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Overview of the FAST Servo-Elastic Module

CREW/NREL Wind Turbine Design Codes Workshop

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CU Campus – Boulder, CO

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Outline

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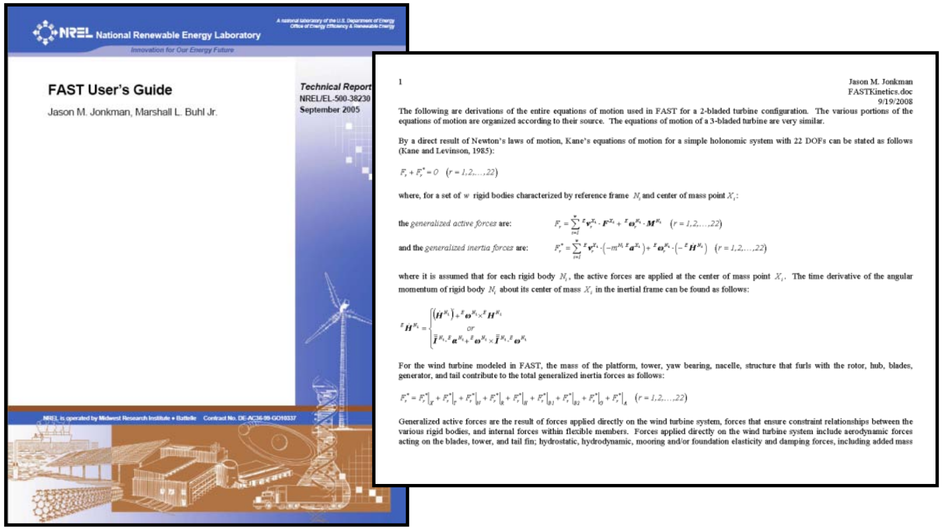
Overview

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:
  - v7.00.01a-bjj (November 2010)
  - Newer in progress
- User's Guide:
  - Jonkman & Buhl (2005)
- Theory Manual (unofficial):
  - Jonkman (2005)



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Innovation for Our Energy Future

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:

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

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

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

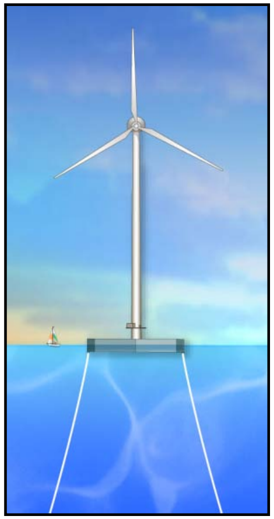
FAST v4 – v7 (2002-present)

- 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

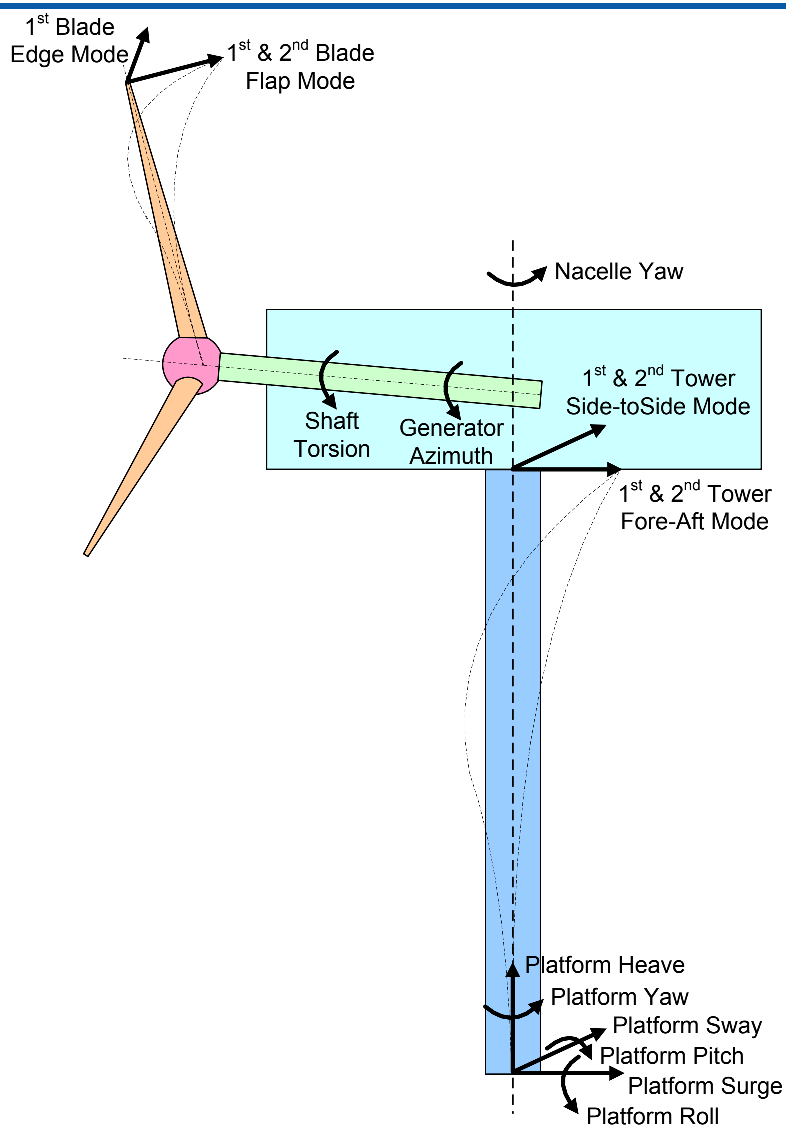
Turbine Configurations – Highlights

- 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

$$F=ma$$

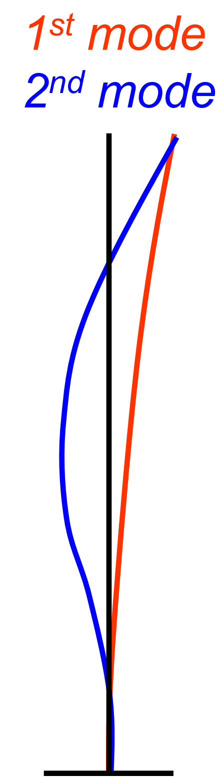
(any questions?)

Overview
Basic Theory (cont)

- Combined multi-body & modal-dynamics formulation:
  - Modal: blades, tower
  - Multi-body: platform, nacelle, generator, gears, hub, tail
- Mode shapes specified as polynomial coefficients:
  - Not calculated internally (found from **BModes** or modal experiment)
- Utilizes relative DOFs:
  - No constraint equations
  - ODEs instead of DAEs
- Equations of motion (EoMs) are derived & implemented using Kane's Method (not an energy method)
- EoM Form:

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

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

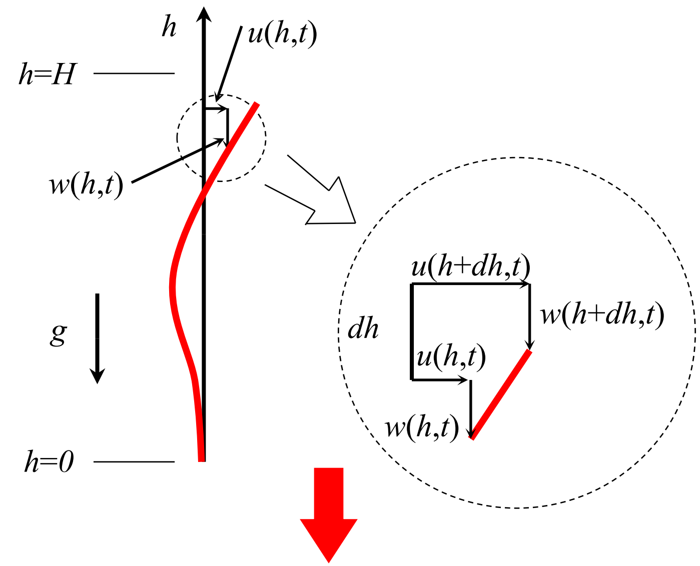


Modal Representation

Overview

Basic Theory (cont)

- Blade & tower beam mode assumptions:
  - Bernoulli-Euler beams under bending:
    - No axial or torsional DOFs
    - No shear deformation
  - Linear modal representation considers small to moderate deflections characterized by lowest modes:
    - Employs small angle approximations with correction for coordinate system orthogonality
    - Includes correction for radial shortening
  - Beams are straight with isotropic material & no mass or elastic offsets:
    - Couplings only due to pretwist (blades only)



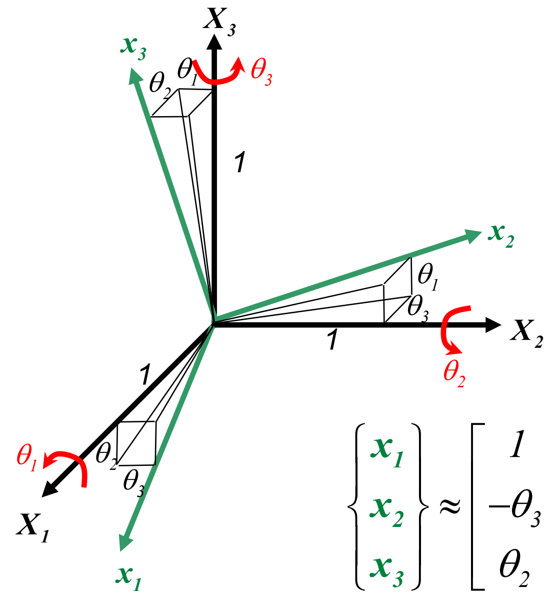
$$w(h,t) = \frac{1}{2}\int_0^h \left[\frac{\partial u(h',t)}{\partial h'}\right]^2 dh'$$

Radial Shortening Effect

Overview

Basic Theory (cont)

- Other assumptions:
  - Support platform pitch, roll, & yaw rotations employ small angle approximations with correction for orthogonality
- All other DOFs may exhibit large displacements w/o loss of accuracy
- Uses the 4th order Adams-Bashforth-Adams-Moulton (ABAM) predictor-corrector fixed-step-size explicit integration scheme:
  - Initialized using 4th order Runge-Kutta scheme



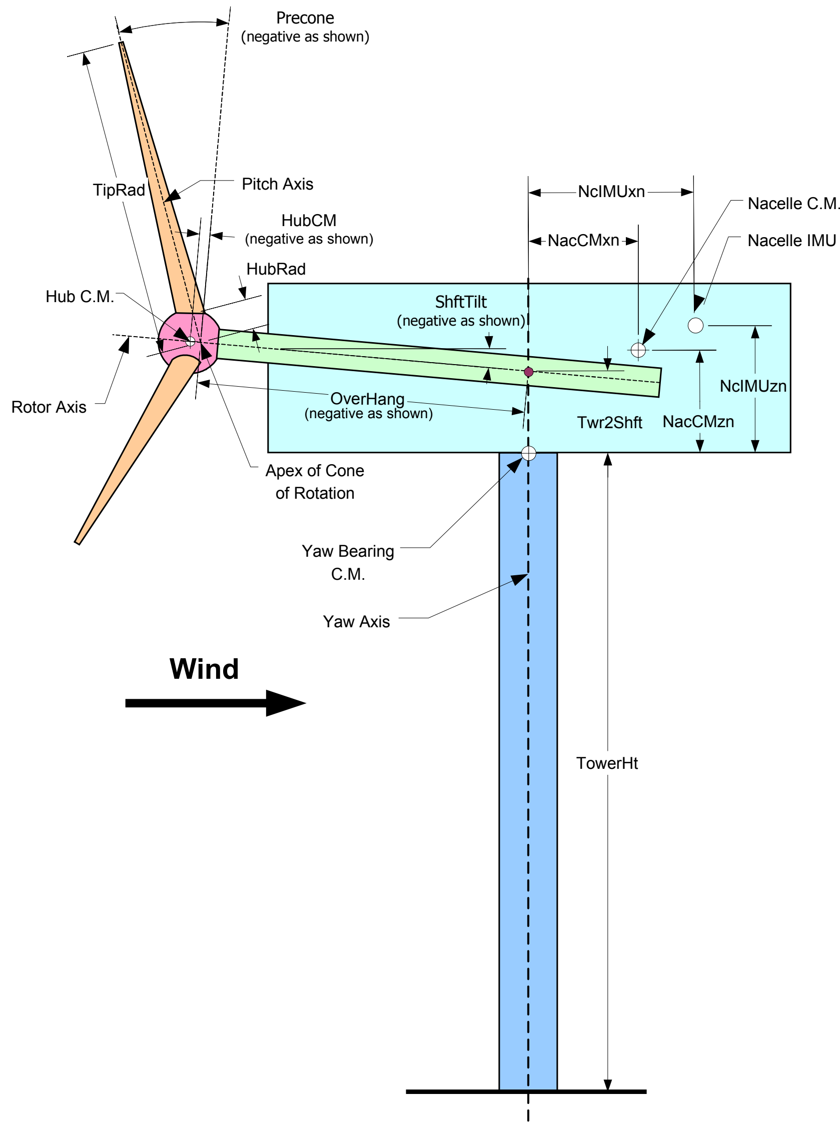
$$\begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix} \approx \begin{bmatrix} 1 & \theta_3 & -\theta_2 \\ -\theta_3 & 1 & \theta_1 \\ \theta_2 & -\theta_1 & 1 \end{bmatrix} \begin{Bmatrix} X_1 \\ X_2 \\ X_3 \end{Bmatrix}$$

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

Correction for Orthogonality

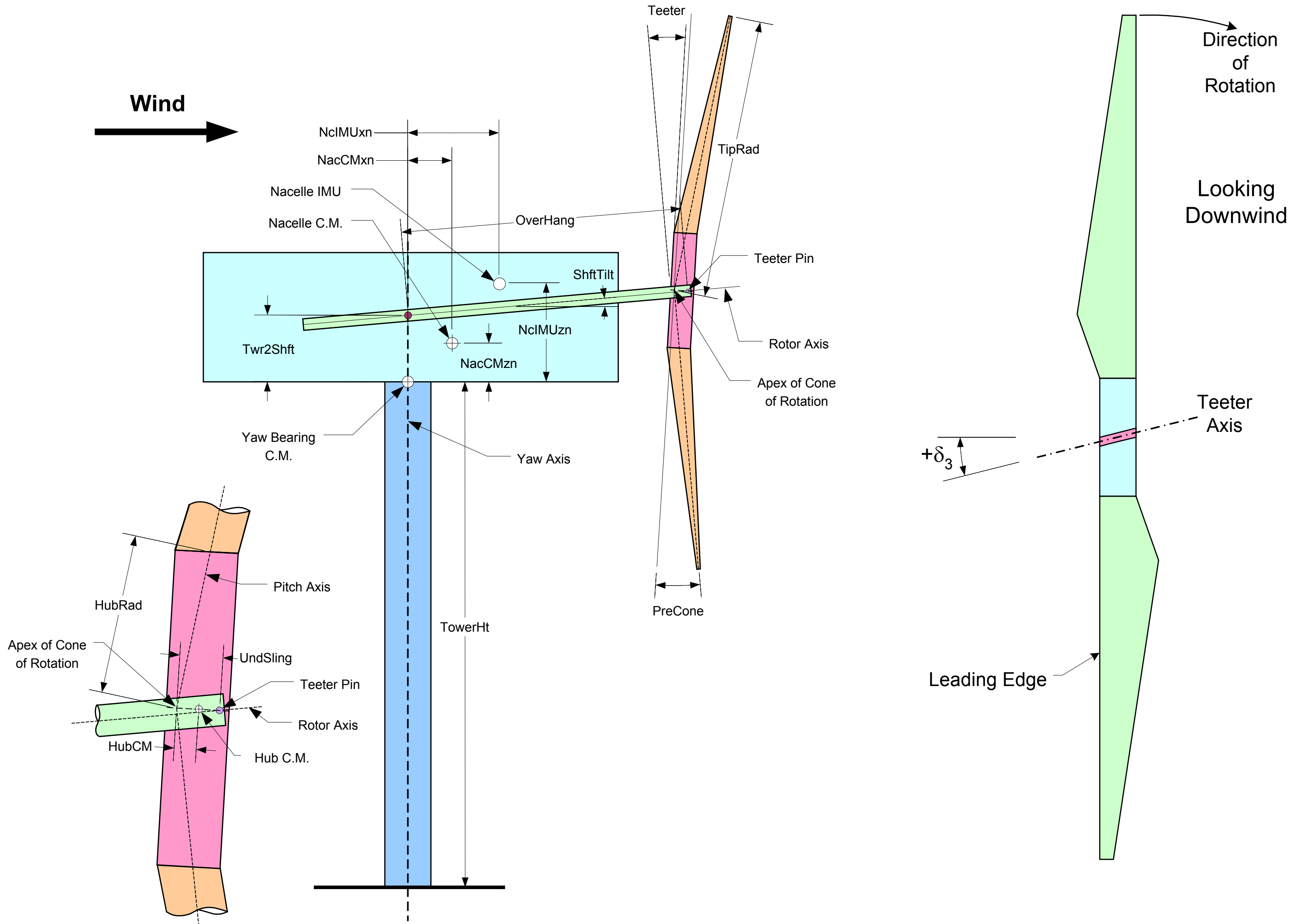
Overview

Turbine Configurations – Upwind, 3-Blader



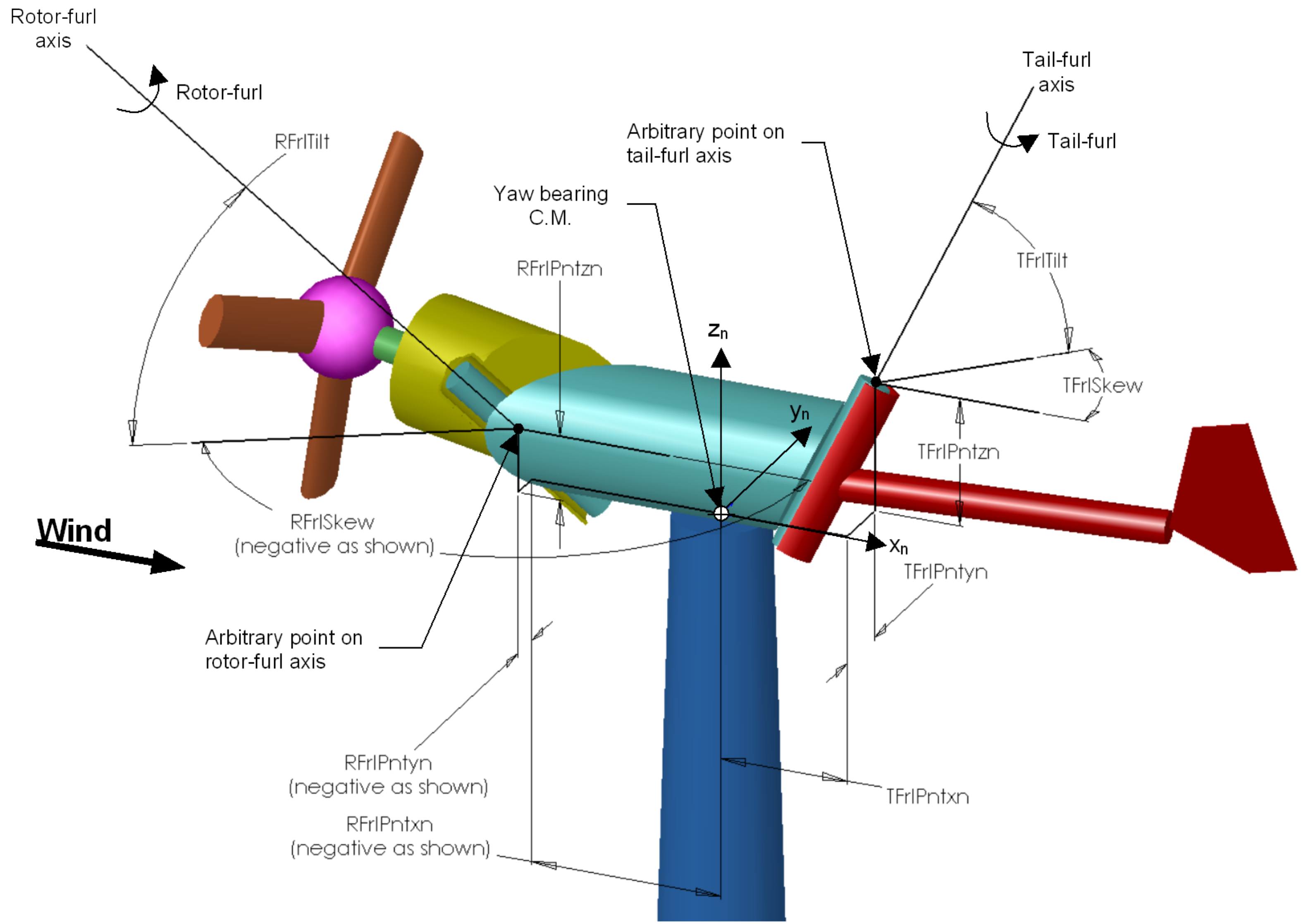
Overview

Turbine Configurations – Downwind, 2-Blader



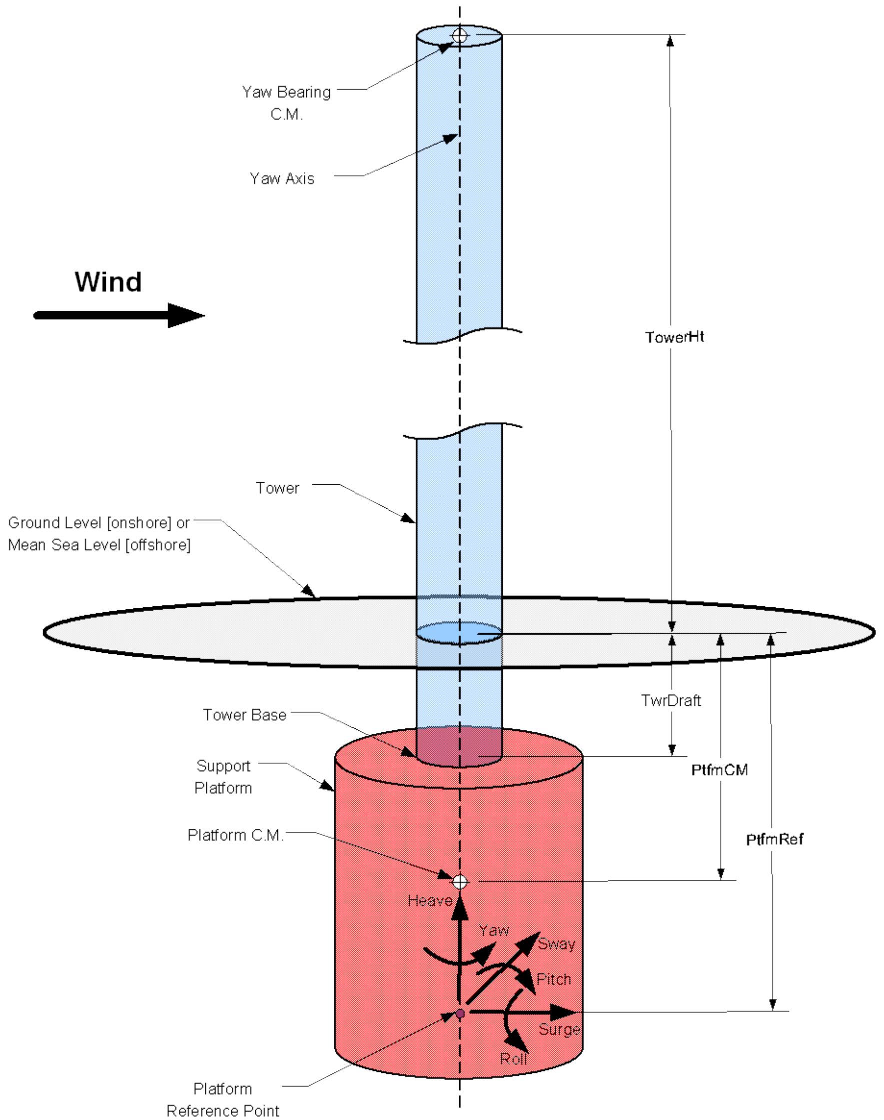
Overview

Turbine Configurations – Furling DOFs



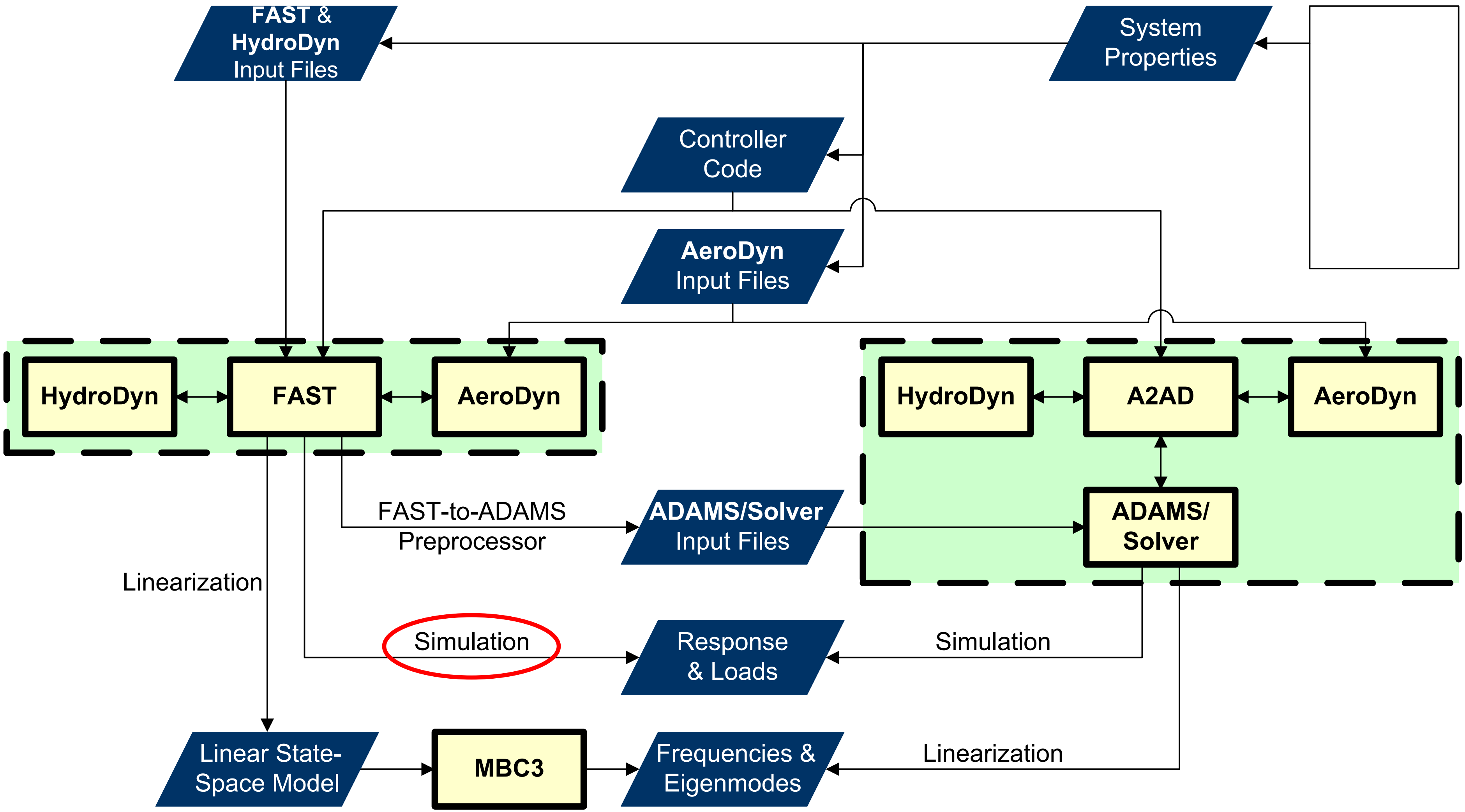
Overview

Turbine Configurations – Support Platform



Overview

Modes of Operation



Simulation
Loads Analysis

- Nonlinear time-domain solution for loads analysis
- Run simulation within command prompt (.exe) or within **MATLAB/Simulink** (.mex*)
- Design situations & conditions:
  - Turbulent & deterministic winds
  - Regular & irregular waves
  - 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
  - Loads:
    - Shear forces
    - Axial forces
    - Bending moments
    - Torsion moments
  - Performance:
    - Wind
    - Power
    - Control settings

Simulation

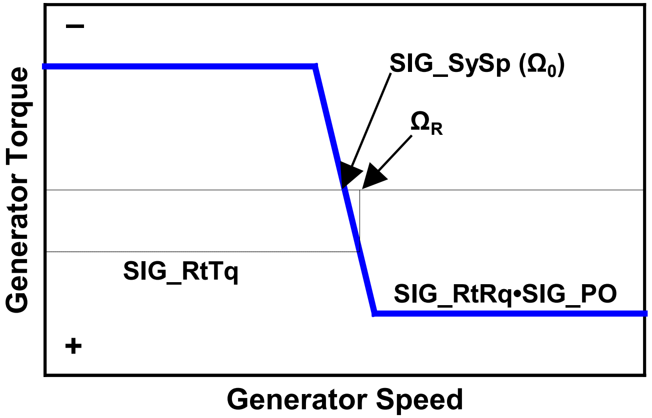
Control Options

- 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 2^{nd} 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

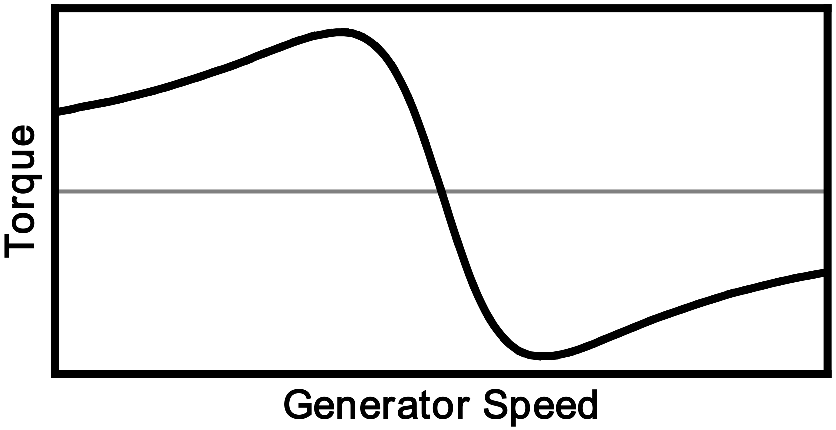
Simulation

Control Options – Default Torque Models

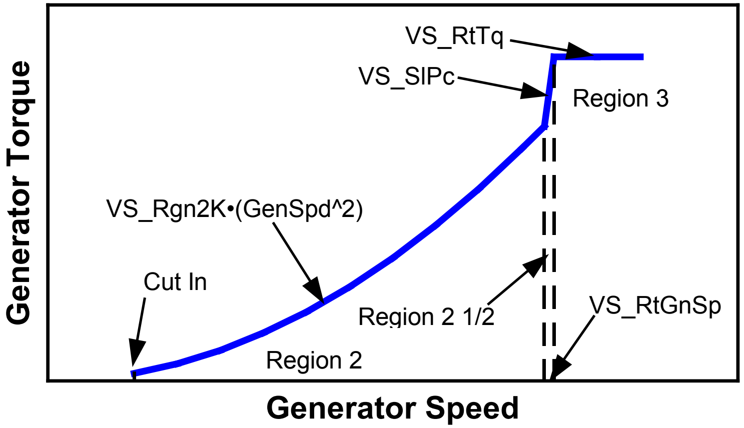
Simple Induction Generator



Thevenin-Equivalent Circuit Generator



Simple Variable-Speed Controller



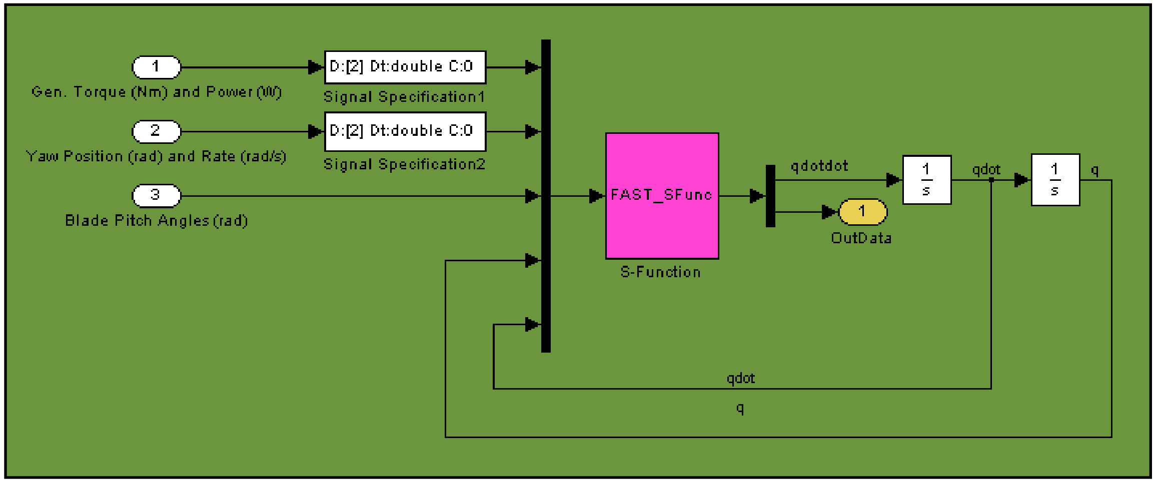
Simulation

Interfacing Active Controllers – 4 Options

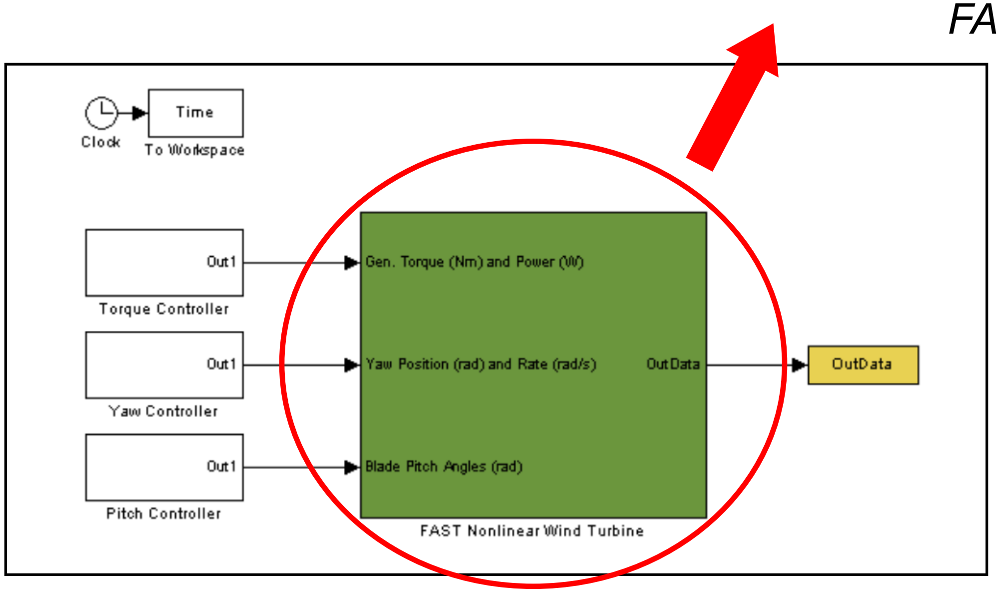
- Select from one of the built-in routines
- Fortran subroutine:
  - Separate routines for each controller (i.e.: Separate routines for blade pitch, generator torque, nacelle yaw, & brake)
  - Sample routines provided with **FAST** archive
  - Requires recompile with each change to controller
- **GH 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
  - Same input files used
  - Controls implemented in block-diagram form

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 v7.00.01a-bjj)

- Improved validity checks on some input parameters
- Increased number of blade & tower gages available for output (gages also available for all blades)
- Added functionality to change polynomial order of blade & tower mode shapes
- Linked with **NWTC Subroutine Library**
- Reworked interface to match **AeroDyn** v13.00.00a-bjj
- Added capability to model offshore wind turbines (**HydroDyn** is an undocumented feature)
- Improved **FAST** S-Function for **MATLAB/Simulink**
- Added new tools for compiling source code & plotting CertTest results

Current & Planned Work

- Move further towards full modularization & co-simulation
- Permit different aero, hydro, & structural discretizations
- Include more built-in outputs (e.g., local blade & tower deflections & shear forces)
- Include more built-in electrical & control options (e.g., PID)
- Add earthquake excitation module (with UC-San Diego)
- Add nacelle-based mass-damper DOFs (with UMass)
- Add blade & tower torsion DOFs:
  - Add chordwise mass & elastic offsets to blades
  - Replace uncoupled flap & lag modes with coupled axial-flap-lag-torsion modes (from **BModes**)
  - Increase number of blade & tower mode DOFs
  - Add blade-pitch DOFs & actuator models
- Interface to **OpenFOAM** for array modeling

Future Opportunities

- Model blade dynamics through nonlinear FE-beam formulation
- Add shaft bending-mode DOFs
- Introduce built-in foundation models
- Develop limited-functionality version (**FAST_EZ**) for ease of use by students to replace **YawDyn**
- Introduce variable-step-size integration scheme
- Correct Coulomb damping models
- Allow for hinged blade root
- Allow for anisotropic material (from **PreComp** or **NuMAD**)
- Allow for built-in curvature & sweep
- Build in **BModes** for runtime calculation of modes
- Add animation capability

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Questions?

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