link ../BoxedEPS.tex

BeamDyn:

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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.

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

figs/static_test-eps-converted-to.pdf

figs/dyn_test-eps-converted-to

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

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
- 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

EPSF/FAST_Modular-eps-converted-to.pdf

State-Space Formulation

- Governing Equation

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

$$\underline{q}^T = \left[\underline{u}^T \quad \underline{p}^T\right] \qquad \underline{v}^T = \left[\underline{\dot{u}}^T \quad \underline{\omega}^T\right] \qquad \underline{a}^T = \left[\underline{\ddot{u}}^T \quad \underline{\dot{\omega}}^T\right]$$

- 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

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

EPSF/E1Curved-eps-converted-to.pdf

- 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

EPSF/CX100Sketch-eps-converted-to.pdf

EPSF/normalized1-eps-conv

- 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

EPSF/CX100Setup-eps-converted-to.pdf

EPSF/CX100Disp_New-eps-co

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

Example 2: Convergence Study

- Validation

EPSF/CX100conv3-eps-converted-to.pdf

- Verification

EPSF/CX100elem2-eps-conve

  - Sharp gradients in sectional properties
  - Erratic data

Example 3: Damping Effect

- Cantilever Beam Under Impulsive Load

EPSF/AM2_Excitation-eps-converted-to.p

- Viscous Damping

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

- RMS Error

Example 3: Root forces and moments

- u_1

  EPSF/AM2_u1-eps-converted-to.pdf

- u_2

  EPSF/AM2_u2-eps-converted-to.pdf

- u_3

  EPSF/AM2_u3-eps-co

- p_1

  EPSF/AM2_p1-eps-converted-to.pdf

- p_2

  EPSF/AM2_p2-eps-converted-to.pdf

- p_3

  EPSF/AM2_p3-eps-co

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-converte

- PSD of Applied Force

Example 4: NREL 5-MW Blade (Continued)

- Flapwise Response

EPSF/u_5MW_flap_final-eps-converted-to.pdf

- PSD of Flapwise Response

EPSF/u_5MW_flap_psd_final

- 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

EPSF/TotalNR-eps-converted-to.pdf

Figure: Total number of linear system solves.

EPSF/AveNR-eps-converted-

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?

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References