Overview of the FAST Servo-Elastic Module

NREL Wind Turbine Modeling Workshop

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Outline

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  - FAST – What Is It?
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  - Turbine Configurations
  - Degrees of Freedom
  - Basic Theory
  - Turbine Parameterizations
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- Simulation:
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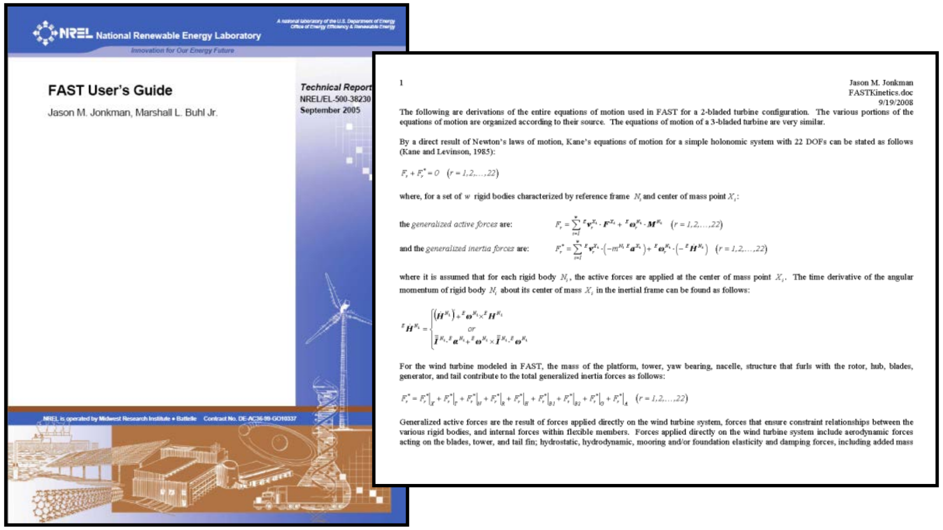
- Future Opportunities

Overview

FAST – What Is It?

- Structural-dynamic model for horizontal-axis wind turbines:
  - Used to stand for **F**atigue, **A**erodynamics, **S**tructures, & **T**urbulence
  - Now just “**FAST**”
  - Coupled to **AeroDyn**, **HydroDyn**, & controller for aero-hydro-servo-elastic simulation
  - Evaluated by Germanischer Lloyd WindEnergie
- Latest version:
  - v7.02.00d-bjj (February 2013)
  - v8 in progress
- User’s Guide:
  - Jonkman & Buhl (2005)
  - Addendum (2013)
- Theory Manual (unofficial):
  - Jonkman (2005)



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Office of Energy Efficiency & Renewable Energy

FAST User’s Guide

Jason M. Jonkman, Marshall L. Buhl Jr.

Technical Report
NREL/EL-500-38230
September 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:

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

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:

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

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

Overview

History

FAST2, FAST3 (pre-1996)
- Developer: B. Wilson, OSU
- Different code for 2- & 3-blades
- Built-in aerodynamics

FAST_AD2, FAST_AD3 (1996)
- Developer: A. Wright, NREL
- Different code for 2- & 3-blades
- **AeroDyn** aerodynamics

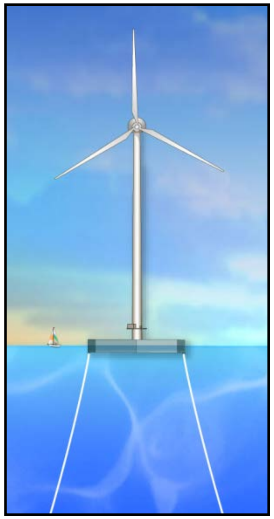
FAST_AD v1 – v3 (1997-2002)
- Developers: N. Weaver, M. Buhl, et al., NREL
- Single code for 2- & 3-blades
- **AeroDyn** aerodynamics

FAST v4 – v7 (2002-present)
- Developer: J. Jonkman, NREL
- Single code for 2- & 3-blades
- Rederived & implemented EoM
- New DOFs (furling, platform)
- **AeroDyn** aerodynamics
- **HydroDyn** hydrodynamics
- Linearization
- FAST-to-ADAMS preprocessor

Overview

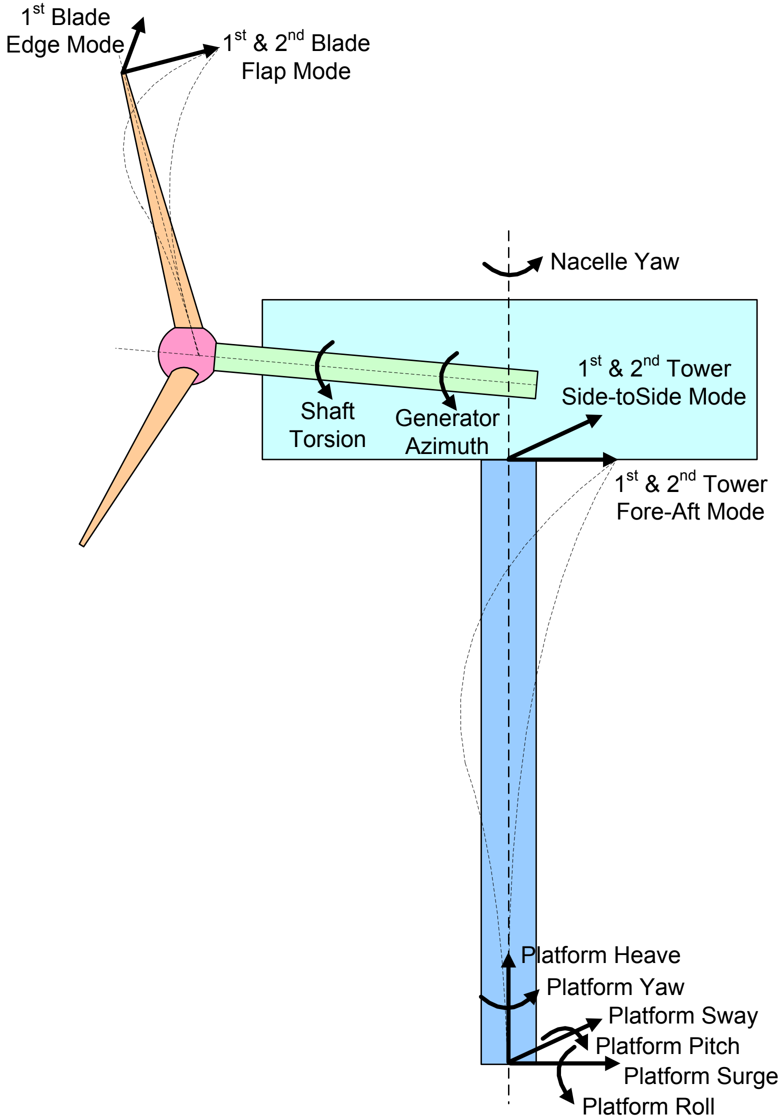
Turbine Configurations

- 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
- Land- or sea-based
- Offshore monopiles or floating
- Rigid or flexible foundation



Overview

Degrees of Freedom



Blades:	2 flap modes per blade 1 edge mode per blade
Tower:	2 fore-aft modes 2 side-to-side modes
Drivetrain:	1 generator azimuth 1 shaft torsion
Nacelle:	1 yaw bearing
Teeter:	1 rotor teeter hinge with optional δ_3 (2-blader only)
Furl:	1 rotor-furl hinge of *arbitrary orientation & location* between the nacelle & rotor 1 tail-furl hinge of *arbitrary orientation & location* between the nacelle & tail
Platform:	3 translation (surge, sway, heave) 3 rotation (roll, pitch, yaw)
Total:	24 DOFs available for 3-blader 22 DOFs available for 2-blader

Overview

Basic Theory

$$F = ma$$

(any questions? ☺)

Overview
Basic Theory (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:

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

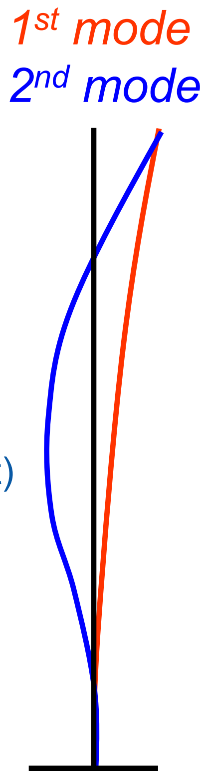
$$\underline{OutData}=\underline{Y}\left(\underline{q},\underline{\dot{q}},\underline{u},\underline{u_d},t\right)=Y_r\left(\underline{q},\underline{u},t\right)\underline{\ddot{q}}+\underline{Y_t}\left(\underline{q},\underline{\dot{q}},\underline{u},\underline{u_d},t\right)$$

- Time stepping using the 4^{th}-order Adams-Bashforth-Moulton (ABM4) predictor-corrector (PC) fixed-step-size integration scheme:
  - Initialized using 4^{th}-order Runge-Kutta (RK4) explicit scheme

Overview

Basic Theory (cont)

- 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 daigonalization 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

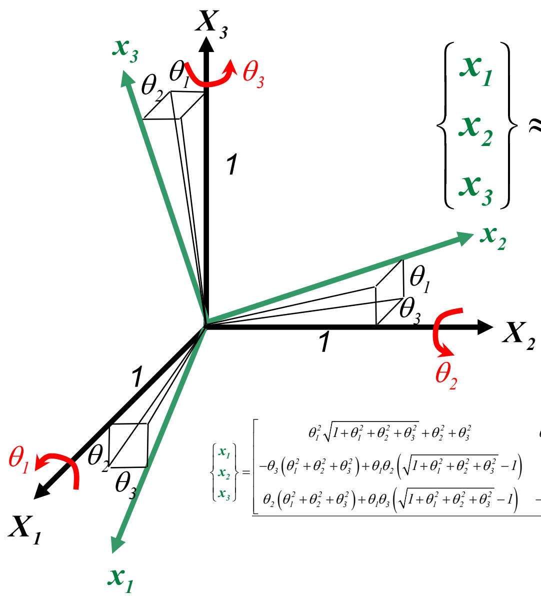


Modal Representation

Overview

Basic Theory (cont)

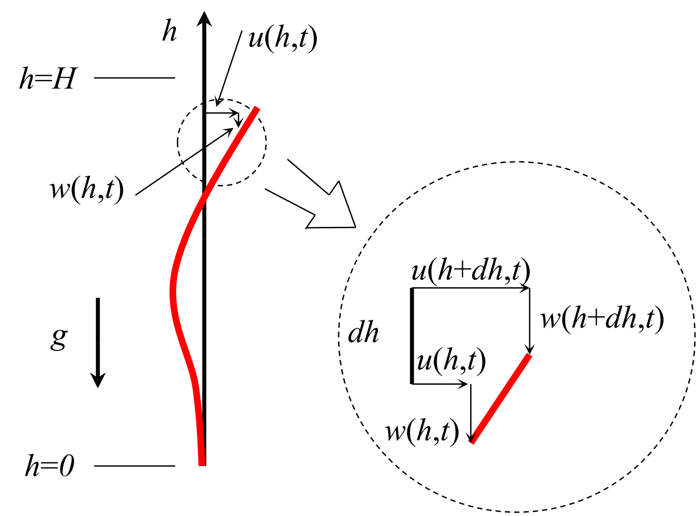
- Support platform pitch, roll, & yaw motions employ small angle approximations with nonlinear correction for orthogonality
- All other DOFs may exhibit large motions w/o loss of accuracy



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

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

Correction for Orthogonality

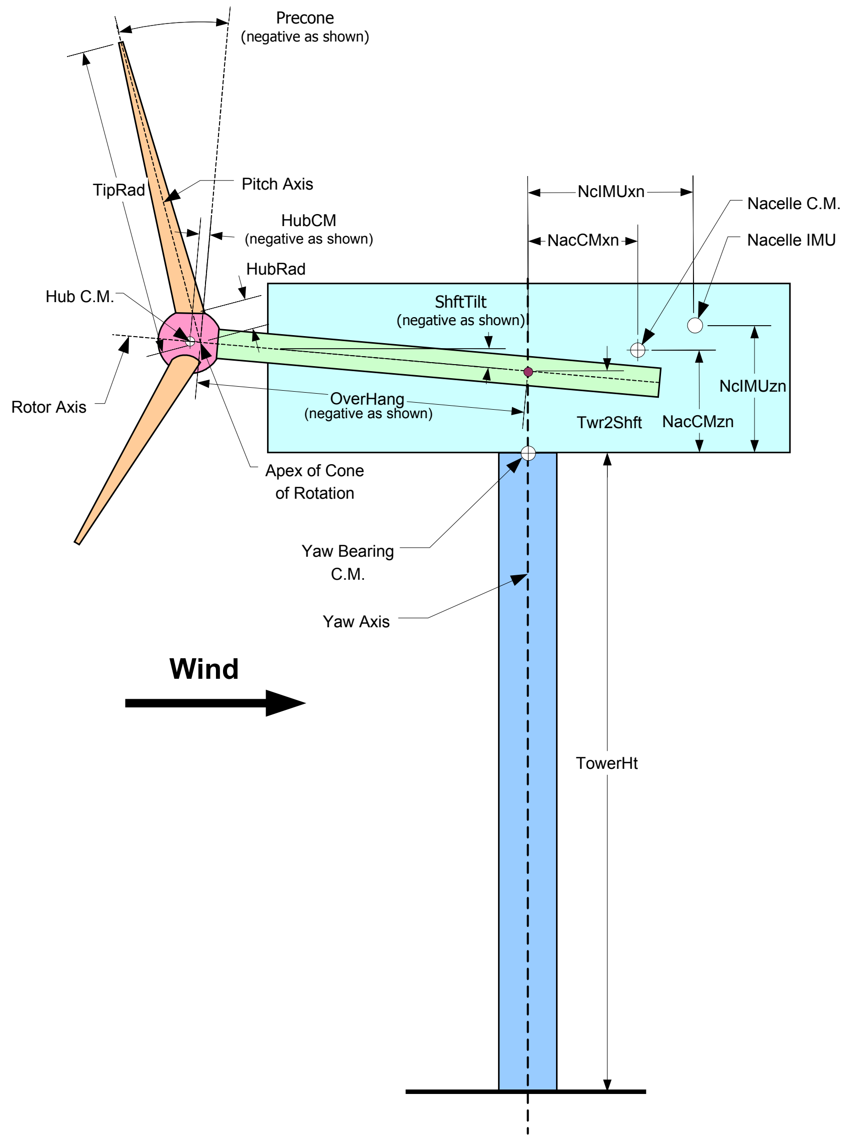


$$w(h,t) = \frac{1}{2}\int_0^h \left[\frac{\partial u(h',t)}{\partial h'}\right]^2 dh'$$

Radial Shortening Effect

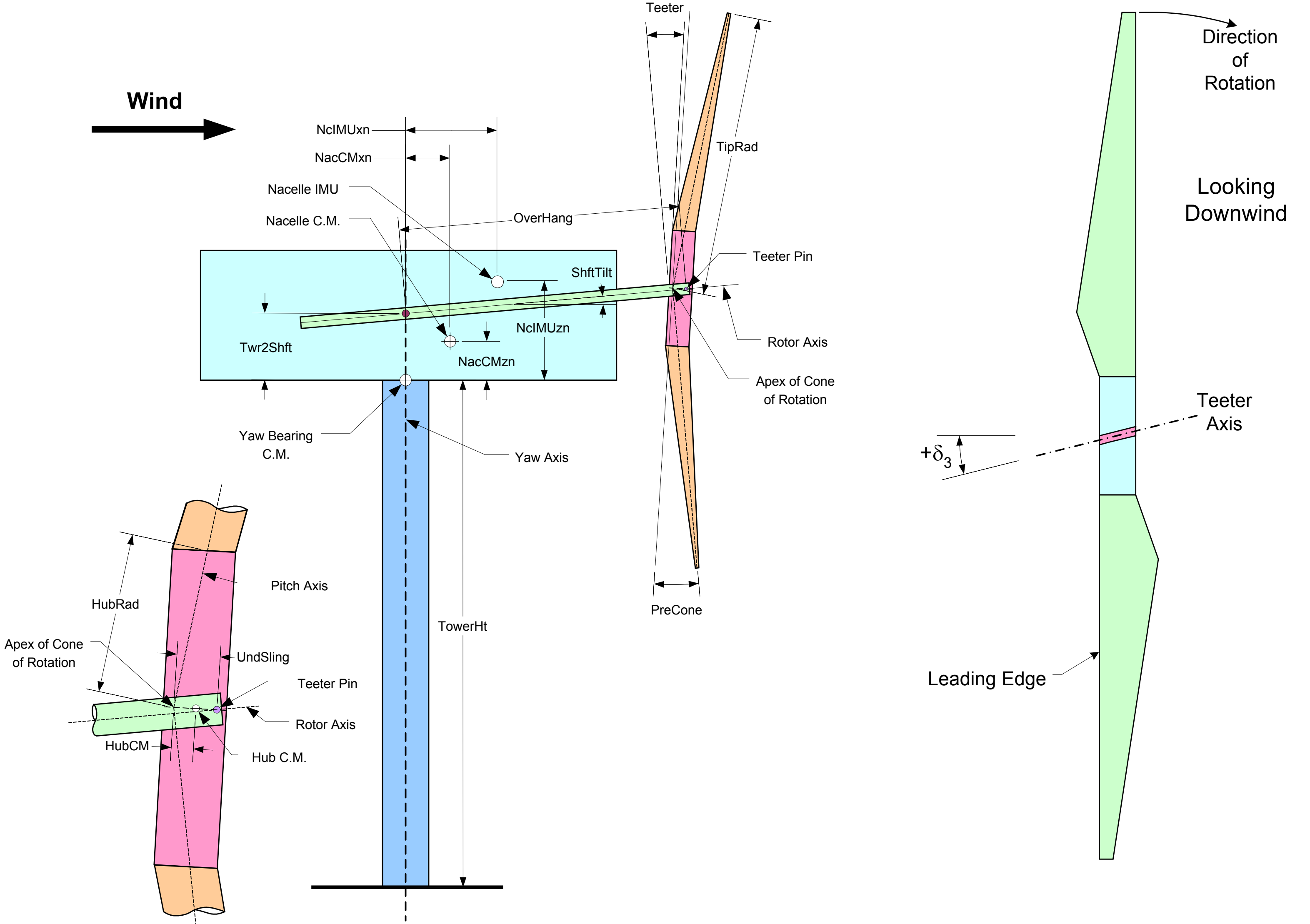
Overview

Turbine Parameterization – Upwind, 3-Blader



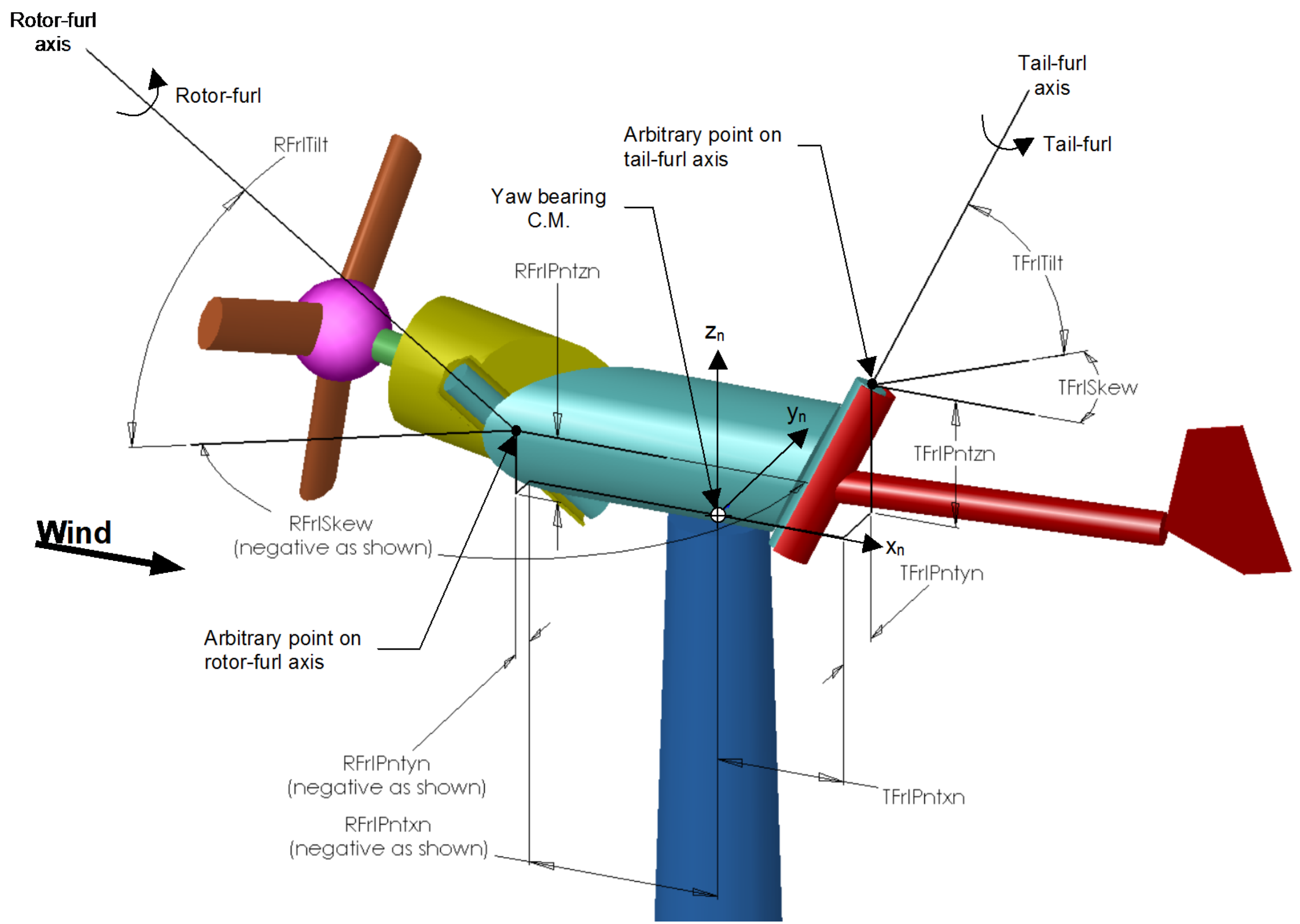
Overview

Turbine Parameterization – Downwind, 2-Blader



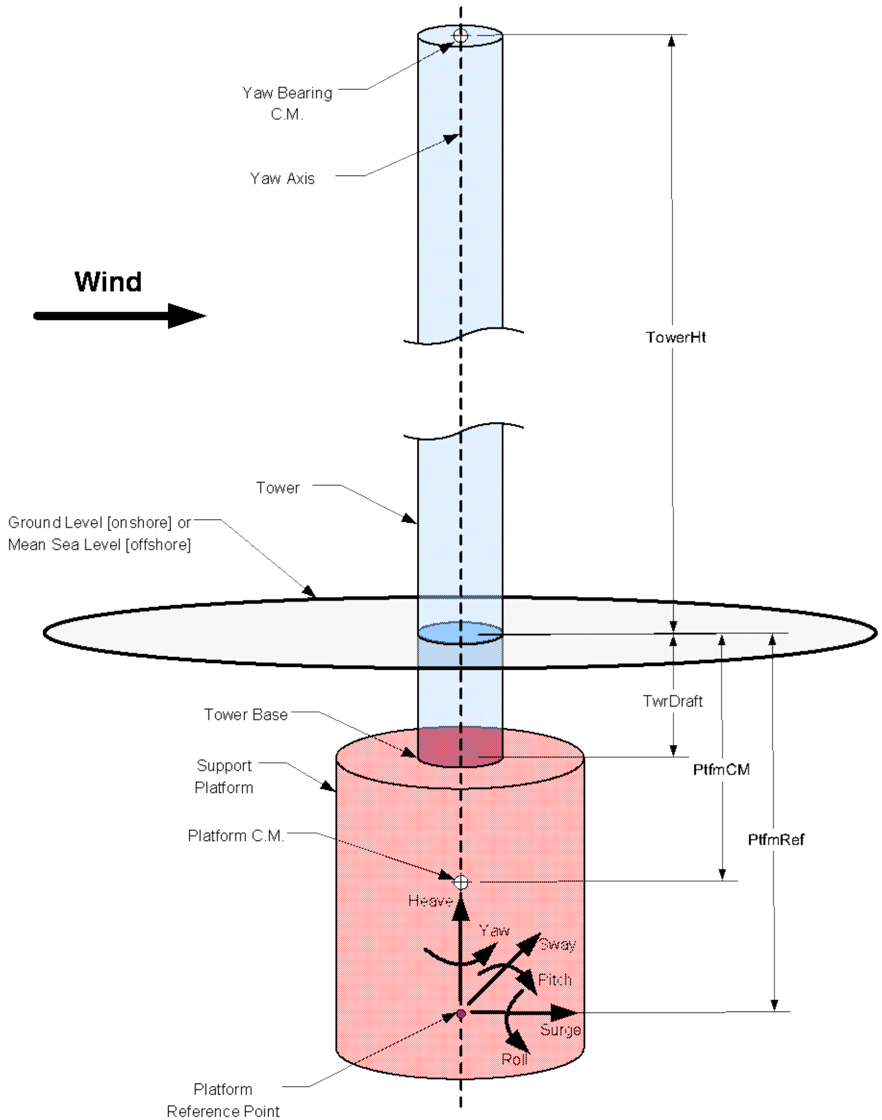
Overview

Turbine Parameterization – Furling DOFs



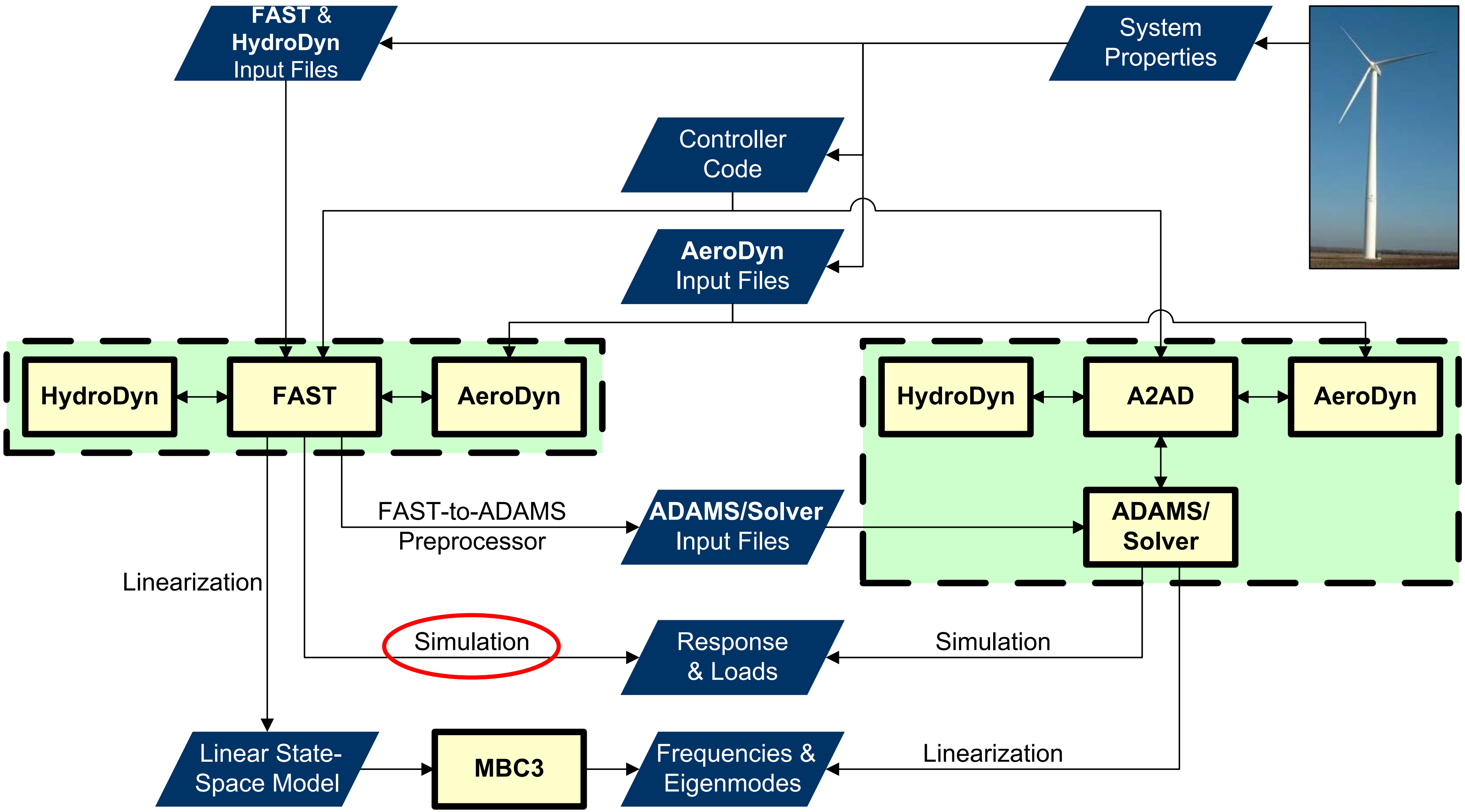
Overview

Turbine Parameterization – Support Platform



Overview

Modes of Operation



Simulation

Loads Analysis

- Nonlinear time-domain solution for loads analysis
- Run simulation within command prompt (.exe), within **MATLAB/Simulink** (.mexw32), or within **LabVIEW** (.dll)
- Design situations & conditions:
  - Turbulent & deterministic winds
  - Regular & irregular waves
  - Earthquake excitation
  - Power production with control
  - Start-up & shut-down maneuvers
  - Idling & parked conditions
  - Control system faults

Design Situation	DLC	Wind Condition	Wave Condition	Directionality	Other Conditions	Type of Analysis
Power production	1.x					
Power production plus occurrence of fault	2.x					
Start up	3.x					
Normal shut down	4.x					
Emergency shut down	5.x					
Parked	6.x					
Parked with fault	7.x					
Transport, assembly, and maintenance	8.x					

Load Case Matrix

Simulation
Inputs & Outputs (I/O)

- IEC-style coordinate systems for I/O
- Input parameters:
  - Simulation control:
    - Total time, time step
  - Feature flags
  - Initial conditions
  - Turbine configuration:
    - Geometry
  - Mass/inertia
  - Distributed blade/tower mass/stiffness
  - Blade/tower mode shapes
  - Control settings
  - Teeter, yaw, & furl springs/dampers
  - Output parameter selection
- Output parameters:
  - Motions:
    - Displacements
    - Velocities
    - Accelerations
    - Translational & rotational
    - Internal DOFs
  - Loads:
    - Shear forces
    - Axial forces
    - Bending moments
    - Torsion moments
  - Performance:
    - Wind
    - Power
    - Control settings

Simulation
Control Options

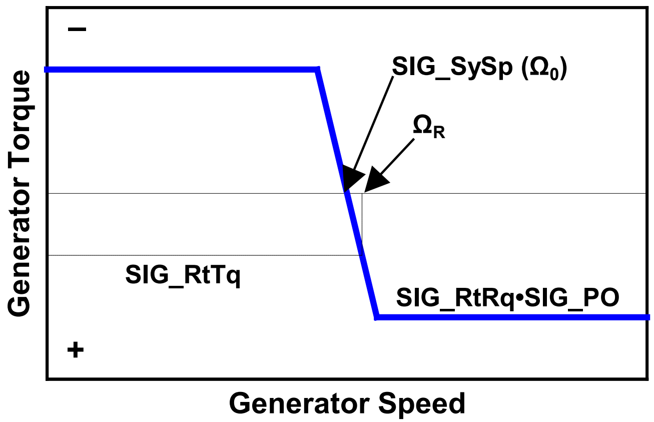
- Active control:
  - Blade pitch:
    - Collective or independent
    - To feather or stall
    - Command the angle
    - No actuator dynamics
    - Sample PID model included
  - Nacelle yaw:
    - Command the angle &/or rate
    - Optional 2nd-order actuator dynamics
  - Generator torque:
    - Fixed (with or without slip) or variable speed
    - Command the torque
    - Indirect electrical power
    - Default models built in
    - Sample table look-up model included
  - High-speed shaft brake:
    - Command the deployment
  - Blade tip brake:
    - Command the deployment

- Passive control:
  - Aerodynamic stall
  - Rotor teeter:
    - Optional damping & soft & hard stops
  - Nacelle yaw:
    - Free or restrained
  - Rotor furl:
    - Optional independent up- & down- springs & dampers
  - Tail furl:
    - Optional independent up- & down- springs & dampers

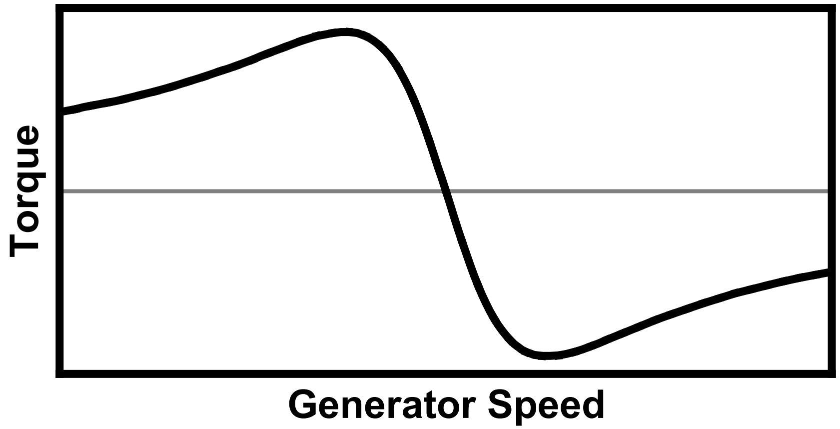
Simulation

Control Options – Default Torque Models

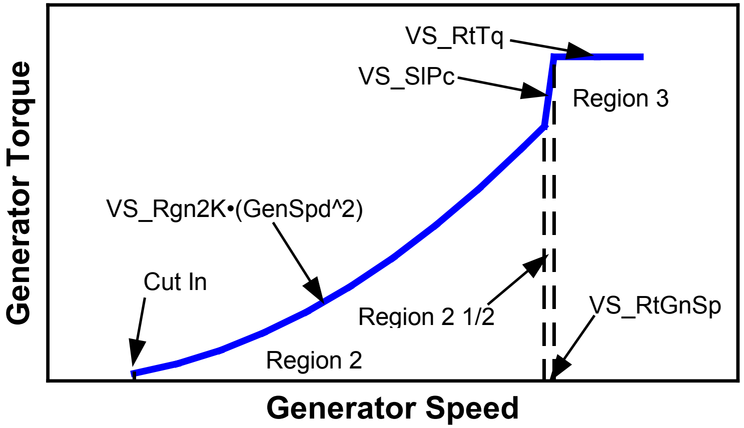
Simple Induction Generator



Thevenin-Equivalent Circuit Generator



Simple Variable-Speed Controller

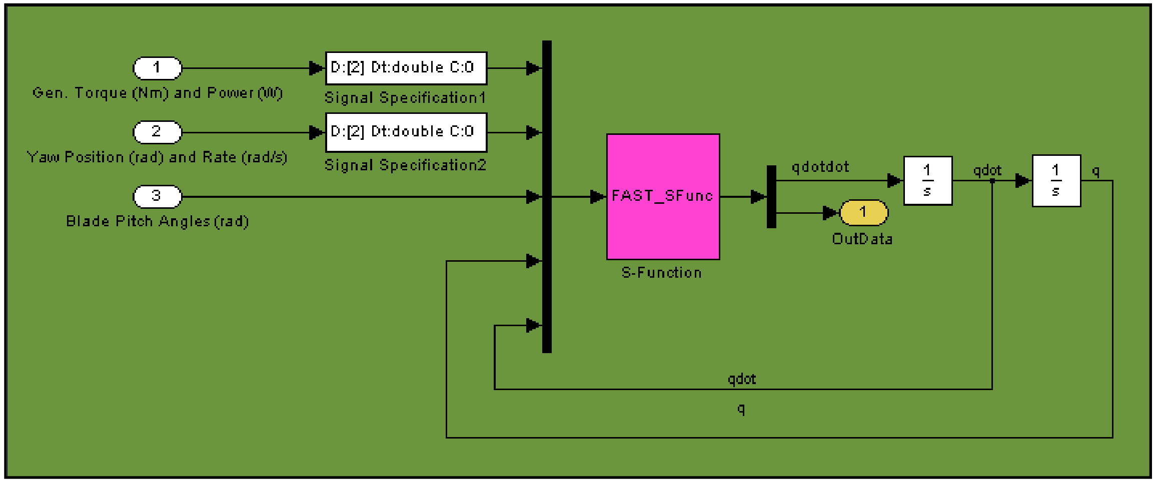


Simulation
Interfacing Active Controllers – 5 Options

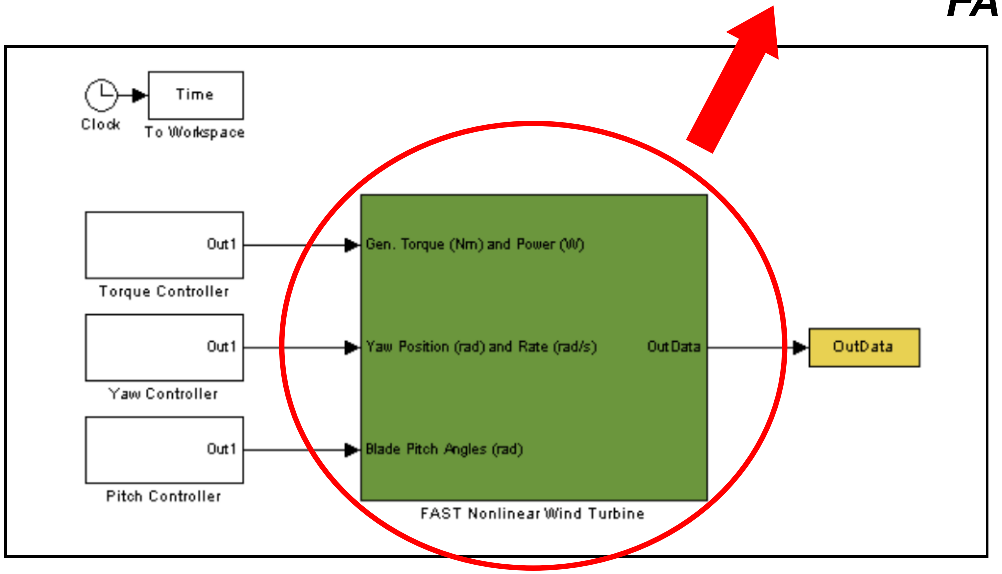
- Select from one of the built-in routines
- Fortran subroutine:
  - Separate routines for each controller (i.e.: separate routines for blade pitch, generator torque, nacelle yaw, & brake)
  - Sample routines provided with **FAST** archive
  - Requires recompile with each change to controller
- **GH Bladed**-style dynamic link library (DLL):
  - DLL interface routines included with **FAST** archive
  - Requires recompile of **FAST** (with interface routines) only once
  - DLL compiled separately from **FAST**:
    - Mixed languages possible – Can be Fortran, C++, etc.
  - DLL is a master controller (i.e.: Pitch, torque, yaw, & brake controlled with same DLL)
- **MATLAB/Simulink**:
  - **FAST** implemented as S-Function block (.mexw32)
  - Controls implemented in block-diagram form
- **LabVIEW**:
  - **FAST** implemented as DLL callable by **LabVIEW**
  - Hardware-in-the-loop (HIL) possible

Simulation

Interfacing Controllers – MATLAB/Simulink



FAST *Wind Turbine Block*



Open Loop Simulink Model

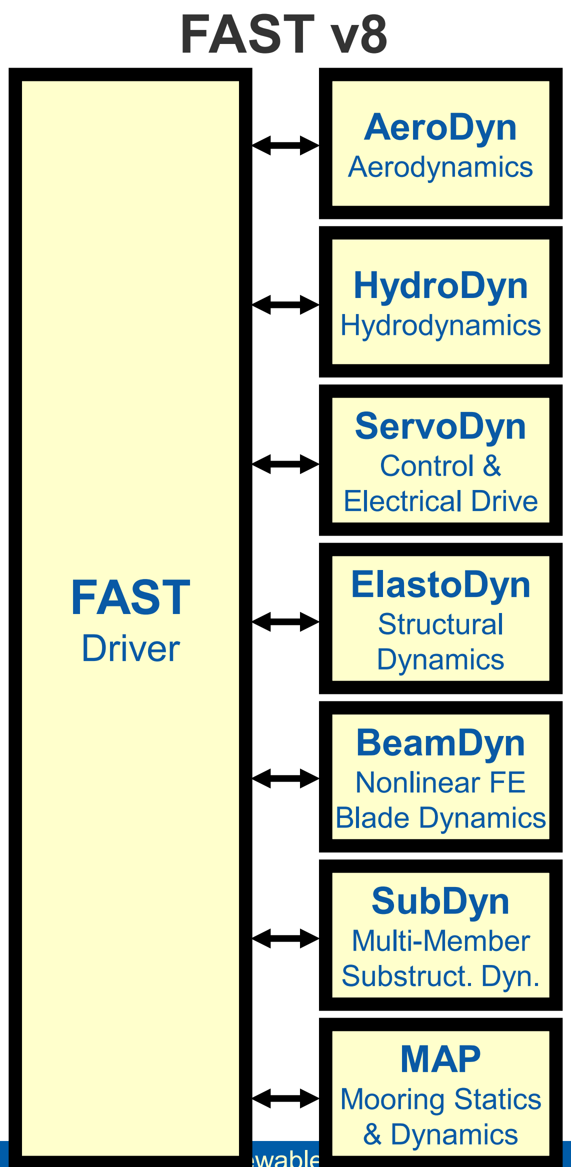
Sample Models Provided with the Archive

Test Name	Turbine Name	No. Blades (-)	Rotor Diameter (m)	Rated Power (kW)	Test Description
Test01	AWT-27CR2	2	27	175	Flexible, fixed yaw error, steady wind
Test02	AWT-27CR2	2	27	175	Flexible, start-up, HSS brake shut-down, steady wind
Test03	AWT-27CR2	2	27	175	Flexible, free yaw, steady wind
Test04	AWT-27CR2	2	27	175	Flexible, free yaw, turbulence
Test05	AWT-27CR2	2	27	175	Flexible, generator start-up, tip-brake shutdown, steady wind
Test06	AOC-15/50	3	15	50	Flexible, generator start-up, tip-brake shutdown, steady wind
Test07	AOC-15/50	3	15	50	Flexible, free yaw, turbulence
Test08	AOC-15/50	3	15	50	Flexible, fixed yaw error, steady wind
Test09	UAE VI downwind	2	10	20	Flexible, yaw ramp, steady wind
Test10	UAE VI upwind	2	10	20	Rigid, power curve, ramp wind
Test11	WP 1.5 MW	3	70	1500	Flexible, variable speed & pitch control, pitch failure, turbulence
Test12	WP 1.5 MW	3	70	1500	Flexible, variable speed & pitch control, ECD event
Test13	WP 1.5 MW	3	70	1500	Flexible, variable speed & pitch control, turbulence
Test14	WP 1.5 MW	3	70	1500	Flexible, stationary linearization, vacuum
Test15	SWRT	3	5.8	10	Flexible, variable speed control, free yaw, tail-furl, EOG01 event
Test16	SWRT	3	5.8	10	Flexible, variable speed control, free yaw, tail-furl, EDC01 event
Test17	SWRT	3	5.8	10	Flexible, variable speed control, free yaw, tail-furl, turbulence

- Others available (CART2, CART3, NREL 5-MW Baseline)

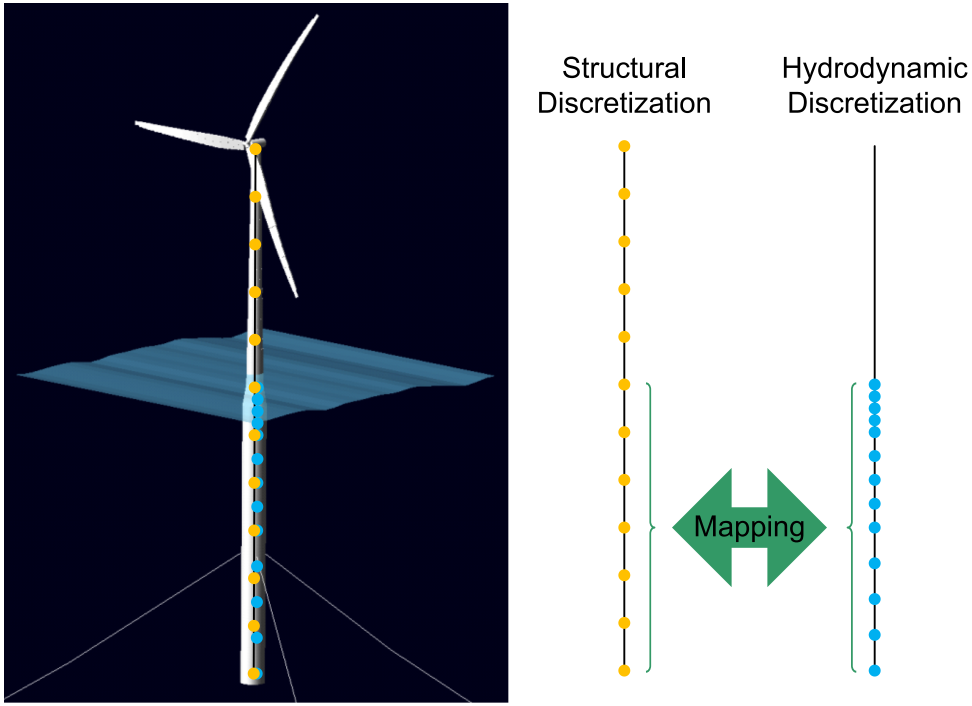
Recent Work

- Changes in v7.02.00d-bjj:
  - Added an optional binary output format (smaller size)
  - Introduced the **LabVIEW** interface
  - Supplied a “Compiling” folder supporting IVF for Windows & gfortran for Windows & Linux
  - Several minor changes & bug fixes
- Developed the new modularization framework:
  - Mathematical basis
  - Module source code template
  - Registry for automatic generation of general code
  - Programmer’s Handbook
  - Simple examples
- Converted **FAST** to the new framework (v8):
  - Split into (each with own input files & source code):
    - **ServoDyn** module for the controller & electrical drive
    - **ElastoDyn** module for structural dynamics
    - **FAST** driver (glue) code



Current & Planned Work

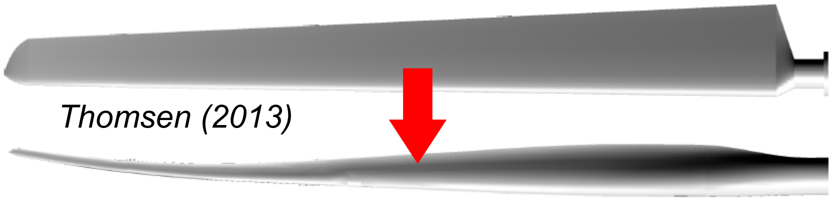
- Further development of the new FAST modularization framework:
  - Develop mapping schemes between independent spatial meshes
  - Improve driver (glue) code for loose coupling with mixed time-step PC approach
  - Address current limitations of **FAST** v8 relative to v7
  - Develop driver (glue) code for tight coupling, including linearization
  - Publish the Programmer's Handbook



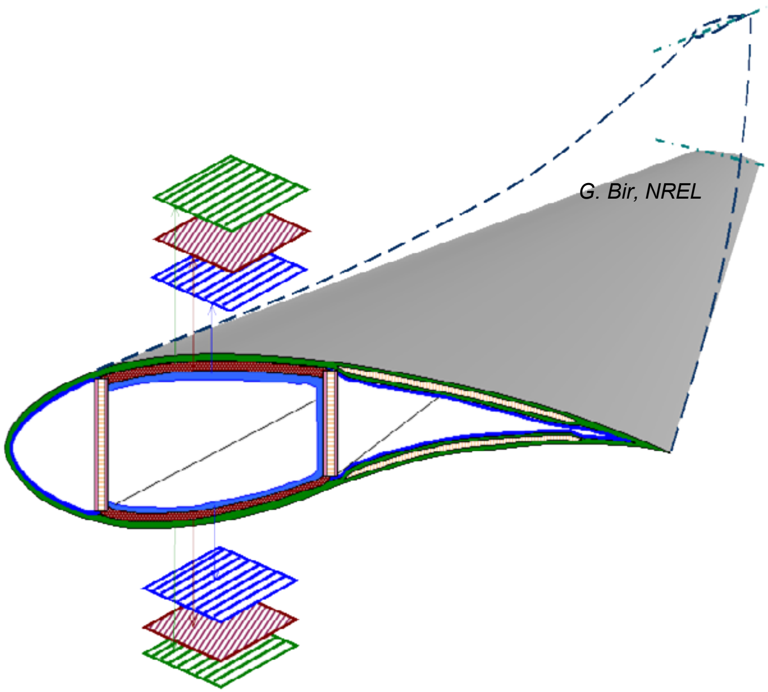
Mapping Independent Structural & Hydrodynamic Discretizations

Current & Planned Work (cont)

- Incorporate higher-fidelity modeling of blades (**BeamDyn**):
  - Finite element (FE) & improved modal approaches
  - Based on Geometrically Exact Beam Theory (GEBT)
  - Full geometric nonlinearity
  - Introduce torsion, shear, & extensional DOFs
  - Allow for anisotropic material couplings (from **PreComp**, **NuMAD**, or **VABS**)
  - Include chordwise mass & elastic offsets
  - Allow for built-in curvature & sweep



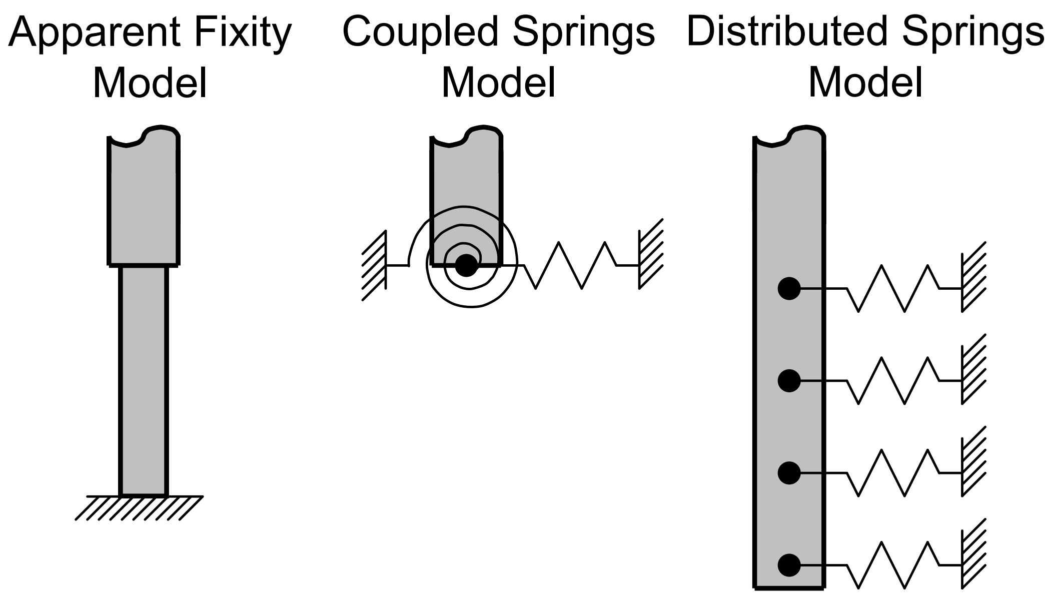
Advancement in Blade Design



Blade Twist Induced By Anisotropic Layup

Current & Planned Work (cont)

- Include more built-in options in **ServoDyn**:
  - Generator Types 1-4
  - Input signal low-pass filtering
  - Variable-speed torque control with transition regions & rate limits
  - Gain-scheduled PI blade-pitch control with rate limits
- Introduce built-in foundation models:
  - Only user-defined implementation in **FAST** v7
- Extend structural model to VAWTs
- Develop interfaces to systems-engineering tools (e.g. for cost & optimization)



Simplified Models of a Monopile with Flexible Foundation

Future Opportunities

- Publish **ElastoDyn** Theory Manual
- Develop limited-functionality version (**FAST_EZ**) for ease of use by students in class
- Add animation capability
- Add blade-pitch DOFs & actuator models
- 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
- Support SMART blade control
- Add measurement noise to control input signals
- Develop general capability for hinged & segmented blades

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Questions?

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