FAST: An Open-Source Platform for Wind Turbine Multi-Physics Engineering Modeling

NAWEA 2017 Symposium

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Ames, IA (USA)

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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.
Outline

- Introduction & Background:
- FAST Modularization Framework
- Structural Dynamics (ElastoDyn & BeamDyn)
- Aerodynamics (AeroDyn & InflowWind)
- Control & Electrical-Drive Dynamics (ServoDyn)
- Hydrodynamics & Offshore Features (HydroDyn, SubDyn, MAP++, & MoorDyn)
- Transition to OpenFAST
- Outlook
Introduction & Background

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Introduction & Background

Modeling Requirements

- Coupled aero-hydro-servo-elastic interaction
- Wind-inflow:
  - Discrete events
  - Turbulence
- Waves:
  - Regular
  - Irregular
- Aerodynamics:
  - Induction
  - Rotational augmentation
  - Skewed wake
  - Dynamic stall
- Hydrodynamics:
  - Diffraction
  - Radiation
  - Hydrostatics
- Structural dynamics:
  - Gravity / inertia
  - Elasticity
  - Foundations / moorings
- Control system:
  - Yaw, torque, pitch
Introduction & Background

Einstein Principle

“A model should be as simple as possible, but no simpler.”
Introduction & Background

Physics Modeling Needs for Engineering Design

- Capture important system physics & couplings
- Range of fidelity to target specific engineering problems in industry & research
- Computational efficiency to support an iterative & probabilistic design processes & optimization
- Nonlinear time-domain for standards-based load analysis
- Linearization for eigenanalysis, controls design, stability analysis, & gradients for optimization
- Support for new technology, including unique needs of nascent offshore industry
- Verification & validation to understand where models are suitable & where they are not

Theory

CAE Tools

Test Data

Computational Solutions
**Introduction & Background**

The FAST Multi-Physics Engineering Tool

- **FAST** is DOE/NREL’s premier open-source wind turbine multi-physics engineering tool
- **FAST** has undergone a major restructuring, w/ a new modularization framework (v8)
- Not only is the new framework supporting expanded functionality, but it is facilitating the establishment of an open-source code-development community for multi-physics engineering models (**OpenFAST**)
Introduction & Background
FAST Module Control Volumes – Fixed-Bottom

Full-System Level
(BeamDyn, IceFloe, & IceDyn Not Shown)
Introduction & Background
FAST Module Control Volumes – Floating

Component Level

Full-System Level

(BeamDyn & OrcaFlexInterface not shown)
Introduction & Background
Key DOE/NREL Tools in the Design Process

Preprocessors

- **AirfoilPrep**
  - Airfoil Data
  - Correction
- **TurbSim**
  - Wind Spectrum
  - Wind Turbulence
- **Hydro. Data**
- **Control & Elec. System**
- **Turbine Configuration**
- **Composite Lay-Up**

Simulators

- **PreComp & NuMAD**
  - Section Analysis
  - Beam Properties
- **BModes**
  - Beam Eigenanalysis
  - Mode Shapes
- **FAST**
  - Aero-Hydro-Servo-Elastics
    - Includes:
      - ElastoDyn
      - BeamDyn
      - AeroDyn
      - InflowWind
      - ServoDyn
      - HydroDyn
      - SubDyn
      - MAP++
      - MoorDyn
      - FEAMooring
      - OrcaFlex-Interface
      - IceFlorie
      - IceDyn

Postprocessors

- **Time-Domain Performance, Responses, & Loads**
- **MCrunch, MExtremes, & MLife**
  - Data Analysis
- **Linearized Models**
- **MBC3**
  - Multi-Blade Transformation
Introduction & Background

Verification (Code-to-Code)

- VEWTDC
- Comparisons of FAST to MSC.ADAMS
- Many 1-on-1 collaborations (e.g.):
  - GL GH
  - Siemens
  - DTU Wind
- Evaluated by GL against GH Bladed
- IEA Wind Task 23 OC3 & Task 30 OC4 projects

OC3 Full-System Test

GL Certificate Approving FAST & ADAMS with AeroDyn
Introduction
Validation (Code-to-Data)

• UAE Phase VI
• SWRT
• CART2 & CART3
• Siemens
• Fixed: OC5 (tank tests, Alpha Ventus)
• Floating:
  – OC5
  – DeepCwind
  – SWAY
  – WindFloat
  – Hywind

*FAST w/ BeamDyn Well Matches BHawC & Data for ATB*

SWRT in high winds – ADAMS has Blade Torsion, FAST doesn’t

Comparison of Uncalibrated WT_Perf Prediction to CART2 Data
FAST Modularization Framework

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FAST Modularization Framework
What is the FAST Modularization Framework?

- A means by which various mathematical models are implemented in distinct modules & interconnected to solve for the global, coupled, dynamic response of a system.
FAST Modularization Framework
Design Features of the Framework

- Module-independent inputs, outputs, states, & parameters
- States in continuous-time, discrete-time, constraint, & “other” form
- Loose & tight* coupling
- Independent time & spatial discretizations
- Time marching, operating-point determination*, & linearization
- Data encapsulation & dynamic allocation
- Checkpoint/restart capability

*Not yet available

Interconnected Physics Domains, Coupled Through a Driver
FAST Modularization Framework
Loose-Coupling Algorithm

- Predictor-Corrector (PC)-based w/ time-step subcycling of modules
- Set-up for future parallelization (steps 1, 2, & 3a)

For Each Time Step
(From $t_n$):
1) Extrapolate Inputs to $t_{n+1}$
2) Advance States to $t_{n+1}$
3) Solve for Outputs & Inputs @ $t_{n+1}$:
   3a) Calculate Outputs
   3b) Derive Inputs From Outputs
   3c) Iterate (Go Back to 3a) or Save
4) Correct (Go Back to 2) or Save

PC-Based Loose-Coupling Algorithm
Within an Individual Module

Coupling of Modules
FAST Modularization Framework
Independent Spatial Discretizations & Mapping

• Module inputs & outputs residing on spatial boundaries use a mesh, consisting of:
  – Nodes & elements (nodal connectivity)
  – Nodal reference locations (position & orientation)
  – One or more nodal fields, including motion, load, &/or scalar quantities

• Mesh-to-mesh mapping supports:
  – Extremely disparate meshes
  – Large motion/deformation
  – Relative motion or follower meshes

• Mapping guiding principles:
  – Load transfer maintains force & moment balance
  – Motion transfer maintains rigid-body motion
  – Load & motion mappings are conjugate
  – Identical meshes lead to 1-to-1 mapping of fields
FAST Modularization Framework
Full-System Linearization

• **FAST** primary used for nonlinear time-domain simulations

• Linearization is about *understanding*:
  – Useful for eigenanalysis, controls design, stability analysis, gradients for optimization, & development of reduced-order models

• Focus to date:
  – Structured source code to enable linearization
  – Developed general approach to linearizing mesh-mapping w/n module-to-module input-output coupling relationships, including rotations
  – Linearized core (but not all) features of *InflowWind, ServoDyn, ElastoDyn*, & *AeroDyn* modules & their coupling
  – Verified implementation

• Note: A linear model of a nonlinear system is only valid in local vicinity of an operating point (OP)

\[
\begin{align*}
\dot{x} &= X(x, z, u, t) \\
0 &= Z(x, z, u, t) \quad \text{with} \quad \frac{\partial Z}{\partial z} \neq 0 \\
y &= Y(x, z, u, t)
\end{align*}
\]

\[
\begin{align*}
u &= u_{op} + \Delta u \quad \text{etc.}
\end{align*}
\]

\[
\begin{align*}
\Delta \dot{x} &= A \Delta x + B \Delta u \\
\Delta y &= C \Delta x + D \Delta u \\
\text{with}
\end{align*}
\]

\[
A = \left[ \frac{\partial X}{\partial x} - \frac{\partial X}{\partial z} \left[ \frac{\partial Z}{\partial z} \right]^{-1} \frac{\partial Z}{\partial x} \right]_{op} \quad \text{etc.}
\]
FAST Modularization Framework
Visualization Capability

- Generation of Visualization Toolkit (VTK) output files
- Initialization/reference configuration &/or time series for animation
- Surface or stick-figure geometry
- Used w/ standard open-source visualization software e.g. ParaView

Stick-Figure Visualization in ParaView
FAST Modularization Framework
Checkpoint/Restart Capability

• **FAST** may generate periodic checkpoint files
• These files can be used to restart **FAST** from that time in case of hardware failure or system availability
• Most useful for computationally expensive simulations:
  – Long (e.g. 1-hr +) simulations
  – Coupled **FAST-OpenFOAM** simulations (**SOWFA**)
FAST Modularization Framework
Officially Released Under Apache 2.0 Open-Source License

Apache License

Version 2.0, January 2004

http://www.apache.org/licenses/

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Structural Dynamics
(ElastoDyn & BeamDyn)

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Structural Dynamics
ElastoDyn – Inputs, Outputs, States, & Parameters

ElastoDyn

Continuous States:
• Displacements
• Velocities

Parameters:
• Geometry
• Mass/inertia
• Stiffness coefficients
• Damping coefficients
• Gravity

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

Outputs:
• Displacements
• Velocities
• Accelerations
• Reaction loads
Structural Dynamics

ElastoDyn – 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 offshore-based (via HydroDyn)
- Offshore fixed-bottom (via SubDyn) or floating (moorings)

*Available in FAST v7, but not yet in v8
Structural Dynamics
ElastoDyn – Degrees of Freedom

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

Teeter: 1 rotor teeter hinge with optional $\delta_3$ (2-blader only)

Drivetrain: 1 generator azimuth
1 shaft torsion

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

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

*Available in FAST v7, but not yet in v8
Structural Dynamics
ElastoDyn – Theory Basis Overview

- Combined multi-body- & modal-dynamics:
  - Modal: blades, tower
  - Multi-body: platform, nacelle, generator, gears, hub, tail

- Utilizes relative DOFs:
  - No constraint equations
  - ODEs instead of DAEs
  - Platform rotations & blade/tower deflections employ small-angle approximations w/ correction for orthogonality (accuracy drops considerably for angles >> 20°)
  - All other DOFs may exhibit large motions w/o loss of accuracy

- Nonlinear equations of motion
- Explicit (RK4) or PC (AB4, ABM4) time integration

Correction for Orthogonality
Structural Dynamics
ElastoDyn – Blade & Tower Modeling Assumptions

- Bernoulli-Euler beams under bending:
  - No axial or torsional DOFs
  - No shear deformation
- Straight beams with isotropic material & no mass/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: \( \theta \approx \frac{\partial u}{\partial h} \), \( \kappa \approx \frac{\partial^2 u}{\partial h^2} \)
    - Employs small angle approximations w/ 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
Structural Dynamics
BeamDyn – Overview

• Previous beam model in FAST (v7 & ElastoDyn module of v8):
  – Euler-Bernoulli beam
  – Straight & isotropic
  – Bending only
  – Assumed-mode method
  – Some geometric nonlinearity

• New BeamDyn module:
  – Geometrically exact beam theory (GEBT)
  – Legendre spectral finite element (LSFE)
  – Both statics & dynamics
  – Time integration via generalized-α
**Structural Dynamics**

**BeamDyn – GEBT**

- **Full 6 × 6 cross-sectional mass & stiffness:**
  - Axial, shear, bending, & torsion
  - Composite-material coupling
  - Timoshenko-like
  - Stiffness-proport’l damping

- **Curved/swept reference axis** (spline-based)

- **Nonlinear geometrically exact large deflection:**
  - Wiener-Milenković rotation parameters
  - Small strains

**BeamDyn Inputs, Outputs, States, & Parameters**

**Continuous States:**
- Displacements
- Velocities

**Parameters:**
- Geometry
- Cross-sectional mass & stiffness
- Damping
- Gravity
- Discretization

**Outputs:**
- Blade motion
- Root reaction loads

---

MTS Systems Corp. (2010)
Structural Dynamics
BeamDyn – LSFE

• LSFE methods combine geometric flexibility of FE methods w/ accuracy of spectral methods:
  – Solution improved through increased basis polynomial order
  – LSFEs employ Lagrangian interpolant shape functions w/ nodes @ Gauss-Lobatto-Legendre (GLL) points
  – Exponential convergence rates for sufficiently smooth solutions
  – Limited applications to structures

Analyze blade w/ single element
Structural Dynamics
BeamDyn – Spatial Integration

• Both Gauss & Trapezoidal-Rule spatial integration

**BeamDyn** Analysis of NREL 5-MW Blade w/ 49 Cross-Sectional Stations
Aerodynamics (AeroDyn & InflowWind)

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Aerodynamics Inputs, Outputs, States, & Parameters

**InflowWind**
- **States:** None
- **Parameters:**
  - Undisturbed wind inflow

**AeroDyn**
- **Continuous States:** Induction in DBEMT
- **Discrete States:** States in B-L dynamic stall
- **Constraint States:** Induction in BEMT
- **Parameters:**
  - Geometry
  - Airfoil data
  - Air Density
- **Outputs:** Aero. loads

**Inputs:**
- Turbine disp.
- Turbine velocities
- Wind velocities

**Outputs:**
- Wind @ input positions

**Inputs:** Positions

**Outputs:** Wind @ input positions
Aerodynamics
User Inputs

- Undisturbed wind inflow in *InflowWind*:
  - Uniform, but time-varying
  - Full-field (FF) turbulence
  - User-defined

- Aerodynamic submodel selection:
  - Quasi-steady, dynamic, or no wake
  - Steady or unsteady airfoil aerodynamics, including dynamic stall

- 2-D/3-D airfoil properties:
  - $C_L$, $C_D$, $C_M$ (vs. AoA & Re) & dynamic-stall parameters
  - *AirfoilPrep*

- Tower influence & drag properties
Aerodynamics

Wake – Blade-Element/Momentum Theory (BEMT)

- Blades discretized into elements
- Momentum balance in annuli:
  - Linear → axial induction \((a)\)
  - Angular → tangential induction \((a')\)
  - Implemented per element per blade
  - Nonlinear solve requires iteration
- Blade-element loads from airfoil data:
  - Drag terms can optionally be used in induction calculation
- Limitations to theory:
  - No interaction between annuli (2-D only) (3D effects from AirfoilPrep)
  - Instantaneous reaction of wake to loading changes
  - Needs corrections for high induction, tip & hub losses, & skewed flow
  - Despite these, BEMT is applied in many conditions
Aerodynamics
Wake – Dynamic BEMT (DBEMT)*

- Transient loading leads to a dynamic wake:
  - Turbulence/gusts
  - Skewed flow
  - Pitch control

- DBEMT models time- & spatial-varying induction across the rotor

- Based on Stig Øye:
  - Low-pass time-filtered BEMT
  - Applied both to axial & tangential inductions

- Replaces old Generalized Dynamic Wake (GDW) model available in older versions of AeroDyn, which had limitations:
  - Unstable for heavily loaded rotors (below rated)
  - Proper tip loss requires many more flow states

*Coming soon
Aerodynamics
Unsteady Airfoil Aero

- Dynamically stalled flow field:
  - Static stall dynamically exceeded
  - $C_N$, $C_T$, $C_M$ transiently amplified
  - Flow hysteresis
  - Produced by even slight skew & turbulence

- Beddoes-Leishman model:
  - A semi-empirical model
  - 3 submodels:
    - Unsteady attached flow
    - Trailing-edge flow separation
    - Dynamic stall & vorticity advection
  - Semi-empirical airfoil-dependent parameters derived from static data
  - Applicable for operational conditions, not in deep stall

- **AeroDyn** adds after induction calculations

*Dynamic Stall of S809 Airfoil*
Aerodynamics

Tower Influence & Drag Load

- **Downwind tower-shadow model:**
  - Augments undisturbed wind
  - Simple user-tailored shape

- **Upwind tower-influence model:**
  - Augments undisturbed wind @ blades
  - Based on potential-flow solution around a cylinder
  - Optional Bak correction

- **Tower drag model:**
  - Drag load @ each tower node proportional to square of undisturbed relative wind speed
Control & Electrical Drive (ServoDyn)

Control & Electrical-Drive Functions

- Controls:
  - Operation
  - Start-up & shut-down
  - Safety & protection

- Sensors & actuators:
  - Sensors
  - Servo motors
  - Hydraulics

- Electrical drive:
  - Generator
  - Power electronics
  - Grid

- Faults

Wind Turbine

- Wind Speed
- Power
- Rated
- Cut-Out
- Cut-In
- Control Actions
**Control & Electrical-Drive (ServoDyn)**

**Inputs, Outputs, States, & Parameters**

---

**ServoDyn**

**Continuous States:**
- Analog control signals
- TMD disp. & vel.

**Discrete States:**
- Digital control signals

**Parameters:**
- Controller gains
- Control limits
- TMD configuration
- TMD mass, stiff., & damp

---

**Inputs:**
- Structural motions
- Reaction loads
- Wind measurements

**Outputs:**
- Controller commands
- TMD reactions
Control & Electrical-Drive (ServoDyn) 
Active Control Methods

• Blade pitch:
  – Collective or independent
  – To feather or to stall
  – Command the angle
  – No actuator dynamics
  – Override maneuvers available

• Generator torque:
  – Fixed (w/ or w/o slip of induction generator) or variable speed
  – Command the torque
  – Indirect electrical power
  – Default models built in
  – Enable for startup or disable for shutdown

• HSS brake:
  – Command the deployment

Simple Induction Generator (SIG)

Thevenin-Equivalent Circuit (TEC) Generator

Simple Variable-Speed Controller
Control & Electrical-Drive (ServoDyn)
Active Control Methods (cont)

• Nacelle yaw:
  – Command the angle &/or rate
  – 2nd-order actuator determines the torque
  – Override maneuvers available

• Tuned-mass dampers (TMDs):
  – Tower- &/or nacelle-based
  – Fore-aft &/or side-to-side or omni-directional
  – Optional stops
  – Optional semi-active or active control
  – Developed by UMass

• Blade-tip brake*:
  – Command the deployment

*Available in FAST v7, but not yet in v8
Control & Electrical-Drive (ServoDyn)
Interfacing Active Controllers – 5 Options

1) Select from one of the built-in routines

2) Fortran subroutine:
   - Separate routines for each controller (i.e.: separate routines for blade pitch, generator torque, nacelle yaw, & brake)
   - Requires recompile w/ each change to controller source code
   - Sample variable-speed torque controller based on table look-up provided w/ FAST archive
   - Sample PID blade-pitch controller provided w/ FAST archive

3) Bladed-style dynamic link library (DLL):
   - 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 w/ same DLL)
   - Sample NREL 5-MW baseline controllers provided w/ FAST archive
4) **MATLAB/Simulink:**
- FAST implemented as S-Function block
- Controls implemented in block-diagram form
- SimPowerSystems toolbox for detailed electrical drive

5) **LabVIEW**:
- FAST implemented as DLL callable by LabVIEW
- Hardware-in-the-loop (HIL) possible

*Available in FAST v7, but not yet in v8*
Control & Electrical-Drive (ServoDyn)
Passive Control Methods

• Apart from ServoDyn, FAST offers passive control methods:
  – TMDs w/o 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

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Hydrodynamics & Offshore Features (HydroDyn, SubDyn, MAP++, & MoorDyn)

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Hydrodynamics & Offshore Features

Offshore Modules of FAST

- **HydroDyn** – Hydrodynamics for fixed & floating
- **SubDyn** – Fixed substructure structural dynamics
- **MAP++** – Mooring quasi-statics
- **MoorDyn** – Lumped-mass mooring dynamics
- Not presented:
  - **FEAMooring** – FE mooring dynamics
  - **OrcaFlex-FAST** coupling for mooring dynamics
  - **IceFloe** – Sea-ice dynamics from DNV-GL
  - **IceDyn** – Sea-ice dynamics from UMich
HydroDynamics & Offshore Features
HydroDyn – Inputs, Outputs, States, & Parameters

Inputs:
- Substructure disp.
- Substructure vel.
- Substructure accel.

Continuous States:
- State-space-based radiation “memory”

Discrete States:
- Convolution-based radiation “memory”

Parameters:
- Geometry
- Hydrodynamic coefficients
- Undisturbed incident waves
- Water Density
- Gravity

Outputs:
- Hydro. loads
Hydrodynamics & Offshore Features
HydroDyn – Waves & Current

- Regular, irregular, or white noise waves:
  - Pierson-Moskowitz, JONSWAP, white-noise, or user-defined spectrum
  - Or optional use of externally generated wave elevations or full wave kinematics
- Wave direction & directional spreading:
  - Requires $S(\omega, \beta) = S(\omega)D(\beta)$
- 1st- (Airy) & 2nd-order (Sharma/Dean):
  - Analytical for finite-depth
- Steady sea currents:
  - IEC-style sub-surface, near-surface, & depth-independent
  - Or user-defined
Hydrodynamics & Offshore Features

HydroDyn – Hydrodynamic Loading

- Strip theory (Morison):
  - For “slender” members
  - Inertia, added mass, viscous, & buoyancy loads
  - Multiple interconnected members
- Potential flow (WAMIT):
  - For “large” platforms
  - Radiation, diffraction, & buoyancy loads
  - Linear state-space-based radiation formulation alternative to convolution
  - 1\textsuperscript{st}- (RAO) & 2\textsuperscript{nd}-order (QTF)
  - 2\textsuperscript{nd}-order via Newman’s approximation or full QTF
- Hybrid combination of these two

Strip-Theory Nodes for the OC4-DeepCwind Semisubmersible

\[
\begin{align*}
\dot{y} &= Ax + Bu \\
y &= Cx
\end{align*}
\]

Reformulation of Radiation Convolution to Linear SS Form
Hydrodynamics & Offshore Features
SubDyn – Inputs, Outputs, States, & Parameters

SubDyn

Continuous States:
- Displacements
- Velocities

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

Inputs:
- Hydrodynamic loads
- TP* displacements
- TP* velocities
- TP* accelerations

Outputs:
- Displacements
- Velocities
- Accelerations
- Reaction loads

*TP = Transition piece
Hydrodynamics & Offshore Features
SubDyn – Key Features

- Linear frame finite-element beam model
- Craig-Bampton dynamic system reduction
- Static-improvement method

Finite-Element Discretization of the OC3-Tripod

SubDyn Flow Chart
Hydrodynamics & Offshore Features
MAP++ – Key Features

- Quasi static
- Multi-segmented array of taut or catenary lines
- Elastic stretching
- Apparent weight of lines
- Clump weights & buoyancy tanks
- Seabed friction
- Nonlinear geometric restoring
- Developed by ABS

**Inputs:**
- Platform disp.

**Parameters:**
- Line properties
- Line connectivity
- Gravity

**Constraint States:**
- Line tensions
- Joint locations

**Outputs:**
- Line tensions
- Line disp.

Example Multi-Segmented Mooring System Analyzed by MAP++
Hydrodynamics & Offshore Features

MoorDyn – Key Features

Continuous States:
• Displacements
• Velocities

Parameters:
• Line properties
• Line connectivity
• Gravity

Inputs:
• Platform disp.

Outputs:
• Line tensions
• Line disp.

- Lumped-mass dynamics
- Multi-segmented array of taut or catenary lines
- Elastic stretching & damping
- Still-water hydrodynamic added mass & drag
- Apparent weight of lines
- Clump weights & buoyancy tanks
- Seabed friction
- Nonlinear geometric restoring
- Developed by UMaine

Lumped-Mass Mooring Dynamics
Transition to OpenFAST

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Transition to OpenFAST

Users of DOE/NREL-Developed Tools

- Used worldwide by designers/manufacturers, consultants, certifiers, researchers, educators, & students:
  - Annually, there are over 10,000 unique downloads by over 4,000 users from 2,000 organizations in 100 countries
- Transitioning from an NREL-centric development to a development community
Welcome to the National Wind Technology Center’s Information Portal for wind and water power research.

Over the past two decades, the U.S. Department of Energy has sponsored software development and data collection for use by the wind and water power engineering community. The software and data on this website are primarily for the benefit of the U.S. Government and organizations that collaborate with the Department of Energy’s Wind and Water Power Technologies Office. Others are welcome to use the software and data, but please note that they are meant for professionals with expertise in wind and/or water power technologies.

You can browse the site without logging in.
Transition to OpenFAST

NWTC Forum
Transition to OpenFAST
Establishing a FAST Development Community

• New software-engineering framework for **FAST** under development:
  – Well-documented source code
  – Extensive automated regression & unit testing
  – Robust multi platform & compiler build system

• Future direction:
  – Establish strategic board
  – Advertise new development community paradigm
  – Establish development community training workshops

**Vision for a FAST Development Community**
Transition to OpenFAST
New OpenFAST github Organization & Repository

- Renamed FAST to OpenFAST w/ new version numbering
- Added one repo w/ source code for all glue codes, modules, & module drivers
- Developed build systems:
  - CMake on Mac, Linux, & Cygwin (Windows)
  - Visual Studio Projects for Windows
- Introduced github issues for developer-related questions e.g. bugs, compiling, testing, & feature requests
- Documentation being transferred & developed
Outlook

NAWEA 2017 Symposium
September 26, 2017
Ames, IA (USA)

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

Ongoing Developments

- Aerodynamics:
  - 2D interpolation of airfoil data for AoA + Re or control
  - Dynamic wake
  - New wind-farm engineering model (FAST.Farm)
  - SOWFA-FAST v8 interface

- Offshore:
  - Soil-structure interaction
  - Wave stretching
  - Validation in IEA Wind Task 30 (OC5)

- Further linearization:
  - BeamDyn
  - Floating offshore: HydroDyn, MAP++

- WISDEM-FAST v8 interface

- Transition to a developer community
Outlook
Future Needs

- Active flow-control actuators
- CFD- & empirically derived corrections to aerodynamic models
- Vortex methods
- Aero-acoustics
- Modal-reduced form of BeamDyn
- Drivetrain dynamics
- Structural flexibility of members that have previously been considered rigid (esp. for floating platforms)
- High-order wave models
- Further verification & validation
- VAWTs & flying electric generators
Outlook

Conclusions

• Engineering models required to address design challenges, so that wind turbines are:
  – Innovative
  – Optimized
  – Reliable
  – Cost-effective

• Improved models are needed to address/develop:
  – Upscaling to larger sizes
  – Novel architectures & controls
  – Coupling to offshore platforms
  – Design at the wind-plant level
  – System-wide optimization
Support unique needs of nascent offshore industry

Wind-plant level inflow, wakes, & control for performance & loads

Coupling with aerodynamically tailored blades

Visualization for interpretation of complex geometry & response

Visualization for interpretation of complex geometry & response

Support for new technology (e.g., sensors, actuators)

Coupling to mechanical & electrical systems

• Framework & development community
• Computational efficiency for iterative & probabilistic design
• Range of fidelity to target specific problems in industry & research
• Links to systems engineering

Improved aero to address biggest source of error

V&V to understand where models are suitable & where they are not

Outlook – Vision for Future Engineering Models
Outlook
A Final Thought – Quoting George E. P. Box

“Essentially, all models are wrong, but some are useful.”
More information @: https://nwtc.nrel.gov

Carpe Ventum!

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