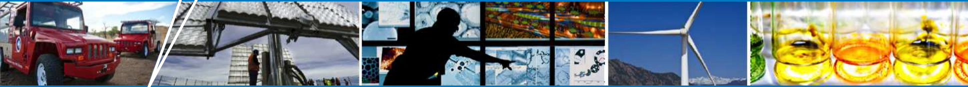
BeamDyn: A High-Fidelity Wind Turbine Blade Solver in the FAST Modular Framework



Qi Wang[1], Nick Johnson[2]
Michael A. Sprague[1], Jason Jonkman[1]

[1]National Renewable Energy Laboratory
[2]Colorado School of Mines

AIAA SciTech 2015
Kissimmee, FL
5–9 January 2015

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

Objective

- Objective: create efficient high-fidelity beam models for wind turbine blade analysis that can
  - Capture geometrical nonlinearity systematically
  - Capture anisotropic and heterogeneous behavior of composite materials rigorously
  - Modeling moving beams (translation and rotation)
  - 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

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

Approach

- Implementation
  - Geometrically Exact Beam Theory (GEBT)

Approach

- Implementation
  - Geometrically Exact Beam Theory (GEBT)
    - First proposed in 1973 (Reissner, 1973)

Approach

- Implementation
  - Geometrically Exact Beam Theory (GEBT)
    - First proposed in 1973 (Reissner, 1973)
    - Extended to composite beams (Hodges, 2006)

Approach

- Implementation
  - Geometrically Exact Beam Theory (GEBT)
    - First proposed in 1973 (Reissner, 1973)
    - Extended to composite beams (Hodges, 2006)
    - Displacement-based implementation (Bottasso and Borri, 1998; Bauchau, 2013)

Approach

- Implementation
  - Geometrically Exact Beam Theory (GEBT)
    - First proposed in 1973 (Reissner, 1973)
    - Extended to composite beams (Hodges, 2006)
    - Displacement-based implementation (Bottasso and Borri, 1998; Bauchau, 2013)
    - Mixed implementation (Yu and Blair, 2012; Wang et al., 2013)
  - Legendre Spectral Finite Element (LSFE) (Patera, 1984)

Approach

- Implementation
  - Geometrically Exact Beam Theory (GEBT)
    - First proposed in 1973 (Reissner, 1973)
    - Extended to composite beams (Hodges, 2006)
    - Displacement-based implementation (Bottasso and Borri, 1998; Bauchau, 2013)
    - Mixed implementation (Yu and Blair, 2012; Wang et al., 2013)
  - Legendre Spectral Finite Element (LSFE) (Patera, 1984)
    - A *p*-version high-order finite element

Approach

- Implementation
  - Geometrically Exact Beam Theory (GEBT)
    - First proposed in 1973 (Reissner, 1973)
    - Extended to composite beams (Hodges, 2006)
    - Displacement-based implementation (Bottasso and Borri, 1998; Bauchau, 2013)
    - Mixed implementation (Yu and Blair, 2012; Wang et al., 2013)
  - Legendre Spectral Finite Element (LSFE) (Patera, 1984)
    - A *p*-version high-order finite element
    - Successfully applied to simulation of fluid dynamics, geophysics, elastodynamics

Approach

- Implementation
  - Geometrically Exact Beam Theory (GEBT)
    - First proposed in 1973 (Reissner, 1973)
    - Extended to composite beams (Hodges, 2006)
    - Displacement-based implementation (Bottasso and Borri, 1998; Bauchau, 2013)
    - Mixed implementation (Yu and Blair, 2012; Wang et al., 2013)
  - Legendre Spectral Finite Element (LSFE) (Patera, 1984)
    - A *p*-version high-order finite element
    - Successfully applied to simulation of fluid dynamics, geophysics, elastodynamics
    - Limited usage in structural dynamics
  - FAST Modularization Framework (Jonkman, 2013)
    - State-space formulation for tight-coupling scheme
    - Time integrator for first-order PDEs
- Result: BeamDyn, which can be used as a structural module of 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

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

$$\begin{Bmatrix} \underline{F} \\ \underline{M} \end{Bmatrix} = \underline{\underline{\mathcal{C}}} \begin{Bmatrix} \underline{\epsilon} \\ \underline{\kappa} \end{Bmatrix}$$

GEBT

- Governing Equation

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

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

- Constitutive Equation

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

$$\begin{Bmatrix} \underline{F} \\ \underline{M} \end{Bmatrix} = \underline{\underline{\mathcal{C}}} \begin{Bmatrix} \underline{\epsilon} \\ \underline{\kappa} \end{Bmatrix}$$

- $\mathcal{M}$ and $\mathcal{C}$ are 6×6 sectional mass and stiffness matrices, respcetively

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

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

$$\begin{Bmatrix} \underline{F} \\ \underline{M} \end{Bmatrix} = \underline{\underline{\mathcal{C}}} \begin{Bmatrix} \underline{\epsilon} \\ \underline{\kappa} \end{Bmatrix}$$

- $\mathcal{M}$ and $\mathcal{C}$ are 6×6 sectional mass and stiffness matrices, respcetively
- Elastic couplings are captured

GEBT

- Governing Equation

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

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

- Constitutive Equation

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

$$\begin{Bmatrix} \underline{F} \\ \underline{M} \end{Bmatrix} = \underline{\underline{\mathcal{C}}} \begin{Bmatrix} \underline{\epsilon} \\ \underline{\kappa} \end{Bmatrix}$$

- $\mathcal{M}$ and $\mathcal{C}$ are 6×6 sectional mass and stiffness matrices, respcetively
- Elastic couplings are captured
- Timoshenko-like beam model

- Strain Measures

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

GEBT

- Governing Equation

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

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

- Constitutive Equation

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

$$\begin{Bmatrix} \underline{F} \\ \underline{M} \end{Bmatrix} = \underline{\underline{\mathcal{C}}} \begin{Bmatrix} \underline{\epsilon} \\ \underline{\kappa} \end{Bmatrix}$$

- $\mathcal{M}$ and $\mathcal{C}$ are 6×6 sectional mass and stiffness matrices, respcetively
- Elastic couplings are captured
- Timoshenko-like beam model

- Strain Measures

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

- Geometrically exact: deformed beam geometry is represented exactly

GEBT

- Governing Equation

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

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

- Constitutive Equation

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

$$\begin{Bmatrix} \underline{F} \\ \underline{M} \end{Bmatrix} = \underline{\underline{\mathcal{C}}} \begin{Bmatrix} \underline{\epsilon} \\ \underline{\kappa} \end{Bmatrix}$$

- $\mathcal{M}$ and $\mathcal{C}$ are 6×6 sectional mass and stiffness matrices, respcetively
- Elastic couplings are captured
- Timoshenko-like beam model

- Strain Measures

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

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

FAST Modular Framework

- Data structure: inputs, outputs, states, and parameters
- Interface: glue code
- Loose and tight coupling

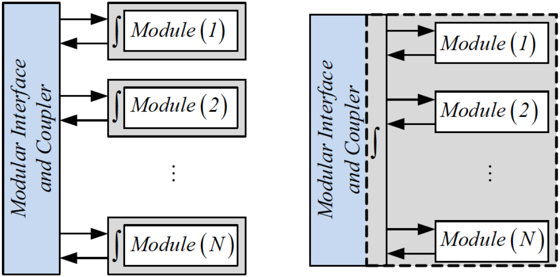


Figure: Loose- (left) and tight- (right) coupling schemes.

State-Space Formulation

- Governing Equation

$$\underline{\underline{\mathfrak{M}}}\ \underline{a} + f(\underline{q}, \underline{v}, t) = 0$$

$$\underline{q}^T = \begin{bmatrix} \underline{u}^T & \underline{p}^T \end{bmatrix} \qquad \underline{v}^T = \begin{bmatrix} \underline{\dot{u}}^T & \underline{\omega}^T \end{bmatrix} \qquad \underline{a}^T = \begin{bmatrix} \underline{\ddot{u}}^T & \underline{\dot{\omega}}^T \end{bmatrix}$$

- State-Space Form

$$\underline{\underline{A}}\ \dot{\underline{\hat{x}}}(t) = \mathfrak{f}(\underline{\hat{x}}(t), t)$$

$$\underline{x}(t) \equiv \begin{Bmatrix} \underline{q}(t) \\ \underline{v}(t) \end{Bmatrix} \qquad \underline{\underline{A}}(\underline{\hat{x}}(t)) = \begin{bmatrix} \underline{\underline{D}} & \underline{\underline{0}} \\ \underline{\underline{0}} & \underline{\underline{M}} \end{bmatrix}$$

$$\underline{\underline{D}}(\underline{\hat{x}}(t)) = \int_0^l \underline{\underline{N}}^T \begin{bmatrix} \underline{\underline{I}}_3 & \underline{\underline{0}} \\ \underline{\underline{0}} & \underline{\underline{H}} \end{bmatrix} \underline{\underline{N}}\, dx_1 \qquad \mathfrak{f}(\underline{\hat{x}}(t), t) = \begin{Bmatrix} \int_0^l \underline{\underline{N}}^T \underline{v}\, dx_1 \\ \underline{F}(\underline{\hat{x}}(t), t) \end{Bmatrix}$$

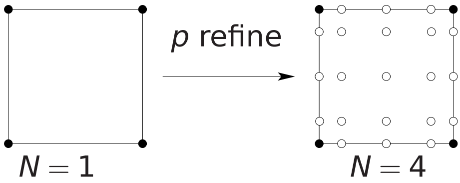
- Second-order Adams-Moulton (AM2)

$$\underline{\underline{A}}_{k+1}(\underline{\hat{x}}_{k+1} - \underline{\hat{x}}_k - \frac{\Delta t}{2}\dot{\underline{\hat{x}}}_k) = \frac{\Delta t}{2}\mathfrak{f}(\underline{\hat{x}}_{k+1}, t_{k+1})$$

Legendre Spectral Finite Elements

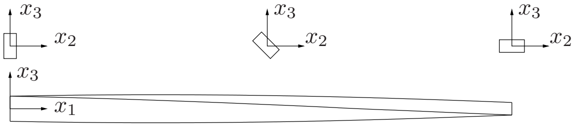
LSFE methods combine the geometric flexibility of the FE method with the accuracy of global spectral methods.

- 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



Example 1: Initially Twisted Beam

- Sketch of Initially Twisted Beam



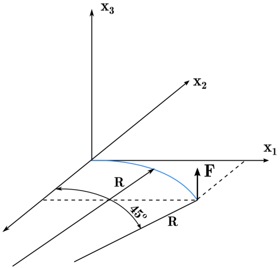
- Result

Table: Comparison of tip displacements of an initially twisted beam

	u_1 (m)	u_2 (m)	u_3 (m)
BeamDyn	-1.132727	-1.715123	-3.578671
ANSYS	-1.134192	-1.714467	-3.584232
Percent Error	0.129%	0.038%	0.155%

Example 1: Initially Curved Beam

- Sketch of Initially Curved Beam



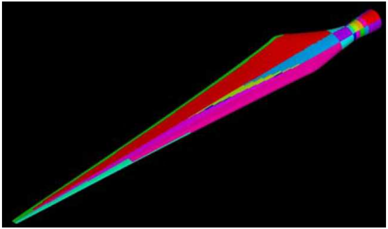
- Result

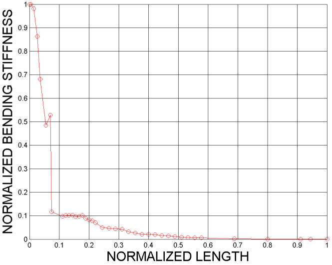
Table: Comparison of tip displacements of an initially curved beam

	u_1 (inches)	u_2 (inches)	u_3 (inches)
BeamDyn (one LSFE)	-23.7	13.5	53.4
Bathe-Bolourchi Bathe and Bolourchi (1979)	-23.5	13.4	53.4

Example 2: CX-100

- Sketch of CX-100



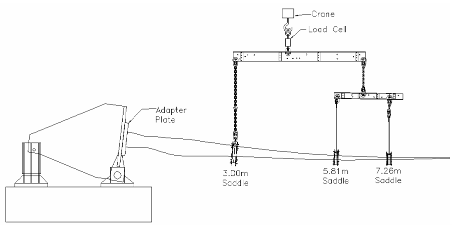


- Sectional Properties at 2.2 m

$$C = 10^3 \times \begin{bmatrix} 193,000 & -75.4 & 12.2 & -75.2 & -1970 & -3500 \\ -75.4 & 19,500 & 4,760 & 62.6 & 67.3 & 11.3 \\ 12.2 & 4,760 & 7,210 & -450 & 17.0 & 2.68 \\ -75.2 & 62.6 & -450 & 518 & 1.66 & -1.11 \\ -1,970 & 67.3 & 17.0 & 1.66 & 2,280 & -879 \\ -3,500 & 11.6 & 2.68 & -1.11 & -875 & 4,240 \end{bmatrix}$$

Example 2: CX-100 (Continued)

- Static Test Configuration



- Deflection

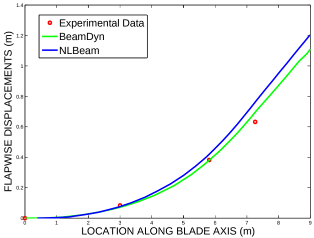
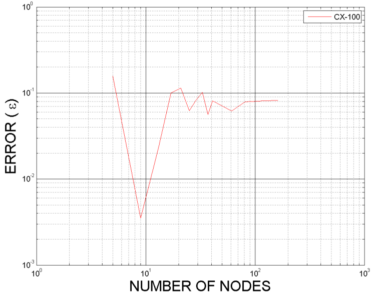


Table: Experimental and BeamDyn simulation results for the CX-100 static test

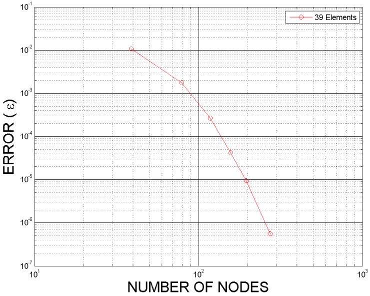
	u_3 at saddle #1 (m)	u_3 at saddle #2 (m)	u_3 at saddle #3 (m)
Experimental	0.083530	0.381996	0.632460
BeamDyn	0.072056	0.381074	0.698850
Percent Error	13.74%	0.24%	10.5%

Example 2: Convergence Study

- Validation

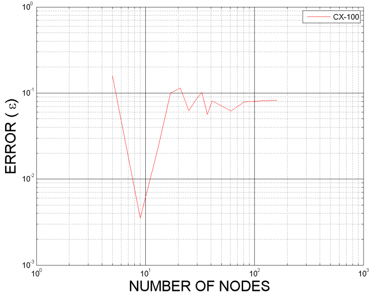


- Verification

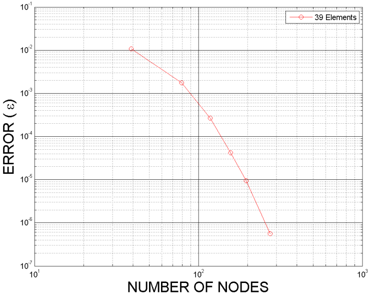


Example 2: Convergence Study

- Validation



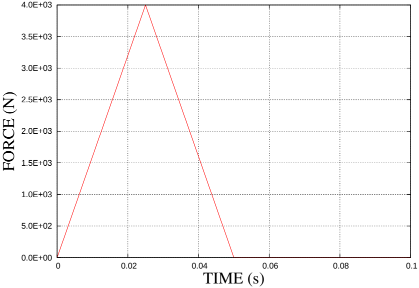
- Verification



- Sharp gradients in sectional properties
- Erratic data

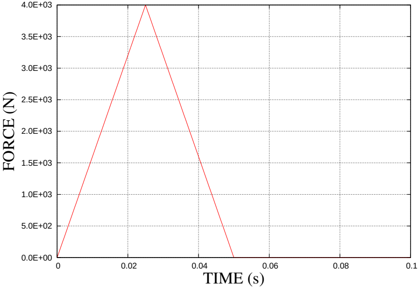
Example 3: Damping Effect

- Cantilever Beam Under Impulsive Load



Example 3: Damping Effect

- Cantilever Beam Under Impulsive Load



- Viscous Damping

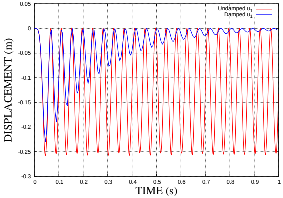
$$\underline{f}_d = \underline{\underline{\mu}}\, \underline{\underline{\mathcal{C}}} \begin{Bmatrix} \dot{\epsilon} \\ \dot{\kappa} \end{Bmatrix}$$

- RMS Error

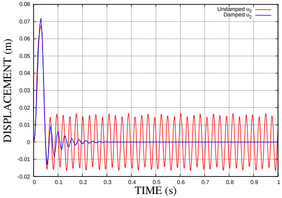
$$\varepsilon_{RMS} = \sqrt{\frac{\sum_{k=0}^{n_{max}} [u_3^k - u_b(t^k)]^2}{\sum_{k=0}^{n_{max}} [u_b(t^k)]^2}}$$

Example 3: Root forces and moments

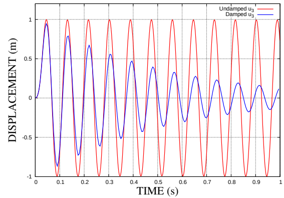
- u_1



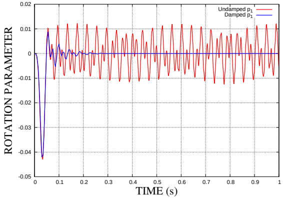
- u_2



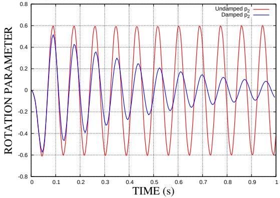
- u_3



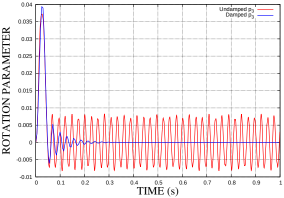
- p_1



- p_2



- p_3



Example 4: NREL 5-MW Blade

Example 4: NREL 5-MW Blade

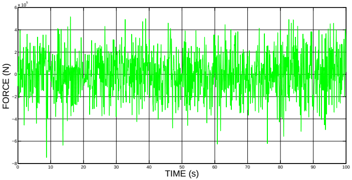
- NREL 5-MW Blade; Cantilevered at root

Example 4: NREL 5-MW Blade

- NREL 5-MW Blade; Cantilevered at root
- White noise force applied at the free tip along flap direction

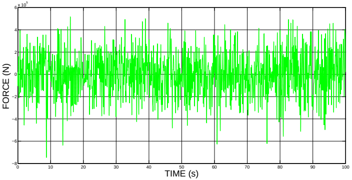
Example 4: NREL 5-MW Blade

- NREL 5-MW Blade; Cantilevered at root
- White noise force applied at the free tip along flap direction
- Time History of Applied Force

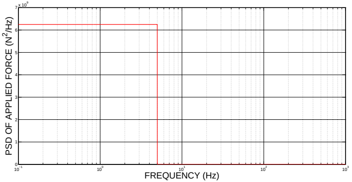


Example 4: NREL 5-MW Blade

- NREL 5-MW Blade; Cantilevered at root
- White noise force applied at the free tip along flap direction
- Time History of Applied Force



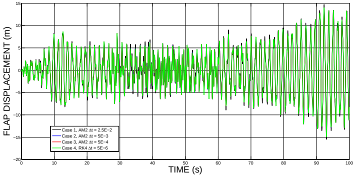
- PSD of Applied Force



Example 4: NREL 5-MW Blade (Continued)

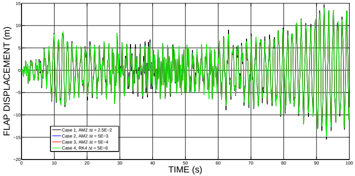
Example 4: NREL 5-MW Blade (Continued)

- Flapwise Response

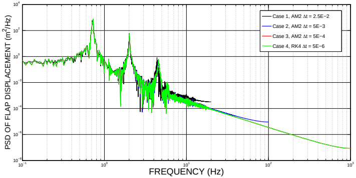


Example 4: NREL 5-MW Blade (Continued)

- Flapwise Response

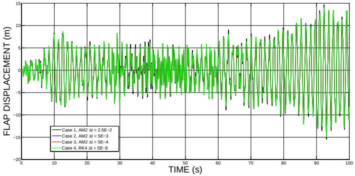


- PSD of Flapwise Response

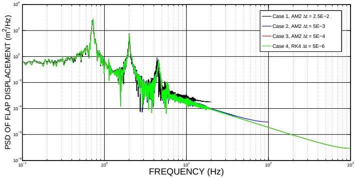


Example 4: NREL 5-MW Blade (Continued)

- Flapwise Response



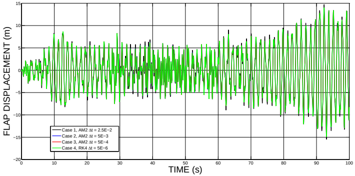
- PSD of Flapwise Response



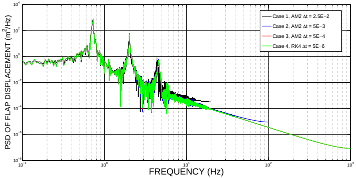
- For an implicit AM2 time step beyond 0.005 s, the solution is nearly identical to the fully resolved explicit RK4 solution

Example 4: NREL 5-MW Blade (Continued)

- Flapwise Response



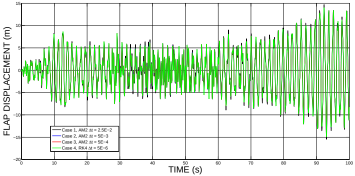
- PSD of Flapwise Response



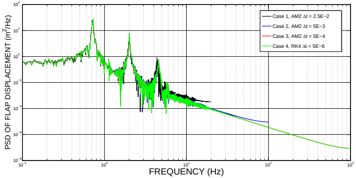
- For an implicit AM2 time step beyond 0.005 s, the solution is nearly identical to the fully resolved explicit RK4 solution
- For an AM2 time step of 0.025 s, the solution remains stable and tracks the other solutions, but error grows at higher frequencies

Example 4: NREL 5-MW Blade (Continued)

- Flapwise Response



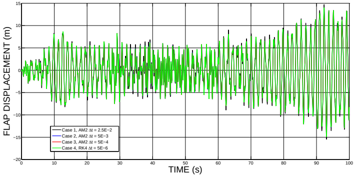
- PSD of Flapwise Response



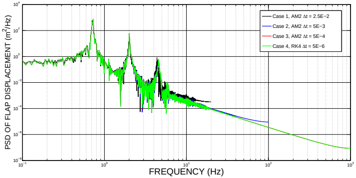
- For an implicit AM2 time step beyond 0.005 s, the solution is nearly identical to the fully resolved explicit RK4 solution
- For an AM2 time step of 0.025 s, the solution remains stable and tracks the other solutions, but error grows at higher frequencies
- The spikes at 0.7 Hz and 2 Hz correspond to the first and second blade flapwise natural frequencies

Example 4: NREL 5-MW Blade (Continued)

- Flapwise Response



- PSD of Flapwise Response



- For an implicit AM2 time step beyond 0.005 s, the solution is nearly identical to the fully resolved explicit RK4 solution
- For an AM2 time step of 0.025 s, the solution remains stable and tracks the other solutions, but error grows at higher frequencies
- The spikes at 0.7 Hz and 2 Hz correspond to the first and second blade flapwise natural frequencies
- The spike above 5 Hz–above the frequency range of excitation–is brought about by nonlinear effects

Example 4: NREL 5-MW Blade (Continued)

- Convergence Rate

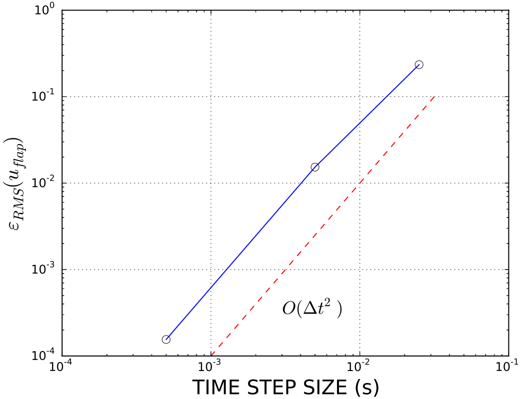


Figure: Normalized RMS error of flapwise displacement histories as a function of time step size for AM2 time integrator. The dashed line shows ideal second-order convergence.

Example 4: NREL 5-MW Blade (Continued)

- Solver Statistics

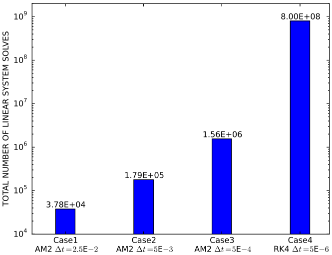


Figure: Total number of linear system solves.

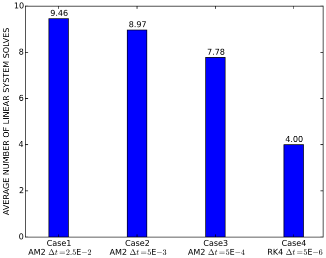


Figure: Average number of linear system solves per step.

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
  - The governing equations are reformulated into state-space form, thus, making it amendable into FAST for tight-coupling analysis
  - The space is discretized by spectral finite elements, which is a p-version finite element, so that exponential convergence rate can be expected for smooth solutions
  - Different time integrators have been implemented in BeamDyn; users will have options based on their needs
  - BeamDyn is implemented following the programming requirements (data structures and interfaces) of the FAST modularization framework

Summary (Continued)

- Future Work
  - Coupling BeamDyn to FAST
  - Full-Turbine validation
  - Enhancement of numerical performance

Questions?

Acknowledgments

- Funded by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.
- Support was provided through an NREL Laboratory Directed Research and Development grant *High-Fidelity Computational Modeling of Wind-Turbine Structural Dynamics*

References

Bathe, K. J., Bolourchi, S., 1979. Large displacement analysis of three-dimensional beam structures. International Journal for Numerical Methods in Engineering 14, 961–986.

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.