Overview of the FAST Servo-Elastic Module

NREL Wind Turbine Modeling Workshop

August 9, 2013
CU – Boulder, CO (USA)

Jason Jonkman, Ph.D.
Senior Engineer, NREL
Outline

• Overview:
  – FAST – What Is It?
  – History
  – Turbine Configurations
  – Degrees of Freedom
  – Basic Theory
  – Turbine Parameterizations
  – Modes of Operation

• Simulation:
  – Loads Analysis
  – Inputs & Outputs (I/O)
  – Control Options
  – Interfacing Controllers

• Sample Models Provided with the Archive
• Recent Work
• Current & Planned Work
• Future Opportunities
Overview
FAST – What Is It?

- Structural-dynamic model for horizontal-axis wind turbines:
  - Used to stand for Fatigue, Aerodynamics, Structures, & Turbulence
  - 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)
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 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

**FAST_AD v1 – v3 (1997-2002)**
- Developers: N. Weaver, M. Buhl, et al., NREL
- Single code for 2- & 3-blades
- **AeroDyn** aerodynamics
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 $\delta_3$ (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)

\[
M(q,u,t)\ddot{q} + f(q,\dot{q},u,u_d,t) = 0
\]

- EoM form:

\[
OutData = Y(q,\dot{q},u,u_d,t) = Y_r(q,u,t)\ddot{q} + Y_l(q,\dot{q},u,u_d,t)
\]

- Time stepping using the 4th-order Adams-Bashforth-Moulton (ABM4) predictor-corrector (PC) fixed-step-size integration scheme:
  - Initialized using 4th-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 diagonalization employed)
    • Bending assumes small strains:
      – 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
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.

Correction for Orthogonality
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

- **FAST & HydroDyn Input Files**
- **AeroDyn Input Files**
- **Controller Code**
- **System Properties**

**HydroDyn** → **FAST** → **AeroDyn**

- **FAST-to-ADAMS Preprocessor**
- **ADAMS/Solver Input Files**

**HydroDyn** → **A2AD** → **AeroDyn**

- **ADAMS/Solver**
- **Response & Loads**
- **Simulation**
- **Frequencies & Eigenmodes**
- **Linearization**

- **Linear State-Space Model**
- **MBC3**

Wind Turbine Modeling Workshop
National Renewable Energy Laboratory
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

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

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

Generator Speed

Generator Torque

Generator Torque

VS_RtTq

VS_SlPc

VS_Rg2K\cdot(GenSpd^2)

Region 3

Region 2 1/2

Region 2

VS_RgSp

Cut In

SIG_SySp (Ω₀)

Ω_R

SIG_RtTq

SIG_RtRq\cdotSIG_PO

VS_RtTq

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

- 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

---

*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 VAWT

- Develop interfaces to systems-engineering tools (e.g. for cost & optimization)

**Simplified Models of a Monopile with Flexible Foundation**

- Apparent Fixity Model
- Coupled Springs Model
- Distributed Springs Model
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
Questions?

Jason Jonkman, Ph.D.
+1 (303) 384 – 7026
jason.jonkman@nrel.gov