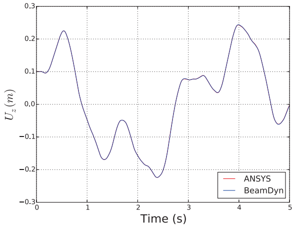
- Time integrator for SDM: Adams-Bashforth-Moulton (ABM4)
- Time integrator for beam: Generalized-α
- Benchmark: ANSYS 60 BEAM188 elements; 10^{-5}s time increment

Example 1: Partitioned Analysis

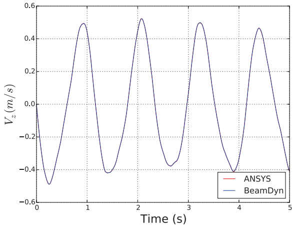
- *Root Displacement*



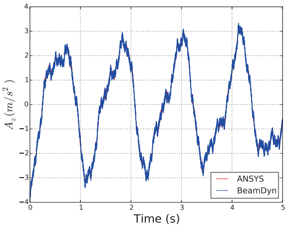
- *Tip Displacement*



- *Root Velocity*

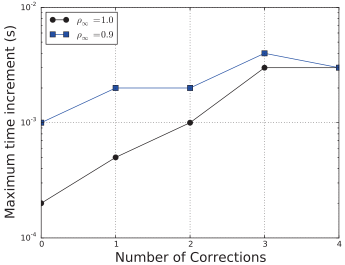


- *Root Acceleration*

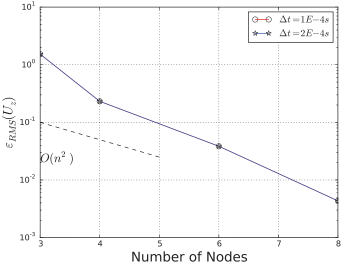


Example 1: Partitioned Analysis

- Stability



- Accuracy



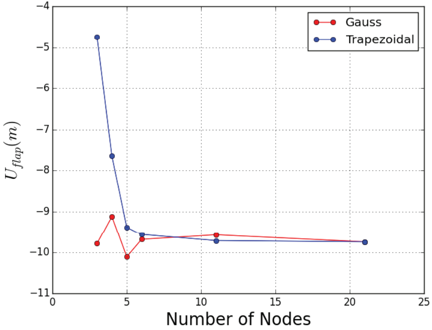
- Corrections and numerical damping help maximum allowable time step size
- RMS Error

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

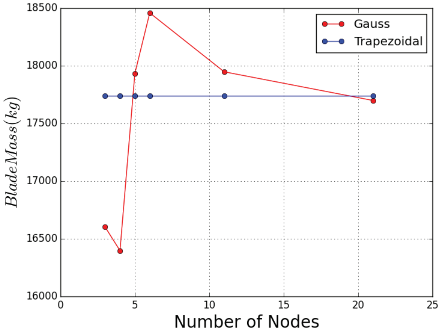
Example 2: NREL 5-MW Wind Turbine

- NREL 5-MW Wind Turbine
  - 61.5m long with initial twist
  - 49 cross-sectinoal stations

Tip Displacement



- Blade Mass



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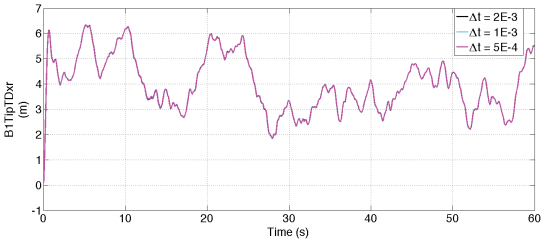
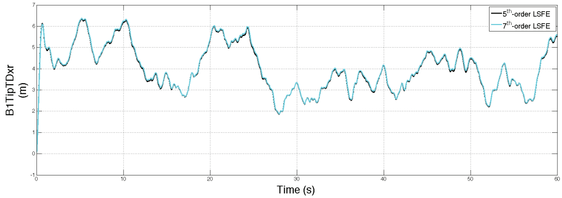
- Time Discretization

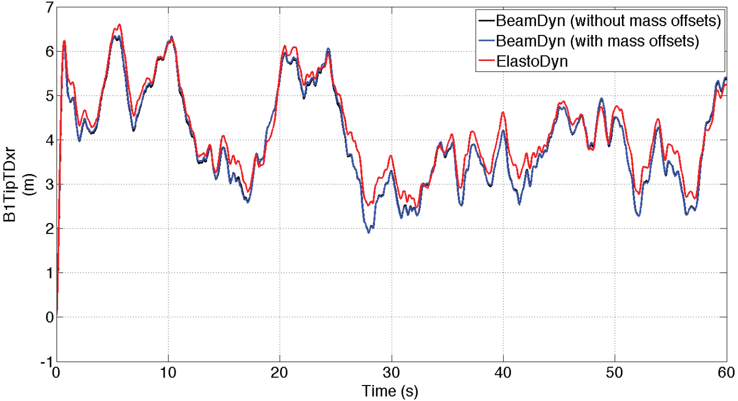


- Space Discretization



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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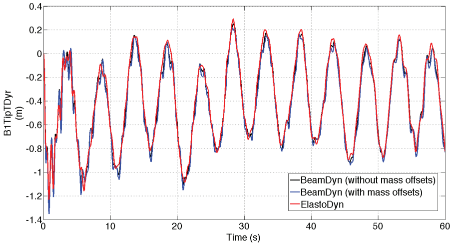
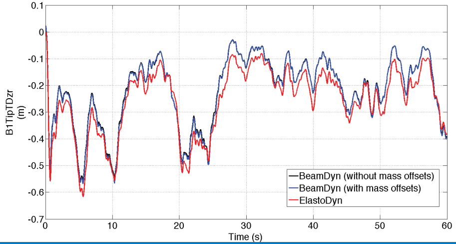
- Tip Displacement U_{edge}



- Tip Displacement U_{axial}



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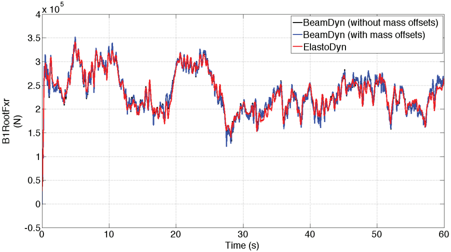
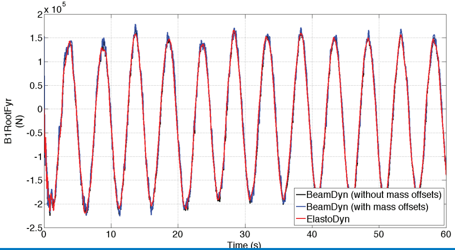
- Root Reaction Force F_{flap}



- Root Reaction Force F_{edge}



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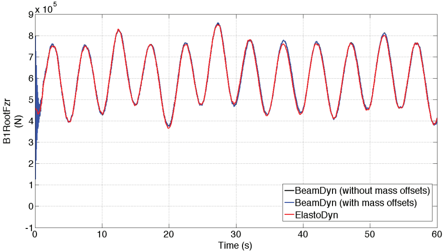
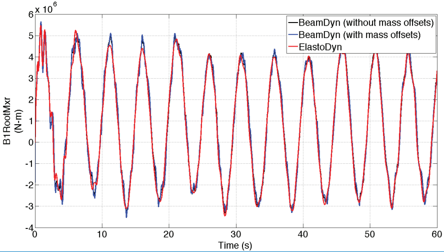


- Root Reaction Moment M_{edge}



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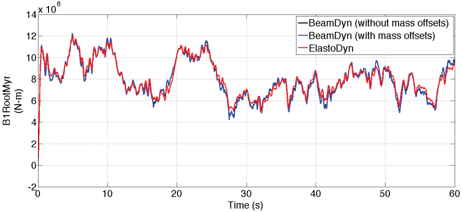
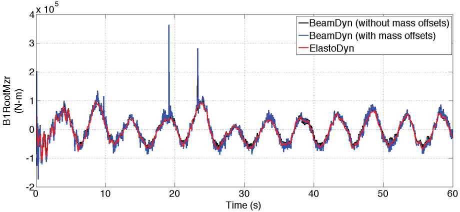
- Root Reaction Moment M_{falp}



- 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.
- Future Work
  - Introducing numerical damping to the coupling algorithm
  - Implement modal-based method

Questions?

Acknowledgments

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References

Bauchau, O. A., 2013. Dymore User's Manual. Http://dymoresolutions.com/dymore4_0/UsersManual/UsersManual.html.

Bottasso, C., Borri, M., 1998. Integrating finite rotations. Computer Methods in Applied Mechanics and Engineering 164, 307–337.

Hodges, D. H., 2006. Nonlinear Composite Beam Theory. AIAA.

Jonkman, J. M., January 2013. The new modularization framework for the fast wind turbine cae tool. In: Proceedings of the 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. Grapevine, Texas.

Patera, A. T., 1984. A spectral element method for fluid dynamics: Laminar flow in a channel expansion. Journal of Computational Physics 54, 468–488.

Reissner, E., 1973. On one-dimensional large-displacement finite-strain beam theory. Studies in Applied Mathematics LII, 87–95.

Wang, Q., Yu, W., Sprague, M. A., April 2013. Gemoetrically nonlinear analysis of composite beams using wiener-milenković parameters. In: Proceedings of the 54th Structures, Structural Dynamics, and Materials Conference. Boston, Massachusetts.

Yu, W., Blair, M., 2012. Gebt: A general-purpose nonlinear analysis tool for composite beams. Composite Structures 94, 2677–2689.