Overview of the ElastoDyn Structural-Dynamics Module

NREL Wind Turbine Modeling Workshop

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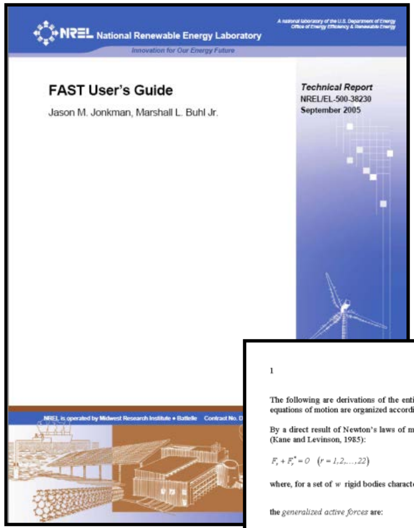
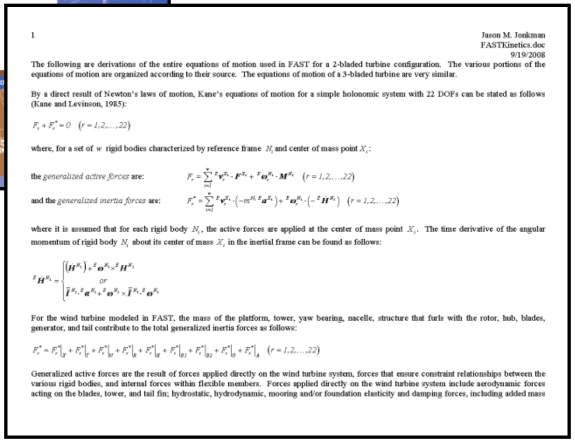
Introduction & Background

ElastoDyn – What Is It?

- Structural-dynamic model for horizontal-axis wind turbines:
  - Used to be a fundamental part of **FAST**
  - Now split out as a callable module in the **FAST** framework with separate input files & source code
  - Includes structural models of the rotor, drivetrain, nacelle, tower, & platform
- Latest version:
  - v1.01.02b-bjj (October 2013)
- User's Guide:
  - Sections of Jonkman & Buhl (2005) & Addendum (2013)
- Theory Manual (unofficial):
  - Jonkman (2005)

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Jason M. Jonkman
FASTKinetics.doc
9/19/2008

The following are derivations of the entire equations of motion used in FAST for a 2-bladed turbine configuration. The various portions of the equations of motion are organized according to their source. The equations of motion of a 3-bladed turbine are very similar.

By a direct result of Newton's laws of motion, Kane's equations of motion for a simple holonomic system with 22 DOFs can be stated as follows (Kane and Levinson, 1985):

$$F_r + F_r^* = 0 \quad (r = 1,2,\ldots,22)$$

where, for a set of w rigid bodies characterized by reference frame N_i and center of mass point X_i:

the *generalized active forces* are: $F_r = \sum_{i=1}^{w} {}^E\mathbf{v}_r^{X_i} \cdot \mathbf{F}^{X_i} + {}^E\boldsymbol{\omega}_r^{N_i} \cdot \mathbf{M}^{N_i} \quad (r = 1,2,\ldots,22)$

and the *generalized inertia forces* are: $F_r^* = \sum_{i=1}^{w} {}^E\mathbf{v}_r^{X_i} \cdot \left(-m^{N_i}\,{}^E\mathbf{a}^{X_i}\right) + {}^E\boldsymbol{\omega}_r^{N_i} \cdot \left(-{}^E\dot{\mathbf{H}}^{N_i}\right) \quad (r = 1,2,\ldots,22)$

where it is assumed that for each rigid body N_i, the active forces are applied at the center of mass point X_i. The time derivative of the angular momentum of rigid body N_i about its center of mass X_i in the inertial frame can be found as follows:

$${}^E\dot{\mathbf{H}}^{N_i} = \begin{cases} \left(\dot{\mathbf{H}}^{N_i}\right) + {}^E\boldsymbol{\omega}^{N_i} \times {}^E\mathbf{H}^{N_i} \\ or \\ \bar{\bar{\mathbf{I}}}^{N_i} \cdot {}^E\boldsymbol{\alpha}^{N_i} + {}^E\boldsymbol{\omega}^{N_i} \times \bar{\bar{\mathbf{I}}}^{N_i} \cdot {}^E\boldsymbol{\omega}^{N_i} \end{cases}$$

For the wind turbine modeled in FAST, the mass of the platform, tower, yaw bearing, nacelle, structure that furls with the rotor, hub, blades, generator, and tail contribute to the total generalized inertia forces as follows:

$$F_r^* = F_r^*\big|_X + F_r^*\big|_T + F_r^*\big|_N + F_r^*\big|_R + F_r^*\big|_H + F_r^*\big|_{B1} + F_r^*\big|_{B2} + F_r^*\big|_G + F_r^*\big|_A \quad (r = 1,2,\ldots,22)$$

Generalized active forces are the result of forces applied directly on the wind turbine system, forces that ensure constraint relationships between the various rigid bodies, and internal forces within flexible members. Forces applied directly on the wind turbine system include aerodynamic forces acting on the blades, tower, and tail fin; hydrostatic, hydrodynamic, mooring and/or foundation elasticity and damping forces, including added mass

Introduction & Background

Inputs, Outputs, States, & Parameters

ElastoDyn

Inputs:
- Aerodynamic loads
- Hydrodynamic loads
- Controller commands
- Substructure reactions @ transition piece

Continuous States:
- Displacements
- Velocities

Parameters:
- Geometry
- Mass/inertia
- Stiffness coefficients
- Damping coefficients

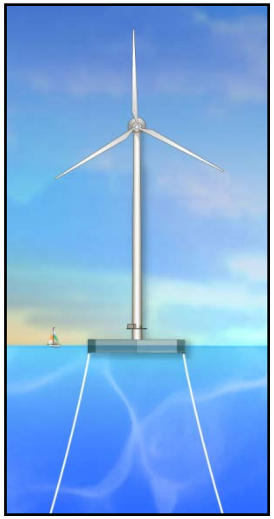
Outputs:
- Displacements
- Velocities
- Accelerations
- Reaction loads

Introduction & Background
Turbine Configurations

- Horizontal-axis (HAWT)
- 2- or 3-bladed rotor
- Upwind or downwind rotor
- Rigid or teetering hub
- Conventional configuration or inclusion of rotor- &/or tail-furling
- Support structure that includes a tower atop a platform
- Land- or sea-based
- Offshore fixed-bottom or floating

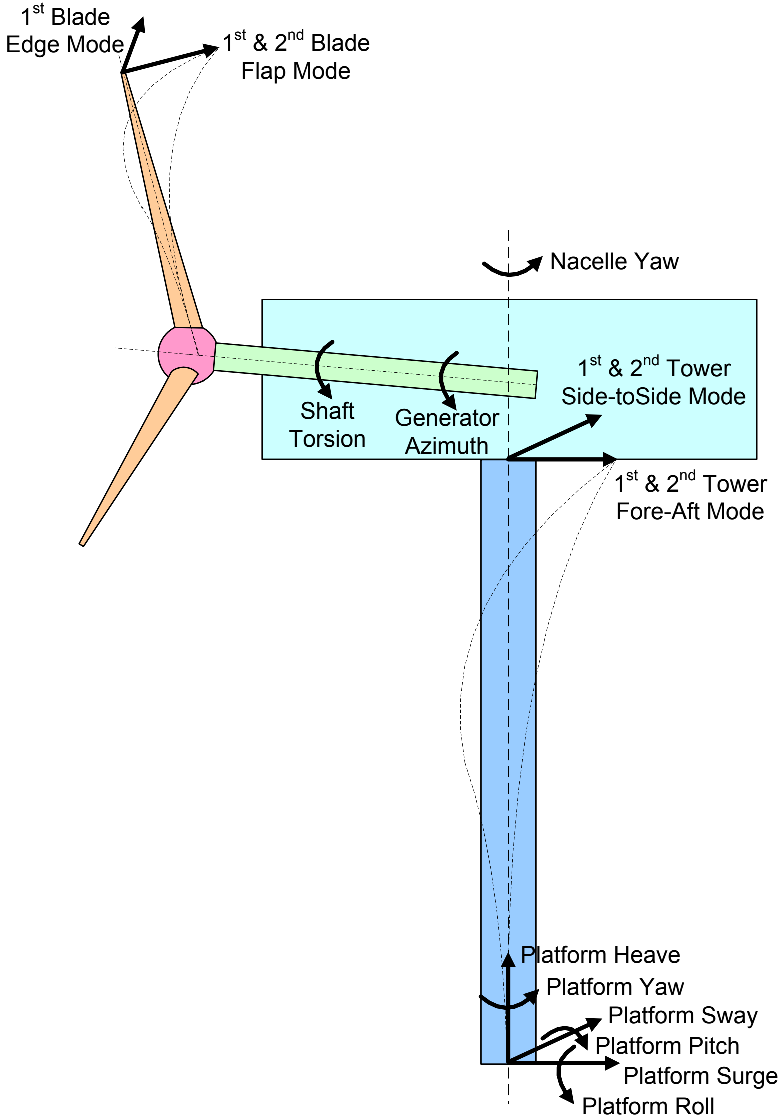






Theory Basis

Degrees of Freedom



Blades: 2 flap modes per blade
1 edge mode per blade

Teeter: 1 rotor teeter hinge with optional δ_3 (2-blader only)

Drivetrain: 1 generator azimuth
1 shaft torsion

Furl: (not yet in **FAST** v8) 1 rotor-furl hinge of *arbitrary* the nacelle & rotor
1 tail-furl hinge of *arbitrary orientation & location* between the nacelle & tail

Nacelle: 1 yaw bearing

Tower: 2 fore-aft modes
2 side-to-side modes

Platform: 3 translation (surge, sway, heave)
3 rotation (roll, pitch, yaw)

Total: 24 DOFs available for 3-blader
22 DOFs available for 2-blader

Theory Basis
Overview

$$F = ma$$

(any questions? ☺)

Theory Basis

Overview (cont)

- Combined multi-body- & modal-dynamics formulation:
  - Modal: blades, tower
  - Multi-body: platform, nacelle, generator, gears, hub, tail
- Utilizes relative DOFs:
  - No constraint equations
  - ODEs instead of DAEs
- *Nonlinear* equations of motion (EoMs) are derived & implemented using Kane's Method (not an energy method)
- EoM form:

$$M\left(\underline{q},\underline{u},t\right)\underline{\ddot{q}}+\underline{f}\left(\underline{q},\underline{\dot{q}},\underline{u},\underline{u_d},t\right)=\underline{0}$$

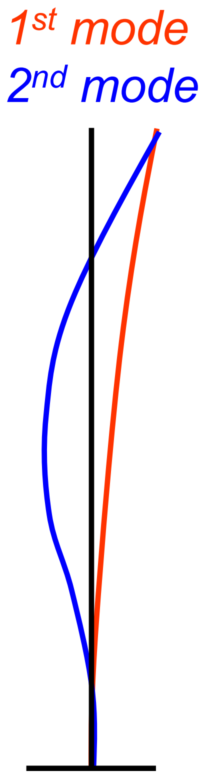
$$\underline{OutData}=\underline{Y}\left(\underline{q},\underline{\dot{q}},\underline{u},\underline{u_d},t\right)=Y_r\left(\underline{q},\underline{u},t\right)\underline{\ddot{q}}+\underline{Y_t}\left(\underline{q},\underline{\dot{q}},\underline{u},\underline{u_d},t\right)$$

- Time integration using one of several options:
  - 4^{th}-order Runge-Kutta (RK4) explicit
  - 4^{th}-order Adams-Bashforth (AB4) multi-step explicit (init. with RK4)
  - 4^{th}-order Adams-Bashforth-Moulton (ABM4) multi-step predictor-corrector (PC) (init. With RK4)

Theory Basis

Blade & Tower Modeling Assumptions

- Bernoulli-Euler beams under bending:
  - No axial or torsional DOFs
  - No shear deformation
- Straight beams with isotropic material & no mass or elastic offsets:
  - Blade pretwist induces flap & edge coupling
- Motions consider small to moderate deflections:
  - Superposition of lowest modes:
    - Mode shapes specified as polynomial coefficients
    - Mode shapes not calculated internally (found from e.g. **BModes** or modal test)
    - Shapes should represent modes, but **FAST** doesn't require orthogonality (no diagonalization employed)
  - Bending assumes small strains: $\theta \approx \frac{\partial u}{\partial h} \quad \kappa \approx \frac{\partial^2 u}{\partial h^2}$
    - Employs small angle approximations with nonlinear corrections for coordinate system orthogonality
- Otherwise, all terms include full nonlinearity:
  - Mode shapes used as shape functions in a nonlinear beam model (Rayleigh-Ritz method)
  - Motions include radial shortening terms (geometric nonlinearity)
  - Inertial loads include nonlinear centrifugal, Coriolis, & gyroscopic terms

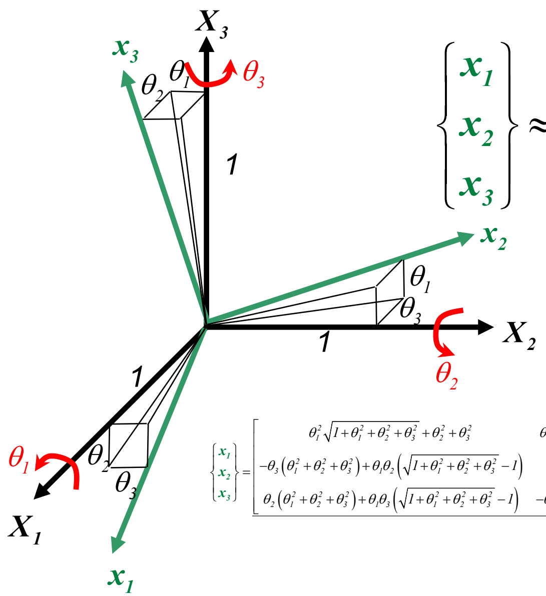


Modal Representation

Theory Basis

Rotations

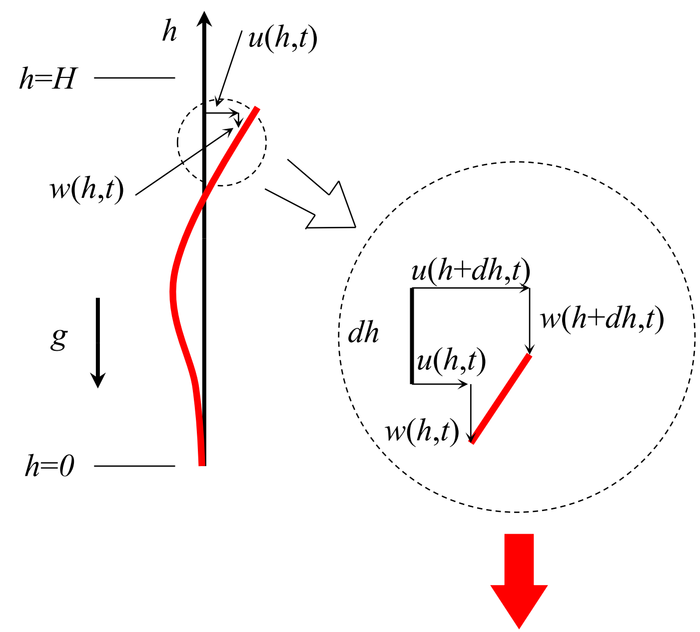
- Support platform pitch, roll, & yaw motions employ small angle approximations with nonlinear correction for orthogonality
- All other DOFs may exhibit large motions w/o loss of accuracy



$$\begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix} \approx \begin{bmatrix} 1 & \theta_3 & -\theta_2 \\ -\theta_3 & 1 & \theta_1 \\ \theta_2 & -\theta_1 & 1 \end{bmatrix} \begin{Bmatrix} X_1 \\ X_2 \\ X_3 \end{Bmatrix}$$

$$\begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix} = \frac{\begin{bmatrix} \theta_1^2\sqrt{1+\theta_1^2+\theta_2^2+\theta_3^2}+\theta_2^2+\theta_3^2 & \theta_3\left(\theta_1^2+\theta_2^2+\theta_3^2\right)+\theta_1\theta_2\left(\sqrt{1+\theta_1^2+\theta_2^2+\theta_3^2}-1\right) & -\theta_2\left(\theta_1^2+\theta_2^2+\theta_3^2\right)+\theta_1\theta_3\left(\sqrt{1+\theta_1^2+\theta_2^2+\theta_3^2}-1\right) \\ -\theta_3\left(\theta_1^2+\theta_2^2+\theta_3^2\right)+\theta_1\theta_2\left(\sqrt{1+\theta_1^2+\theta_2^2+\theta_3^2}-1\right) & \theta_1^2+\theta_2^2\sqrt{1+\theta_1^2+\theta_2^2+\theta_3^2}+\theta_3^2 & \theta_1\left(\theta_1^2+\theta_2^2+\theta_3^2\right)+\theta_2\theta_3\left(\sqrt{1+\theta_1^2+\theta_2^2+\theta_3^2}-1\right) \\ \theta_2\left(\theta_1^2+\theta_2^2+\theta_3^2\right)+\theta_1\theta_3\left(\sqrt{1+\theta_1^2+\theta_2^2+\theta_3^2}-1\right) & -\theta_1\left(\theta_1^2+\theta_2^2+\theta_3^2\right)+\theta_2\theta_3\left(\sqrt{1+\theta_1^2+\theta_2^2+\theta_3^2}-1\right) & \theta_1^2+\theta_2^2+\theta_3^2\sqrt{1+\theta_1^2+\theta_2^2+\theta_3^2} \end{bmatrix}}{\left(\theta_1^2+\theta_2^2+\theta_3^2\right)\sqrt{1+\theta_1^2+\theta_2^2+\theta_3^2}} \begin{Bmatrix} X_1 \\ X_2 \\ X_3 \end{Bmatrix}$$

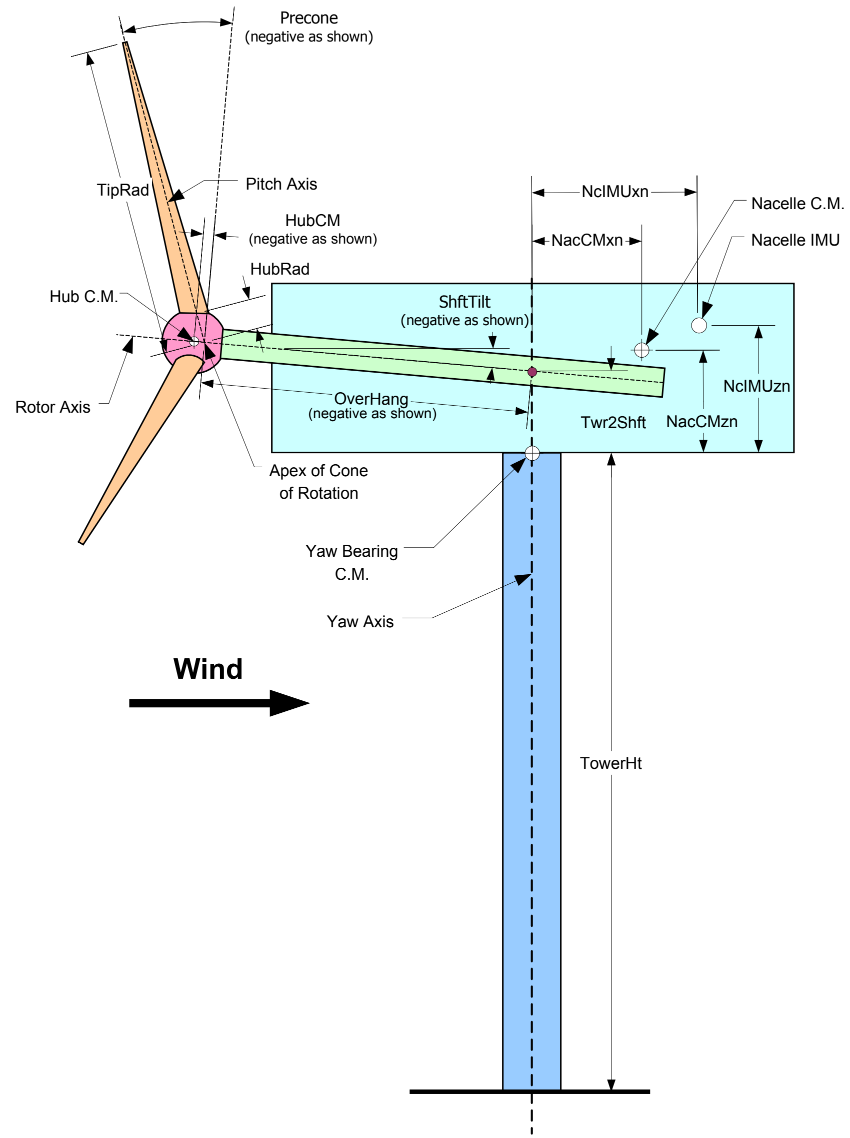
Correction for Orthogonality



$$w(h,t) = \frac{1}{2}\int_0^h \left[\frac{\partial u(h',t)}{\partial h'}\right]^2 dh'$$

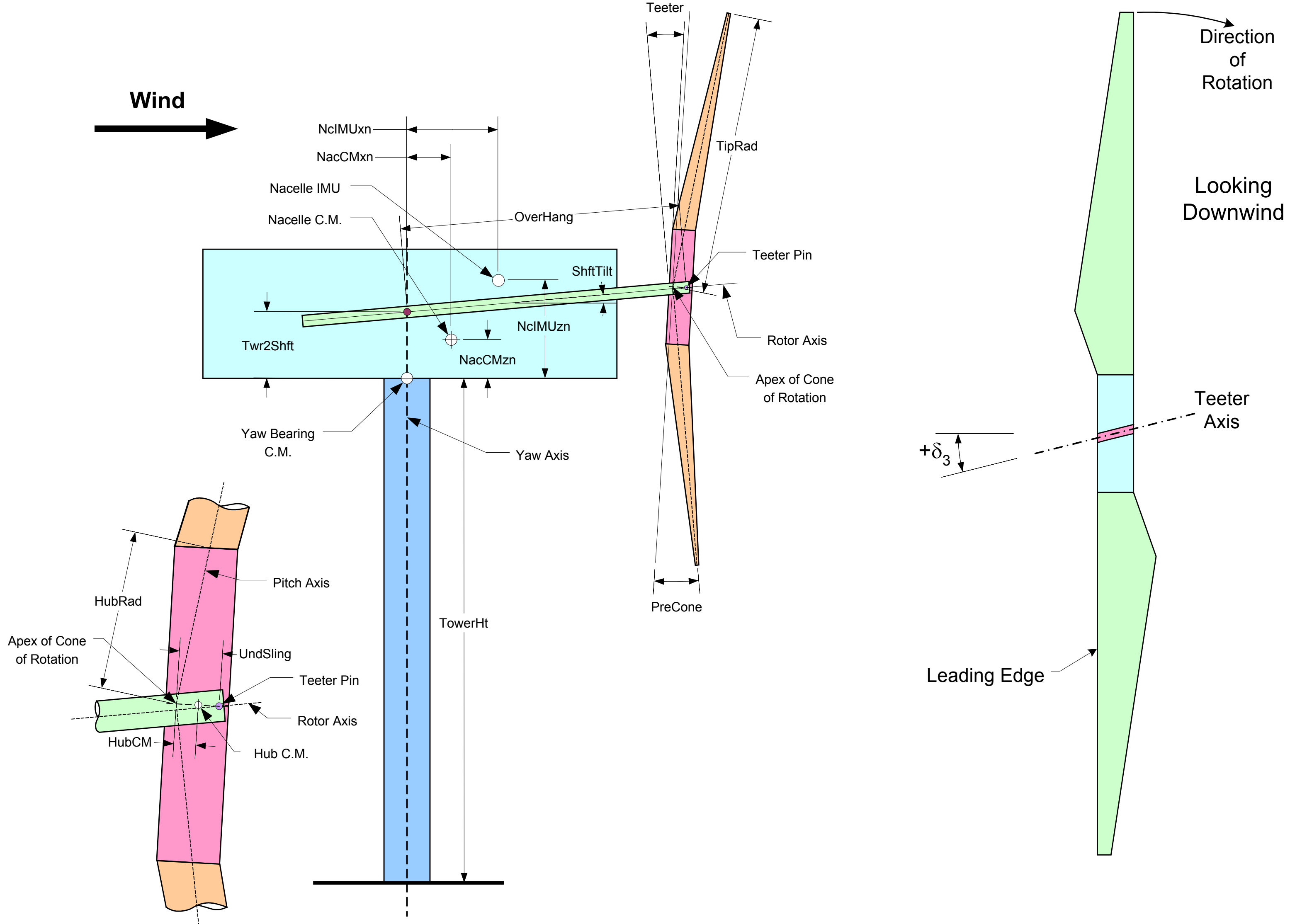
Radial Shortening Effect

Input Geometry
Turbine Parameterization – Upwind, 3-Blader



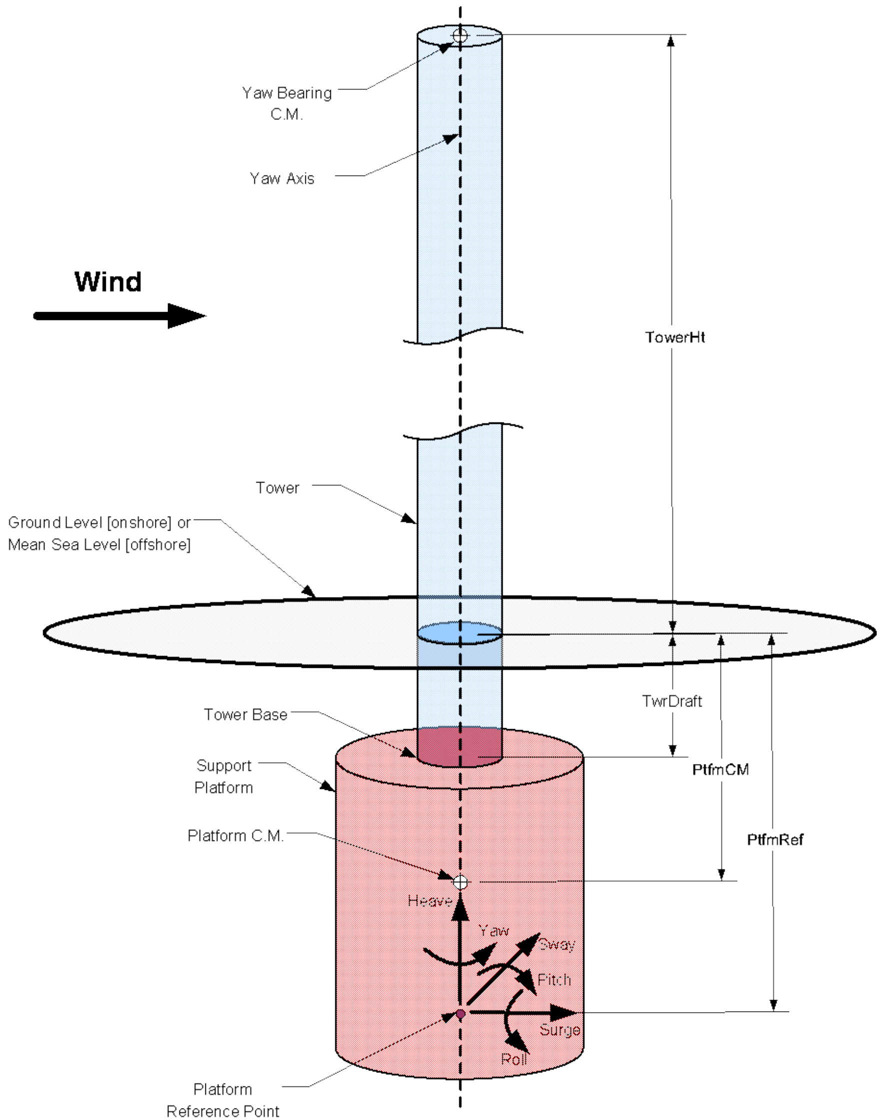
Input Geometry

Turbine Parameterization – Downwind, 2-Blader



Input Geometry

Turbine Parameterization – Support Platform



Structural Features of FAST v8 Compared to v7

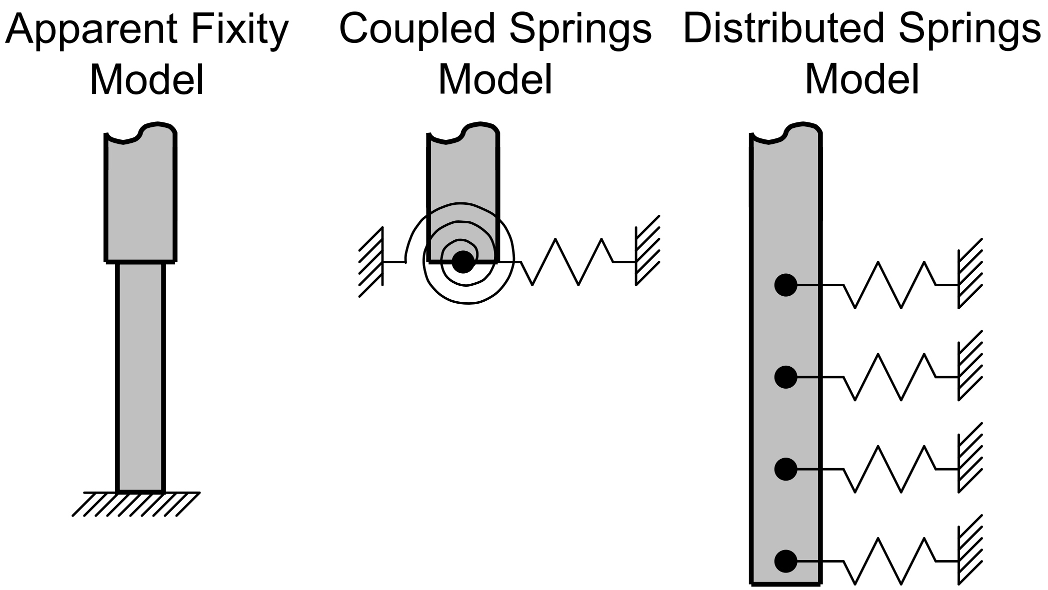
- All new features are being added to the new framework
- Until all features of v7 are included in v8, both will be supported

Structural Dynamics (ElastoDyn, SubDyn, and MAP)

FAST Features	v7.02	v8.03
• Blade-bending DOFs	✓	✓
• Rotor teeter DOF	✓	✓
• Generator azimuth and drivetrain torsion DOFs	✓	✓
• Nacelle-yaw DOF	✓	✓
• Tower-bending DOFs	✓	✓
• Rigid-body platform DOFs	✓	✓
• Furling DOFs	✓	
• Fixed-bottom multi-member substructure DOFs:		✓
– Solved with linear frame finite-element or Craig-Bampton reduction		✓
• Gravitational loading	✓	✓
• Gearbox friction	✓	
• System of independent mooring lines solved quasi-statically	✓	✓
• System of multi-segmented mooring lines solved quasi-statically		✓
• Earthquake excitation	✓	

Recent Work & Current & Planned Work

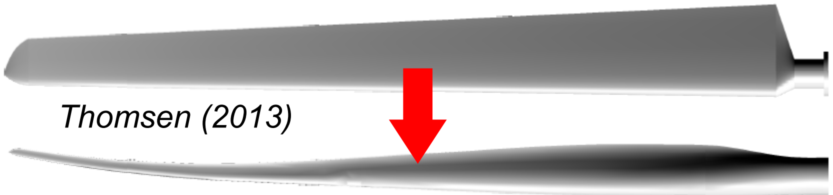
- Recent work:
  - Split out **ElastoDyn** as a callable module in the **FAST** framework with separate input files & source code
- Current & planned work:
  - Address current limitations of **FAST** v8 relative to v7
  - Introduce built-in foundation models:
    - Only user-defined implementation currently available



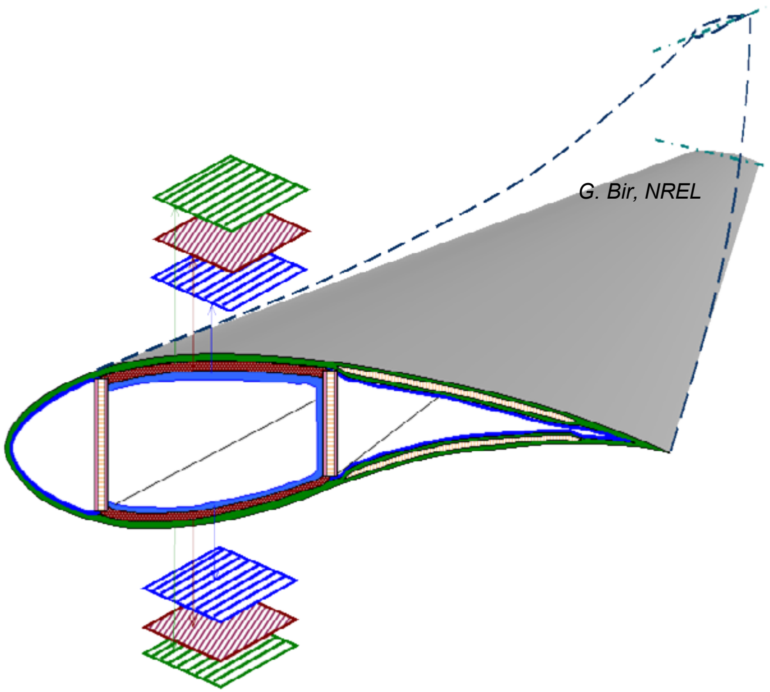
Simplified Models of a Monopile with Flexible Foundation

Current & Planned Work (cont)

- Incorporate higher-fidelity modeling of blades (**BeamDyn**):
  - Spectral finite element (FE) & improved modal approaches
  - Based on Geometrically Exact Beam Theory (GEBT):
    - Linearly elastic material
    - Full geometric nonlinearity
  - Bending, torsion, shear, & extensional DOFs
  - Anisotropic material couplings (from **PreComp**, **NuMAD**, or **VABS**)
  - Chordwise mass & elastic offsets
  - Built-in curvature & sweep



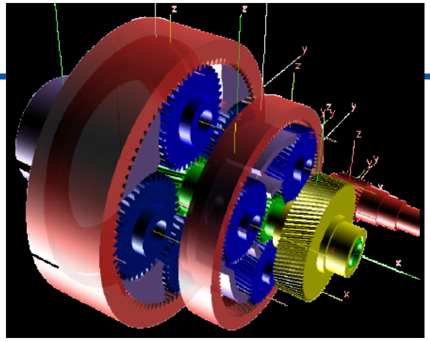
Advancement in Blade Design



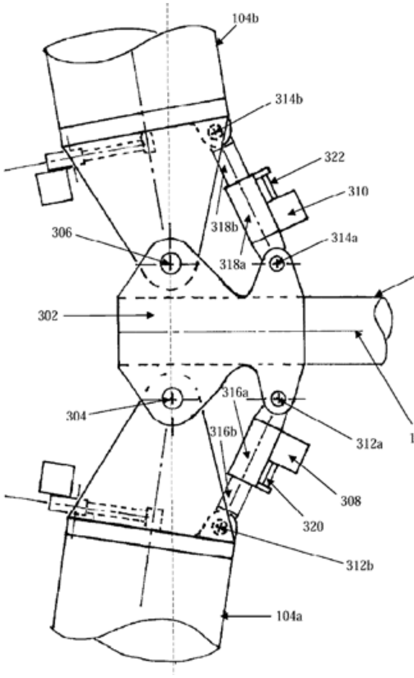
Blade Twist Induced By Anisotropic Layup

Future Opportunities

- Publish **ElastoDyn** Theory Manual
- Add blade-pitch DOFs
- Add drivetrain dynamics & shaft deflection DOFs
- Add nacelle-based mass-damper DOFs (with UMass)
- Improve friction models for yaw, teeter, & furling
- Develop a nonlinear beam FE with reduced DOFs per element
- Develop general capability for hinged & segmented blades



***SIMPACK** Gearbox*



Hub with Flap Hinges

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Questions?

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