

link ../BoxedEPS.tex



Qi Wang¹, Nick Johnson²

¹Michael A. Sprague Energy Laboratory

²Colorado School of Mines

AIAA SciTech 2015

Kissimmee, FL

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

5–9 January 2015



Motivation

- ▶ Beam model currently used in FAST
 - Euler-Bernoulli beam model with shortening effect
 - Two degree-of-freedom
 - 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

figs/static_test-eps-converted-to.pdf

Approach

- ▶ Implementation
 - Geometrically Exact Beam Theory (GEBT)
 - ▶ First proposed in 1973 (?)
 - ▶ Extended to composite beams (?)
 - ▶ Displacement-based implementation (??)
 - ▶ Mixed implementation (??)
 - Legendre Spectral Finite Element (LSFE) (?)
 - ▶ A p -version high-order finite element
 - ▶ Successfully applied to simulation of fluid dynamics, geophysics, elastodynamics
 - ▶ Limited usage in structural dynamics
 - FAST Modularization Framework (?)
 - ▶ 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

► Governing Equation

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

► Constitutive Equation

$$\begin{aligned} \begin{Bmatrix} \underline{h} \\ \underline{g} \end{Bmatrix} &= \underline{\underline{\mathcal{M}}} \begin{Bmatrix} \underline{\dot{u}} \\ \underline{\omega} \end{Bmatrix} \\ \begin{Bmatrix} \underline{F} \\ \underline{M} \end{Bmatrix} &= \underline{\underline{\mathcal{C}}} \begin{Bmatrix} \underline{\epsilon} \\ \underline{\kappa} \end{Bmatrix} \end{aligned}$$

► Strain Measures

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

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

EPSF/FAST_Modular-eps-converted-to.pdf

State-Space Formulation

- ▶ Governing Equation

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

- ▶ $\underline{\underline{q}}^T = [\underline{\underline{u}}^T \quad \underline{\underline{p}}^T]$
State-Space Form

$$\underline{\underline{v}}^T = [\underline{\underline{\dot{u}}}^T \quad \underline{\underline{\omega}}^T]$$

$$\underline{\underline{a}}^T = [\underline{\underline{\ddot{u}}}^T \quad \underline{\underline{\dot{\omega}}}^T]$$

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

$$\underline{\underline{x}}(t) \equiv \begin{Bmatrix} \underline{\underline{q}}(t) \\ \underline{\underline{v}}(t) \end{Bmatrix}$$

$$\underline{\underline{A}}(\underline{\underline{\hat{x}}}(t)) = \begin{bmatrix} \underline{\underline{D}} & \underline{\underline{0}} \\ \underline{\underline{0}} & \underline{\underline{M}} \end{bmatrix}$$

$$\underline{\underline{D}}(\underline{\underline{\hat{x}}}(t)) = \int_0^l \underline{\underline{N}}^T \begin{bmatrix} \underline{\underline{I}} \\ \underline{\underline{0}} \\ \underline{\underline{H}} \end{bmatrix} \underline{\underline{N}} dx_1$$

$$\underline{\underline{f}}(\underline{\underline{\hat{x}}}(t), t) = \begin{Bmatrix} \int_0^l \underline{\underline{N}}^T \underline{\underline{v}} dx_1 \\ \underline{\underline{F}}(\underline{\underline{\hat{x}}}(t), t) \end{Bmatrix}$$

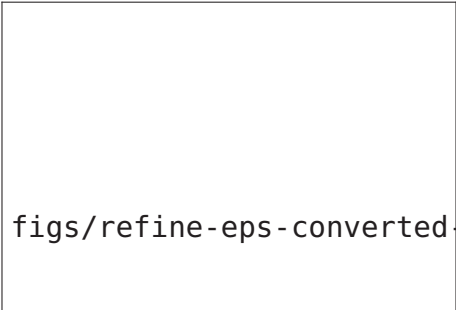
- ▶ Second-order Adams-Moulton (AM2)

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

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



figs/refine-eps-converted-to.pdf

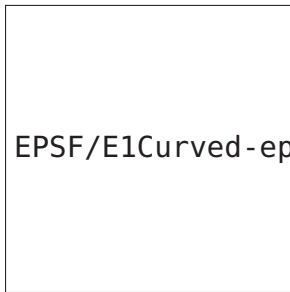
Example 1: Initially Twisted Beam

- ▶ Sketch of Initially Twisted Beam

EPSF/twist_beam-eps-converted-to.pdf

Example 1: Initially Curved Beam

- Sketch of Initially Curved Beam



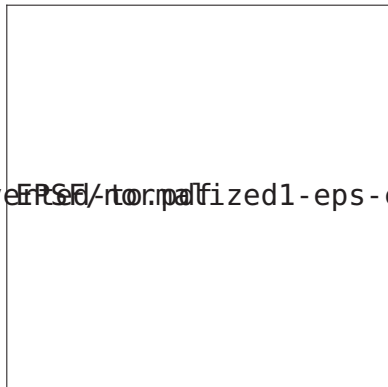
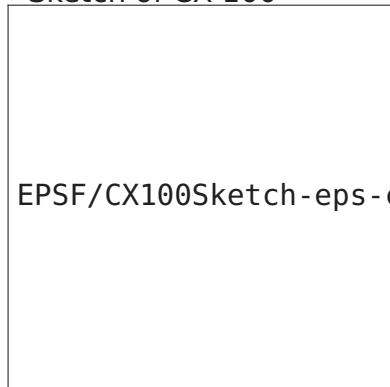
- Result

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 ?	-23.5	13.4	53.4

Example 2: CX-100

► Sketch of CX-100



EPSP/CX100Sketch-eps-converted-to.pdf

► 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

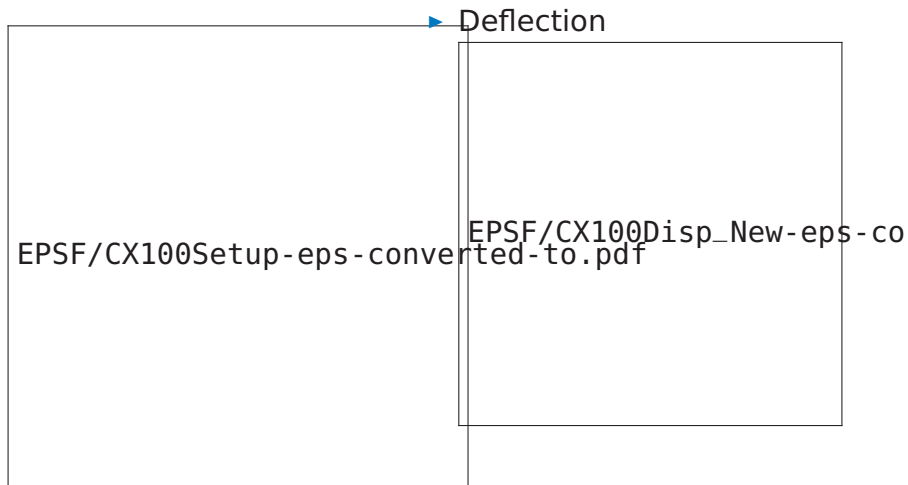
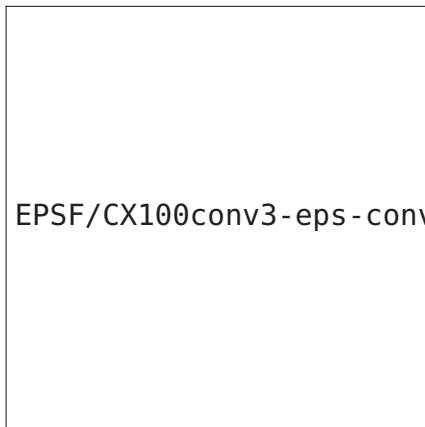


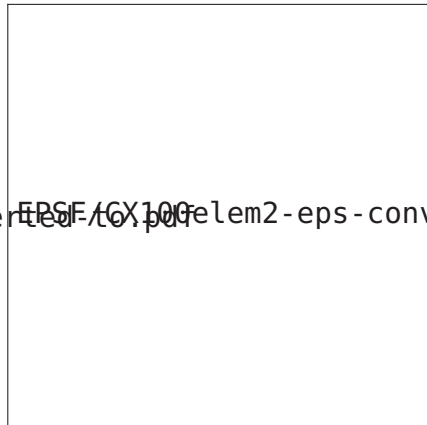
Table: Experimental and BeamDyn simulation results for the CX-100

Example 2: Convergence Study

► Validation



► Verification



EPSF/CX100conv3-eps-converted-to.pdf EPSF/CX100elem2-eps-converted-to.pdf

- Sharp gradients in sectional properties
- Erratic data

Example 3: Damping Effect

- ▶ Cantilever Beam Under Impulsive Load

EPSF/AM2_Excitation-eps-converted-to.pdf

- ▶ Viscous Damping

$$\underline{\underline{f_d}} = \underline{\underline{\mu}} \underline{\underline{C}} \begin{Bmatrix} \dot{\epsilon} \\ \dot{\kappa} \end{Bmatrix}$$

Example 3: Root forces and moments



Example 4: NREL 5-MW Blade

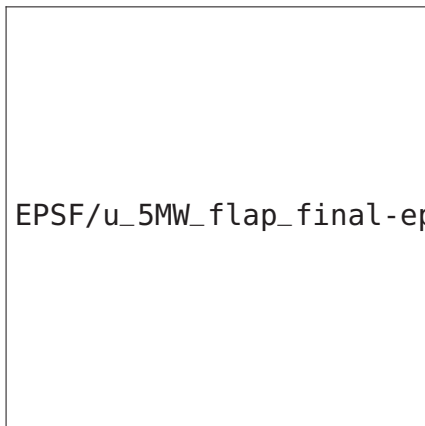
- ▶ NREL 5-MW Blade; Cantilevered at root
- ▶ White noise force applied at the free tip along flap direction
- ▶ Time History of Applied Force

EPSF/5MW_Flap_Force_Final-eps-converted

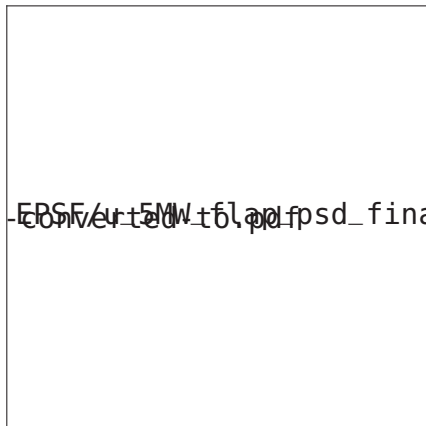
- ▶ PSD of Applied Force

Example 4: NREL 5-MW Blade (Continued)

► Flapwise Response



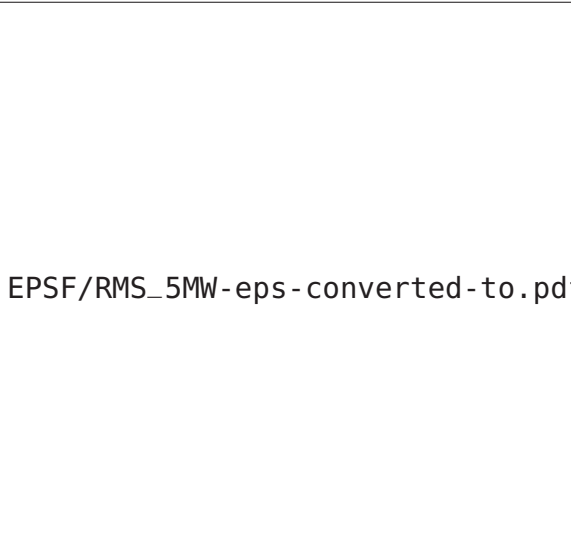
► PSD of Flapwise Response



- 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

Example 4: NREL 5-MW Blade (Continued)

- Convergence Rate



EPSF/RMS_5MW-eps-converted-to.pdf

Example 4: NREL 5-MW Blade (Continued)

► Solver Statistics

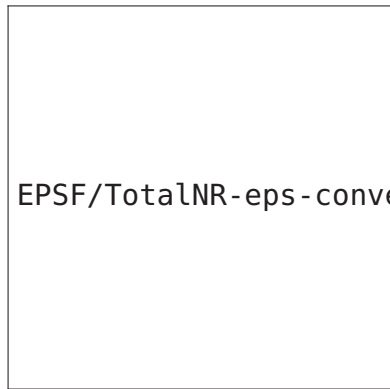


Figure: Total number of linear system solves.

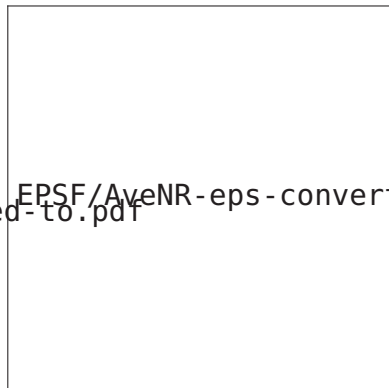


Figure: Average number of linear system solves per step.

► 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