NATIONAL RENEWABLE ENERGY LABORATORY

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

NAWEA 2017 Symposium

September 26, 2017

Ames, IA (USA)

Jason Jonkman, Ph.D.
Senior Engineer, NREL

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

NATIONAL RENEWABLE ENERGY LABORATORY

Introduction & Background

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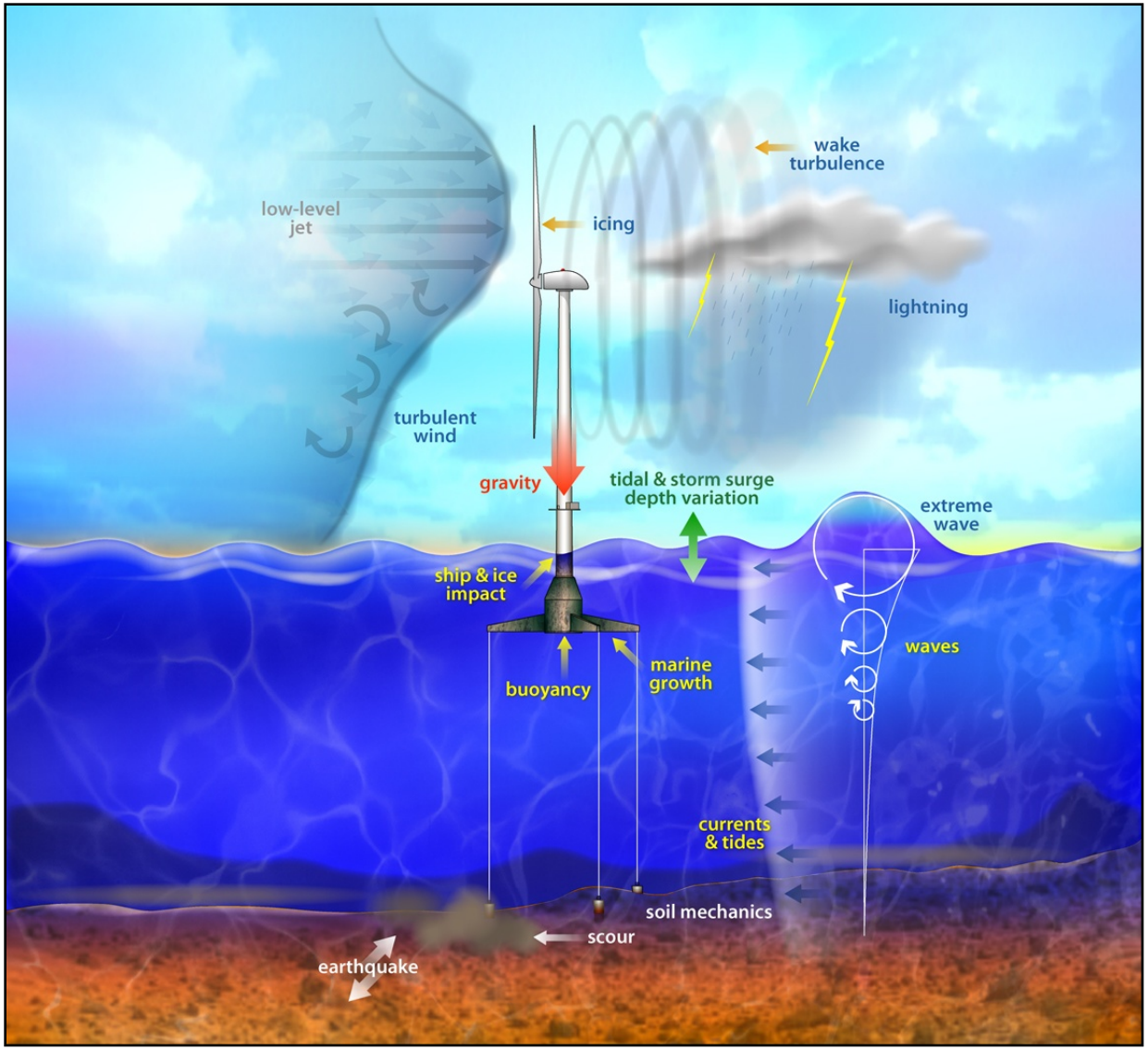
Introduction & Background

Modeling Requirements

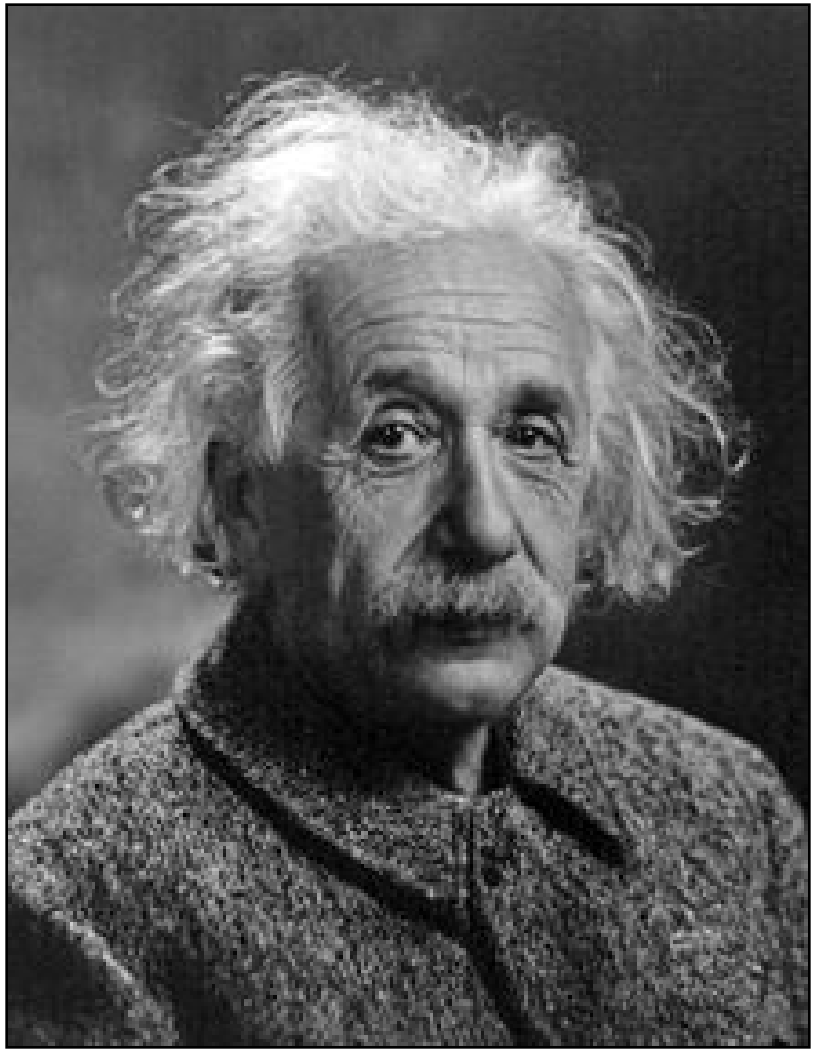


- Coupled aero-hydro-servo-elastic interaction
- Wind-inflow:
  - –Discrete events
  - –Turbulence
- Waves:
  - –Regular
  - –Irregular
- Aerodynamics:
  - –Induction
  - –Rotational augmentation
  - –Skewed wake
  - –Dynamic stall
- Hydrodynamics:
  - –Diffraction
  - –Radiation
  - –Hydrostatics
-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

Introduction & Background

Einstein Principle

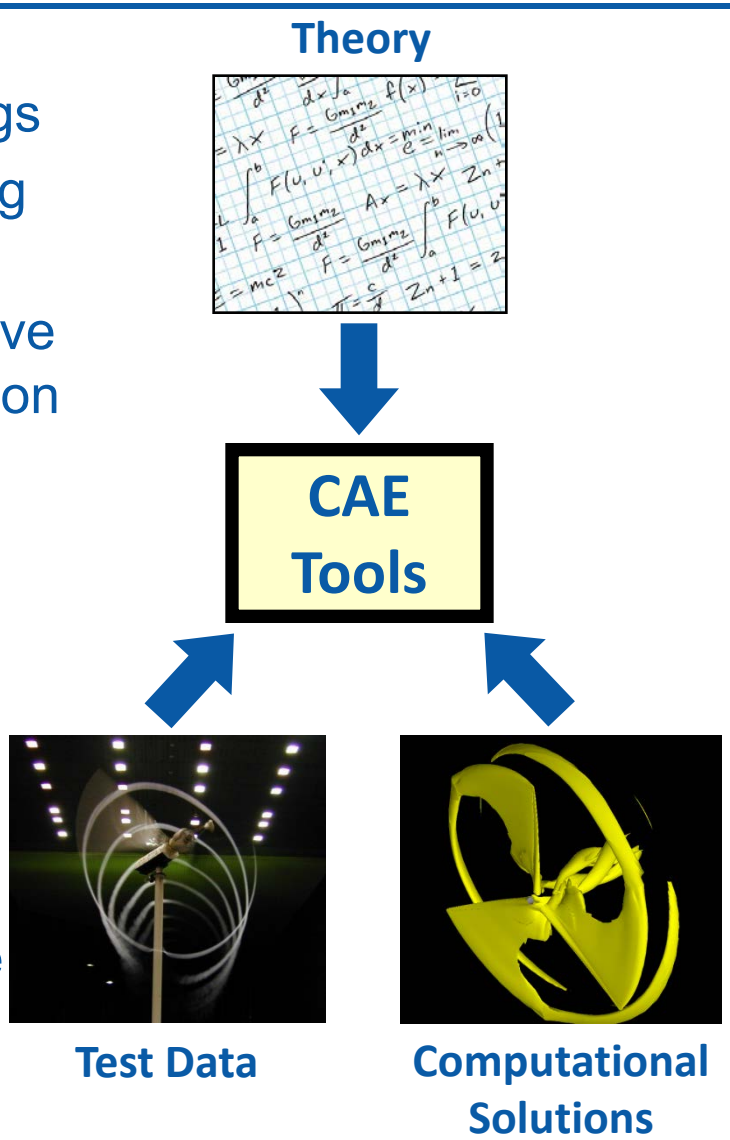
"A model should be as simple as possible, but no simpler."



Introduction & Background

Physics Modeling Needs for Engineering Design

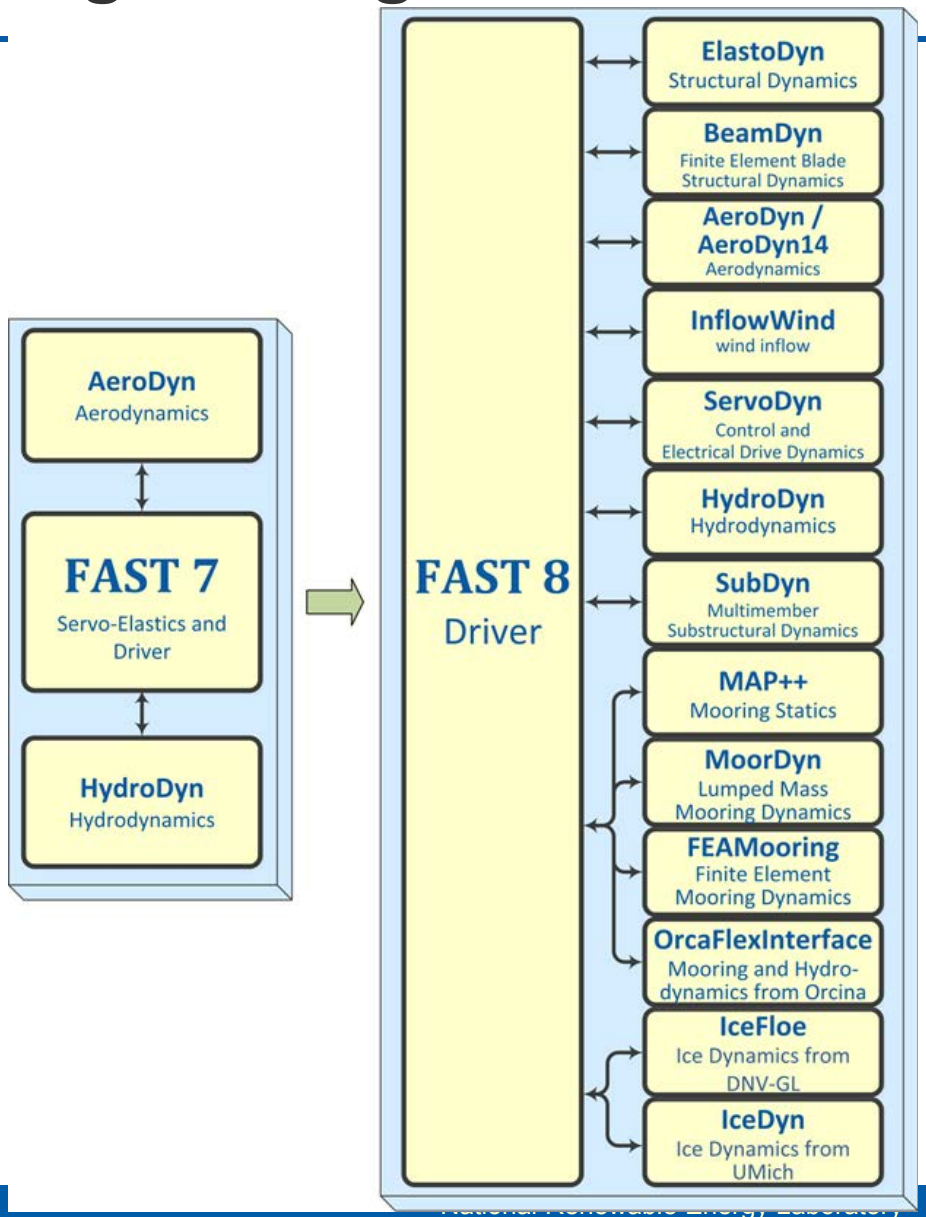
- Capture important system physics & couplings
- Range of fidelity to target specific engineering problems in industry & research
- Computational efficiency to support an iterative & probabilistic design processes & optimization
- Nonlinear time-domain for standards-based load analysis
- Linearization 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



Introduction & Background

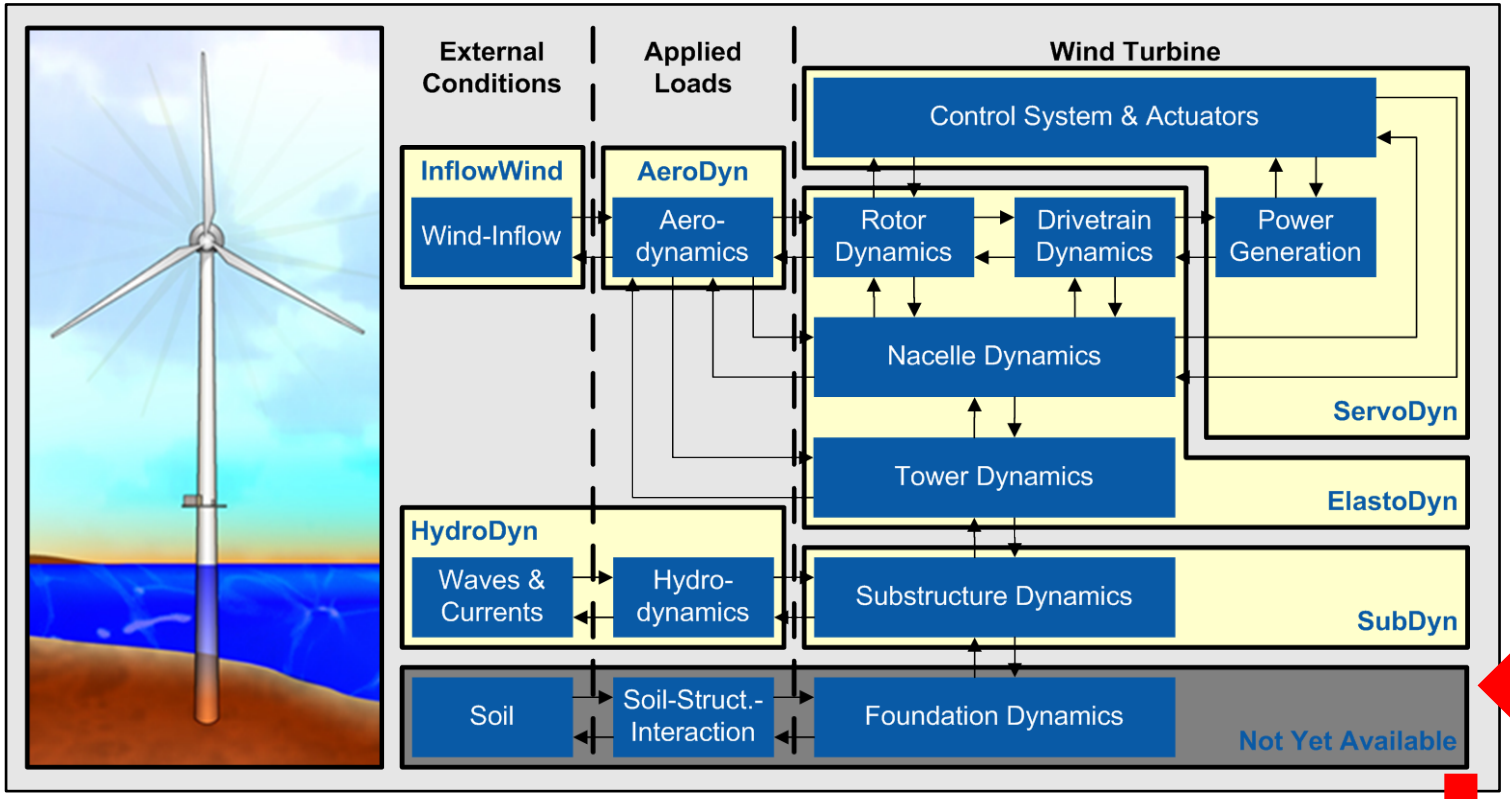
The FAST Multi-Physics Engineering Tool

- **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**)



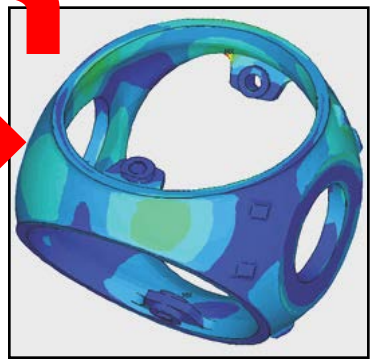
Introduction & Background

FAST Module Control Volumes – Fixed-Bottom



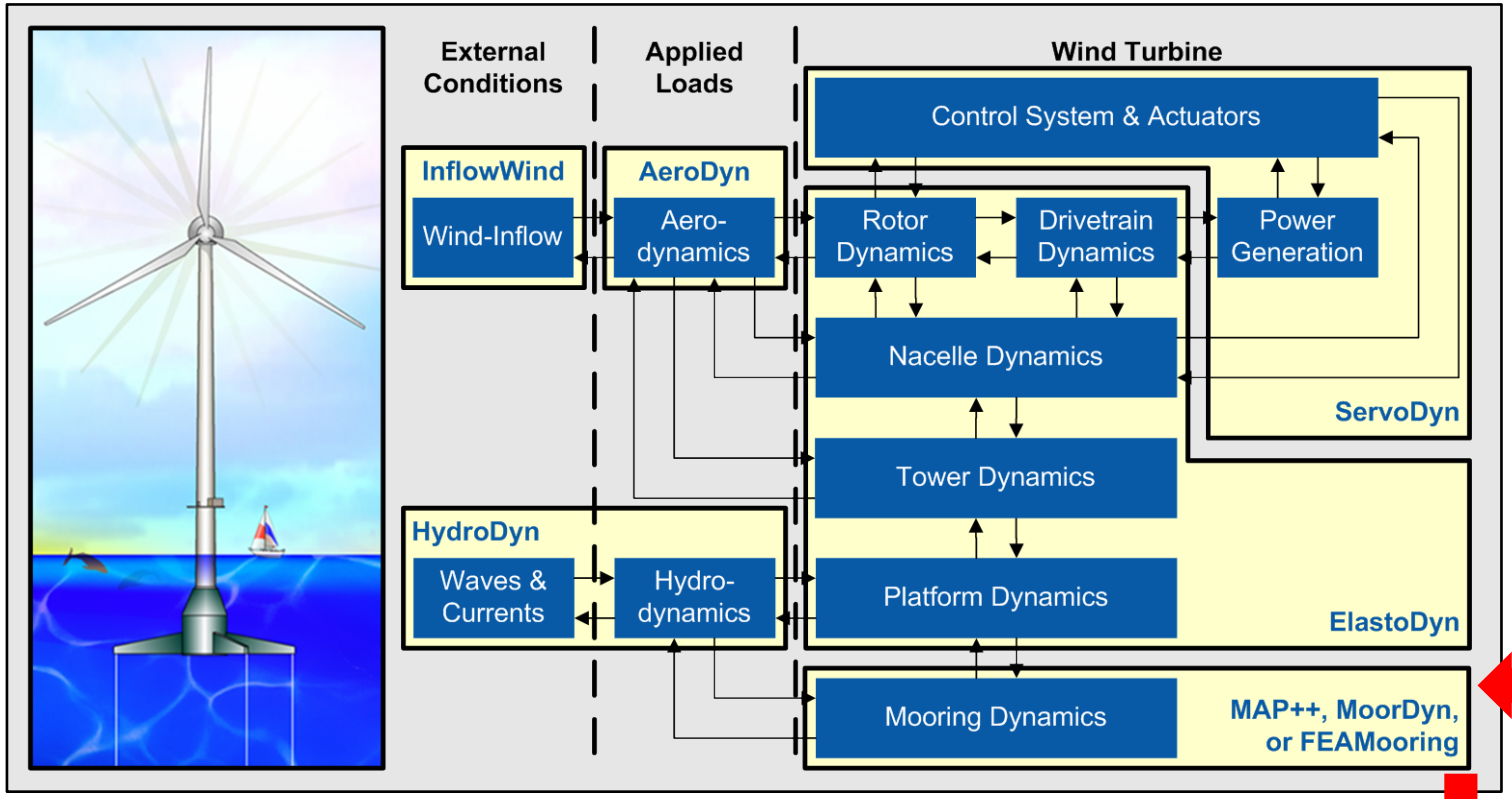
Full-System Level
*(**BeamDyn**, **IceFloe**, & **IceDyn** Not Shown)*

Component Level



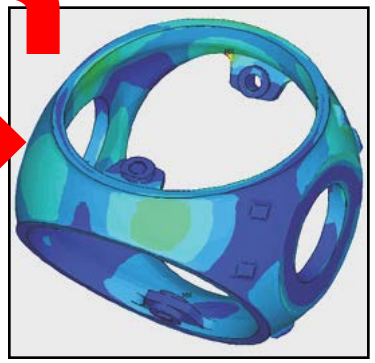
Introduction & Background

FAST Module Control Volumes – Floating



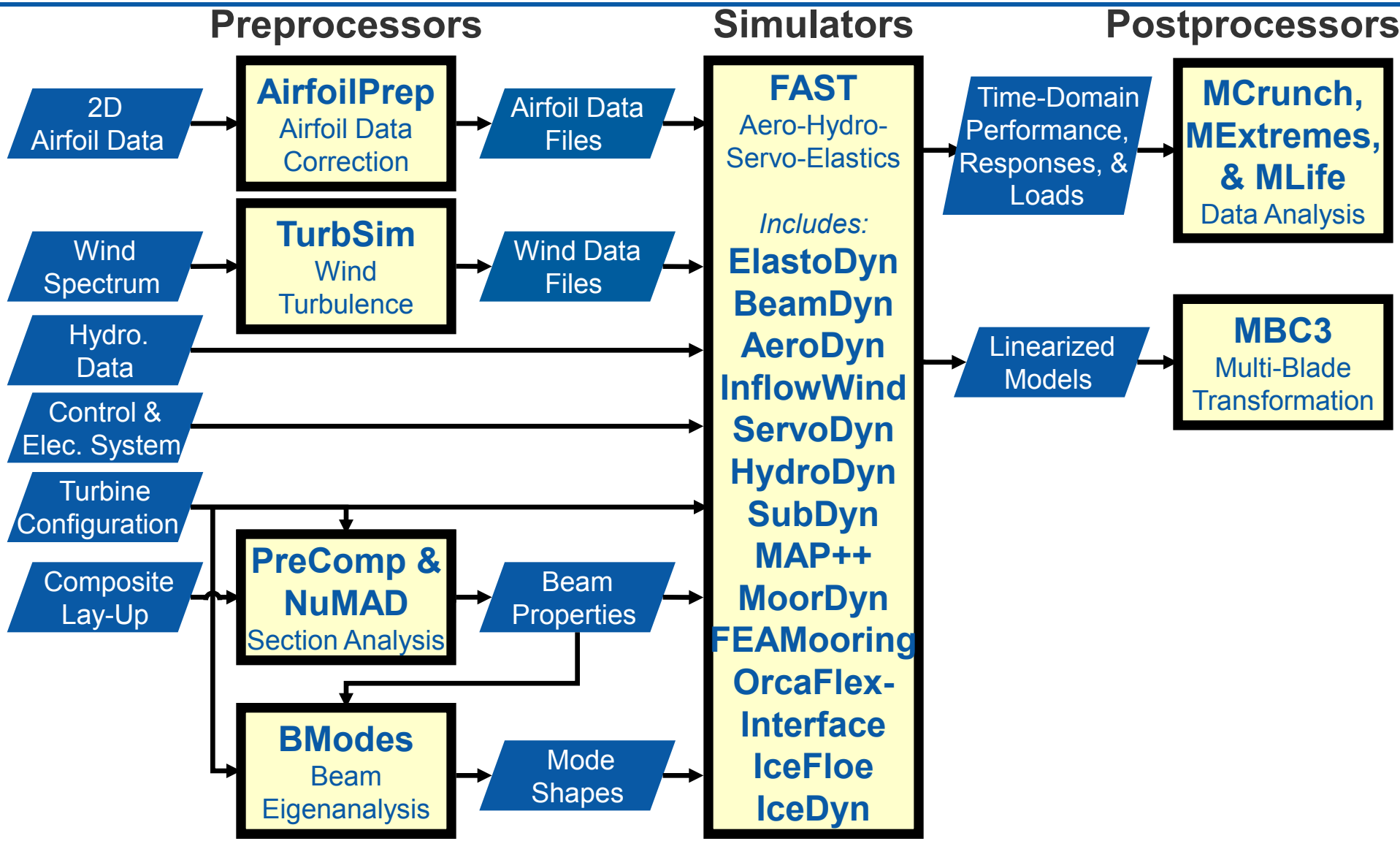
Full-System Level
(***BeamDyn*** & ***OrcaFlexInterface*** *not shown)*

Component Level



Introduction & Background

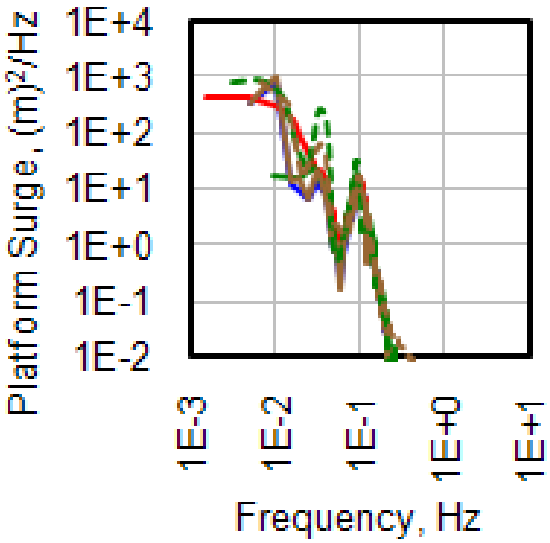
Key DOE/NREL Tools in the Design Process



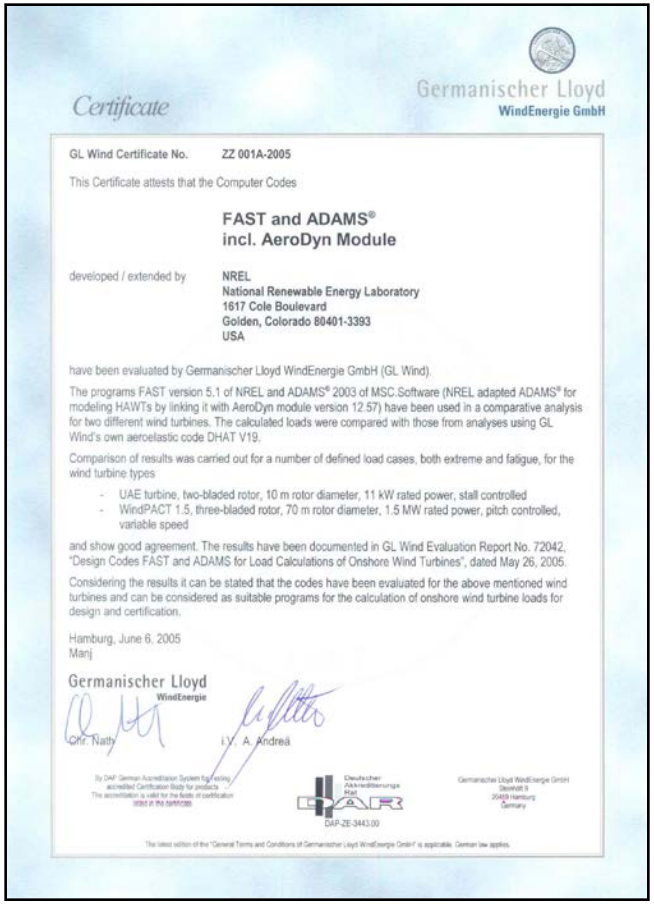
Introduction & Background

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



Certificate

Germanischer Lloyd
WindEnergie GmbH

GL Wind Certificate No. ZZ 001A-2005

This Certificate attests that the Computer Codes

FAST and ADAMS®
incl. AeroDyn Module

developed / extended by

NREL
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
USA

have been evaluated by Germanischer Lloyd WindEnergie GmbH (GL Wind).

The programs FAST version 5.1 of NREL and ADAMS® 2003 of MSC.Software (NREL adapted ADAMS® for modeling HAWTs by linking it with AeroDyn module version 12.57) have been used in a comparative analysis for two different wind turbines. The calculated loads were compared with those from analyses using GL Wind's own aeroelastic code DHAT V19.

Comparison of results was carried out for a number of defined load cases, both extreme and fatigue, for the wind turbine types

- UAE turbine, two-bladed rotor, 10 m rotor diameter, 11 kW rated power, stall controlled
- WindPACT 1.5, three-bladed rotor, 70 m rotor diameter, 1.5 MW rated power, pitch controlled, variable speed

and show good agreement. The results have been documented in GL Wind Evaluation Report No. 72042, "Design Codes FAST and ADAMS for Load Calculations of Onshore Wind Turbines", dated May 26, 2005.

Considering the results it can be stated that the codes have been evaluated for the above mentioned wind turbines and can be considered as suitable programs for the calculation of onshore wind turbine loads for design and certification.

Hamburg, June 6, 2005
Manj

Germanischer Lloyd
WindEnergie

Chr. Nath i.V. A. Andreä

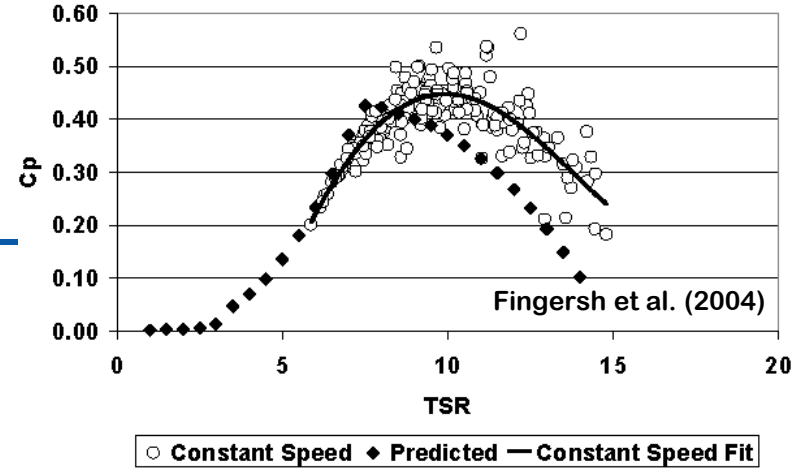
DAP-ZE-3443.00

GL Certificate Approving ***FAST*** *&* ***ADAMS*** *with* ***AeroDyn***

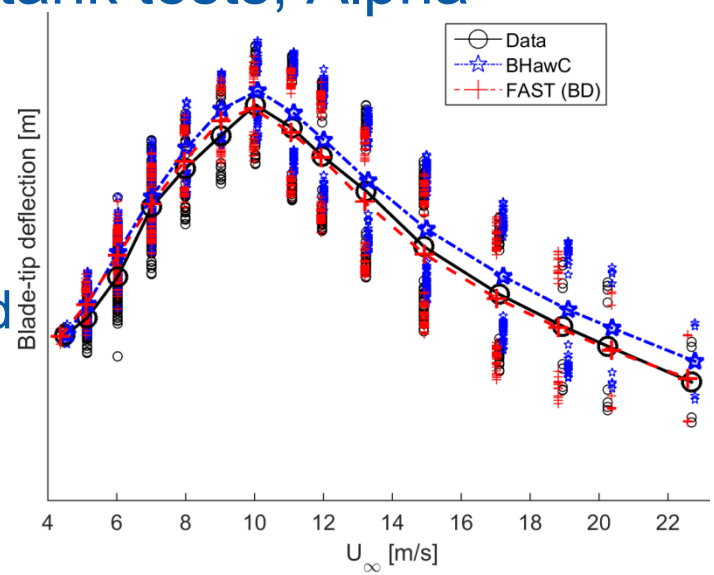
Introduction

Validation (Code-to-Data)

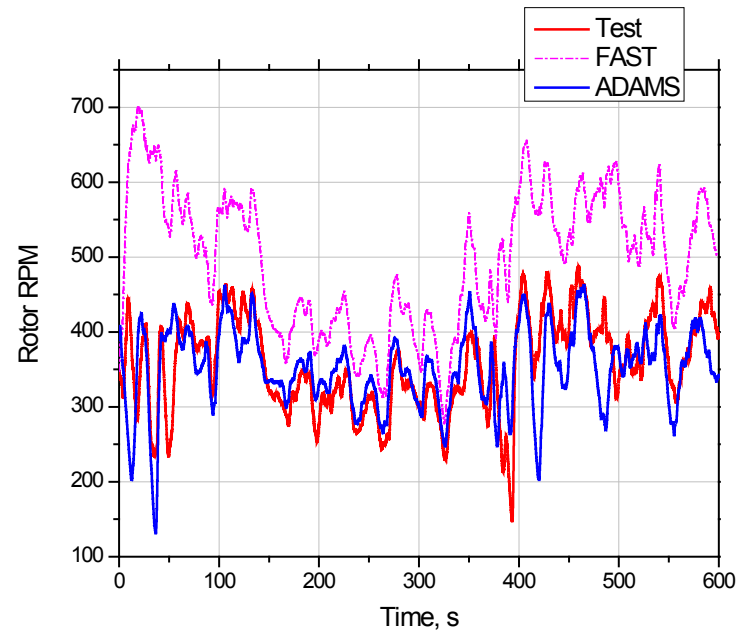
- UAE Phase VI
- SWRT
- CART2 & CART3
- Siemens
- Fixed:OC5 (tank tests, Alpha Ventus)
- Floating:
  - OC5
  - DeepCwind
  - SWAY
  - WindFloat
  - Hywind
  - CFD



*Comparison of Uncalibrated **WT_Perf** Prediction to CART2 Data*



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



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

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FAST Modularization Framework

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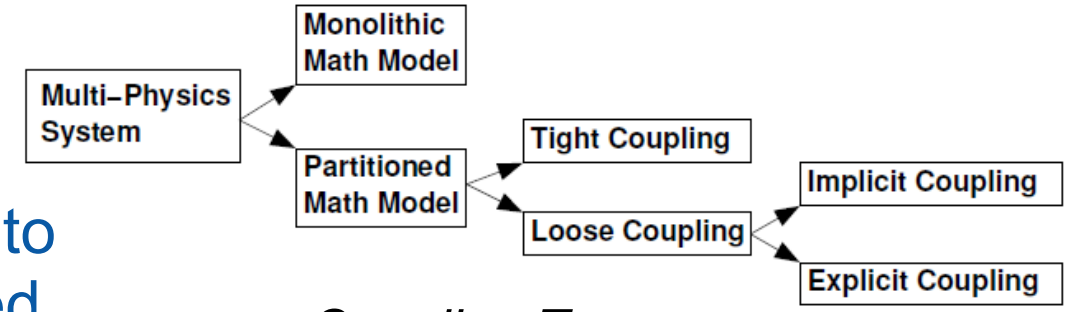
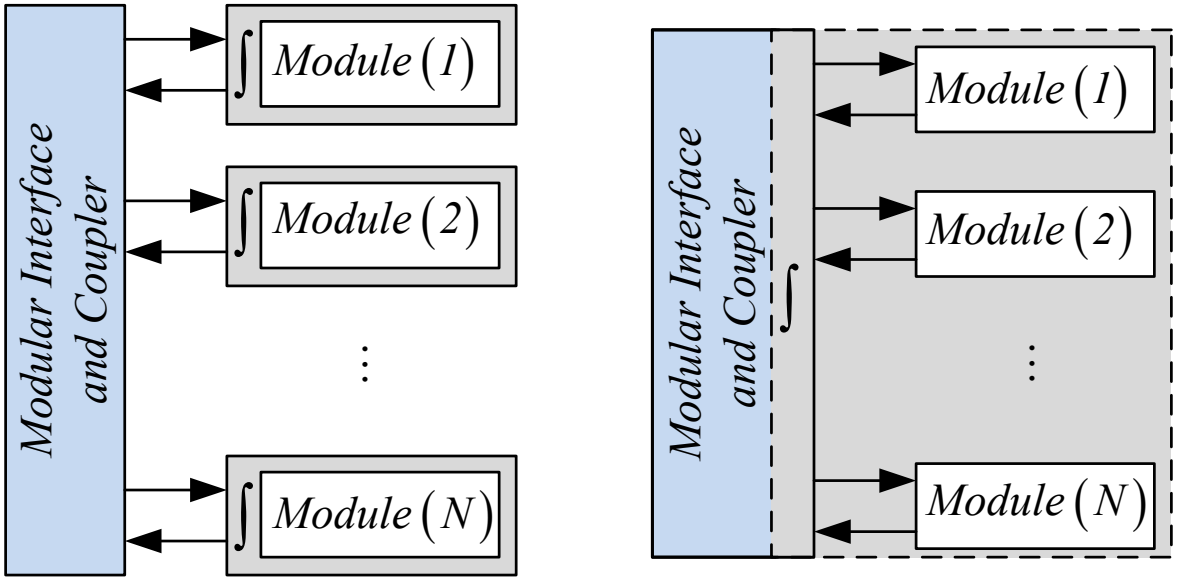
FAST Modularization Framework

What is the FAST Modularization Framework?

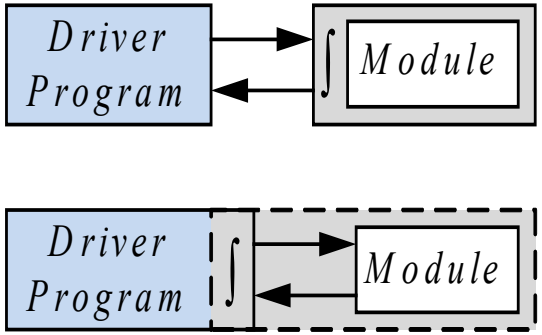
- A means by which various mathematical models are implemented in distinct modules & interconnected to solve for the global, coupled, dynamic response of a system



Coupling Taxonomy



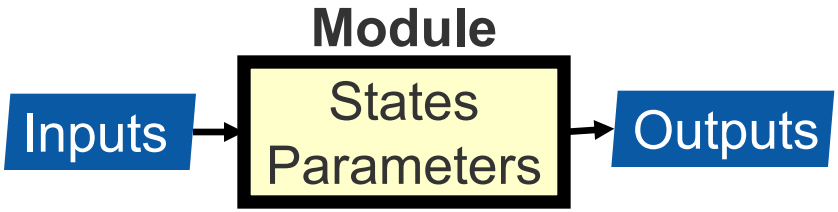
Loose- (Left) & Tight- (Right) Coupling Schemes



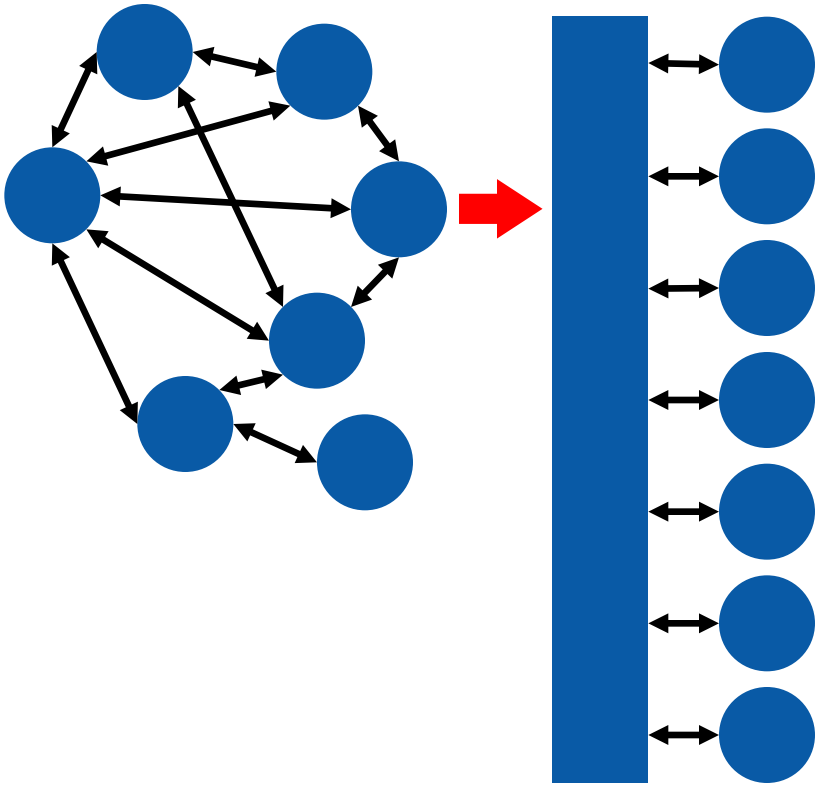
Uncoupled Solution of a Module Intended for Loose (Top) & Tight (Bottom) Coupling

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



Interconnected Physics Domains, Coupled Through a Driver

**Not yet available*

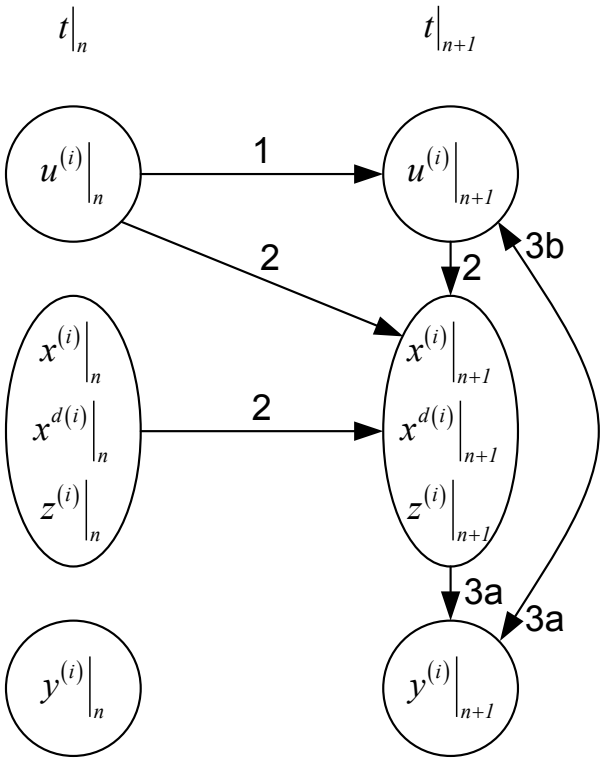
FAST Modularization Framework

Loose-Coupling Algorithm

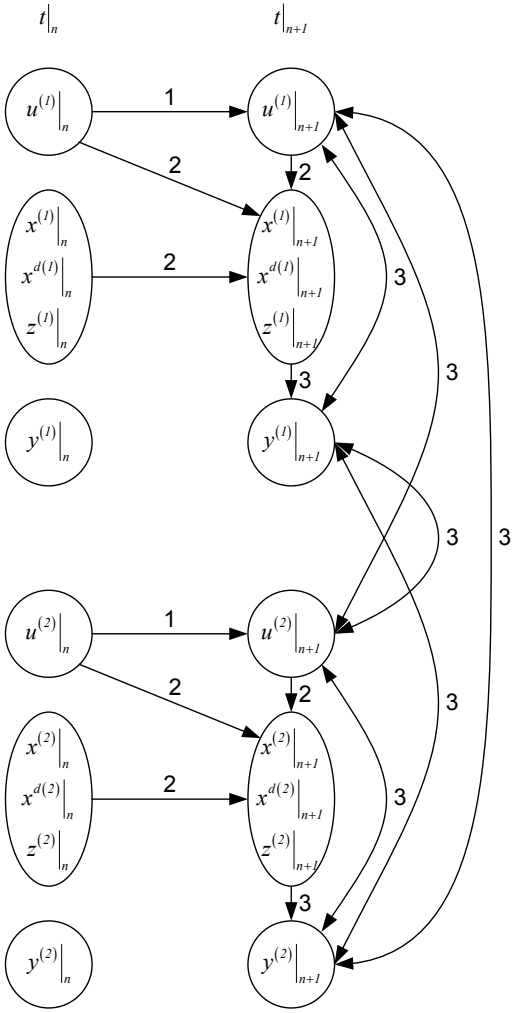
- Predictor-Corrector (PC)-based w/ time-step subcycling of modules
- Set-up for future parallelization (steps 1, 2, & 3a)

```
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

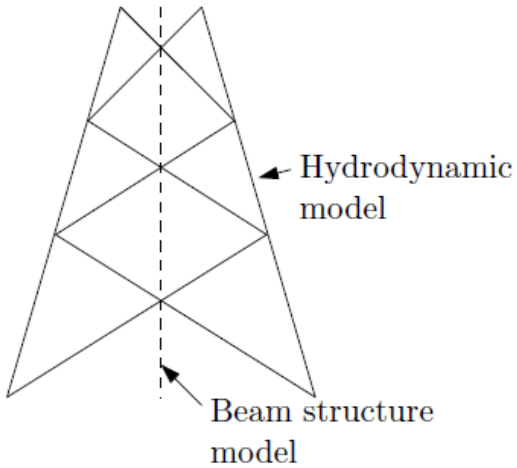


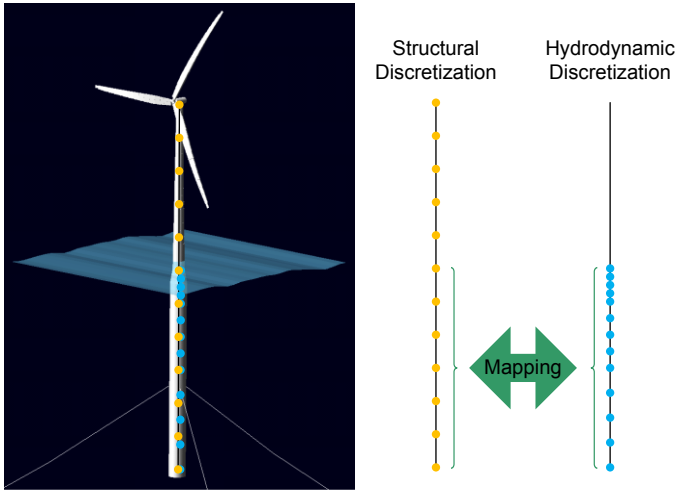
Coupling of Modules

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





Mapping Independent Discretizations

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)

$$\dot{x} = X\left(x,z,u,t\right)$$

$$0 = Z\left(x,z,u,t\right) \quad with \left|\frac{\partial Z}{\partial z}\right| \neq 0$$

$$y = Y\left(x,z,u,t\right)$$

$$u = u\big|_{op} + \Delta u \quad etc.$$

$$\Delta\dot{x} = A\Delta x + B\Delta u$$

$$\Delta y = C\Delta x + D\Delta u$$

$$with$$

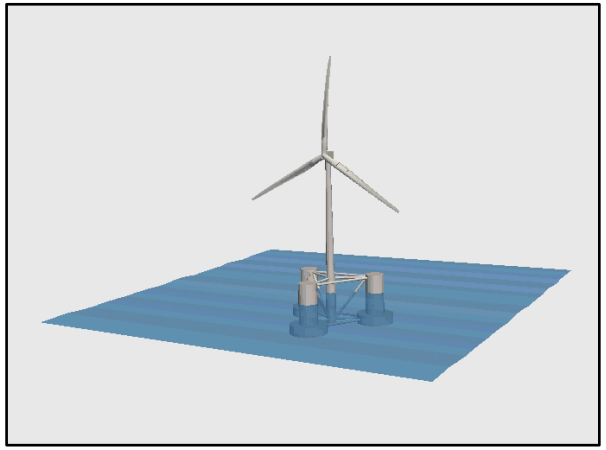
$$A = \left[\frac{\partial X}{\partial x} - \frac{\partial X}{\partial z}\left[\frac{\partial Z}{\partial z}\right]^{-1}\frac{\partial Z}{\partial x}\right]\Bigg|_{op} \quad etc.$$

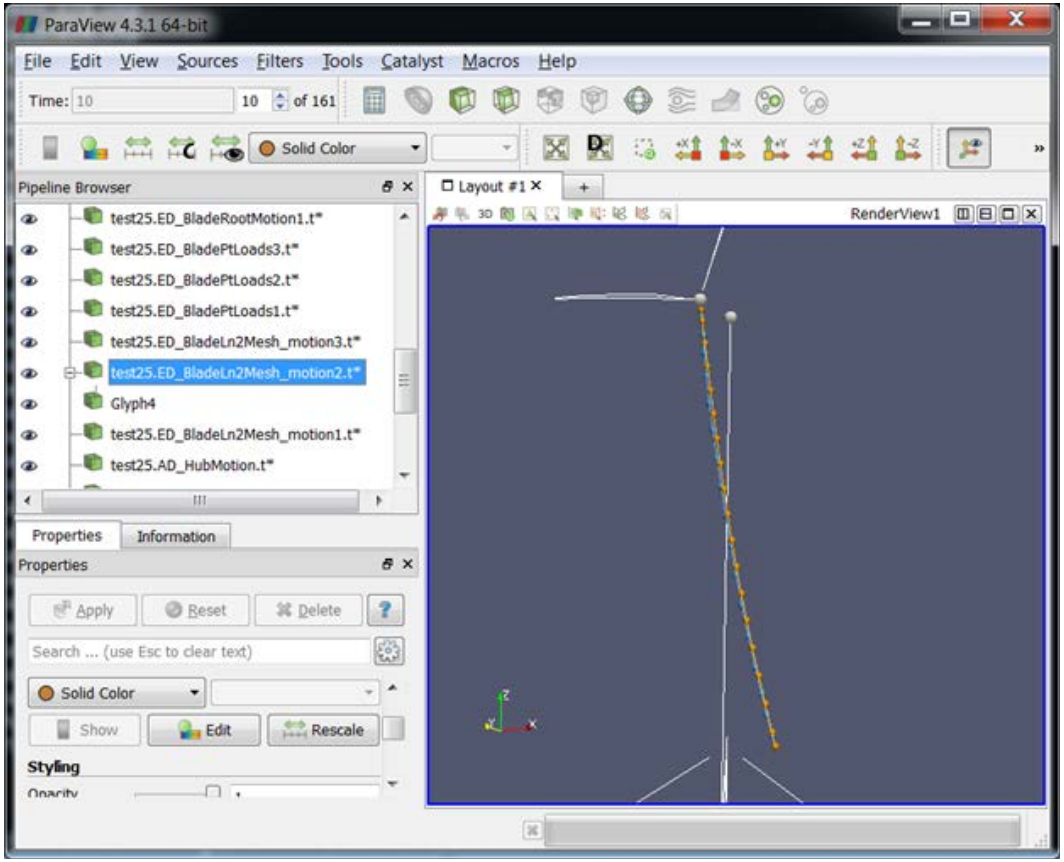
FAST Modularization Framework

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**

Surface Geometry Animation



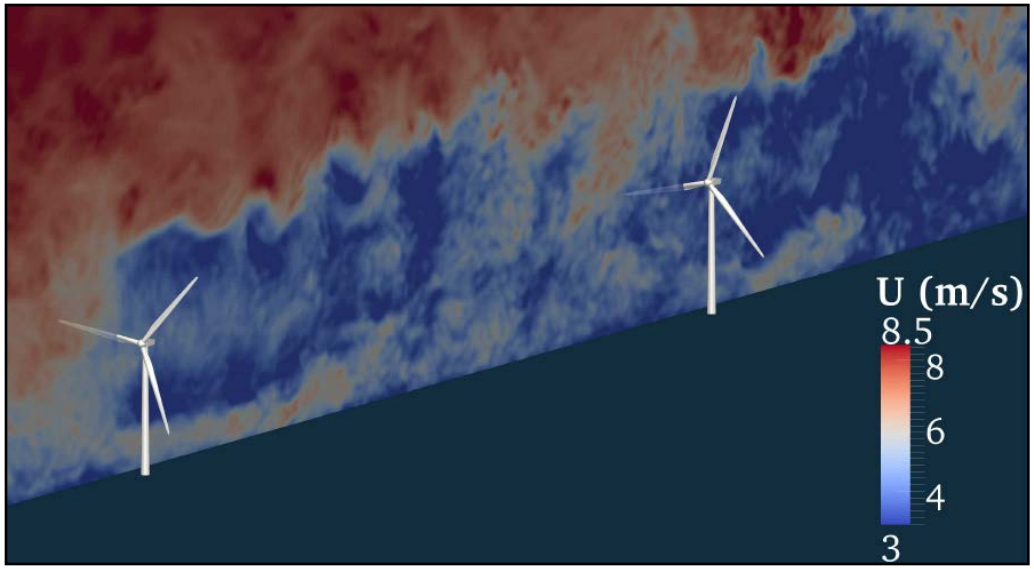


*Stick-Figure Visualization in **ParaView***

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**)



*Example **SOWFA** Simulation*

FAST Modularization Framework

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Structural Dynamics (ElastoDyn & BeamDyn)

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Structural Dynamics

ElastoDyn – Inputs, Outputs, States, & Parameters

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

→

ElastoDyn

Continuous States:
- Displacements
- Velocities

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

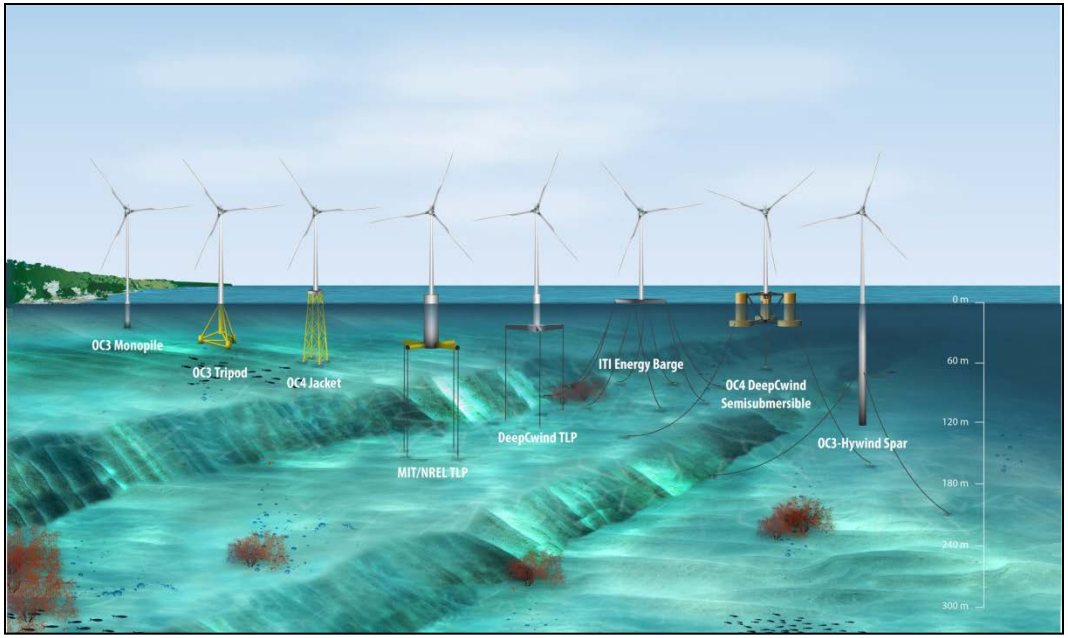
→

Outputs:
- Displacements
- Velocities
- Accelerations
- Reaction loads

Structural Dynamics

ElastoDyn – Turbine Configurations

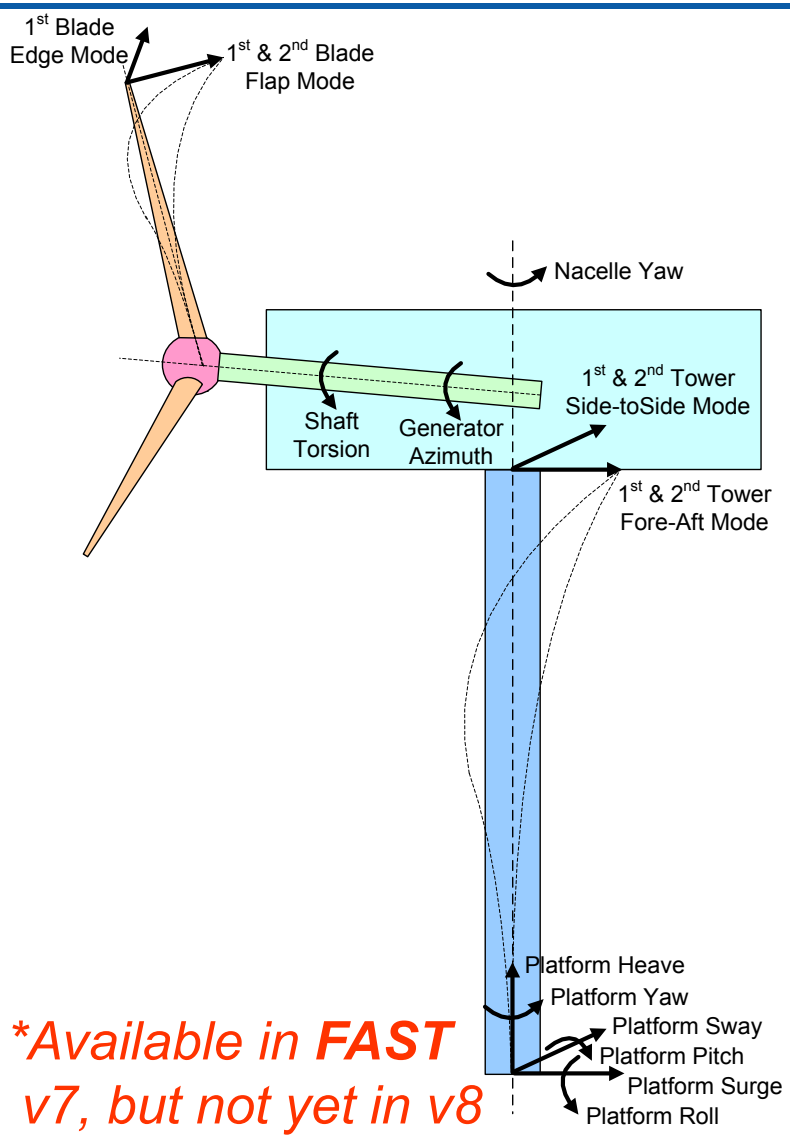
- Horizontal-axis (HAWT)
- 2- or 3-bladed rotor
- Upwind or downwind rotor
- Rigid or teetering hub
- Conventional configuration or inclusion of rotor- &/or tail-furling*
- Support structure that includes a tower atop a platform
- Land- or offshore-based (via **HydroDyn**)
- Offshore fixed-bottom (via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



Available in **FAST v7, but not yet in v8*

Structural Dynamics

ElastoDyn – Degrees of Freedom



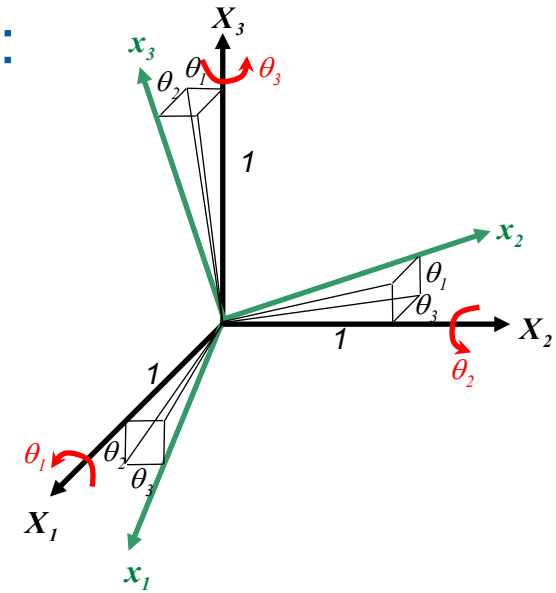
Available in **FAST v7, but not yet in v8*

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*:	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

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



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

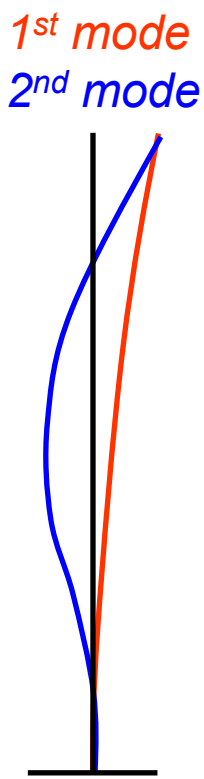
$$\begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix} = \frac{\begin{bmatrix} \theta_1^2\sqrt{1+\theta_1^2+\theta_2^2+\theta_3^2}+\theta_2^2+\theta_3^2 & \theta_3\left(\theta_1^2+\theta_2^2+\theta_3^2\right)+\theta_1\theta_2\left(\sqrt{1+\theta_1^2+\theta_2^2+\theta_3^2}-1\right) & -\theta_2\left(\theta_1^2+\theta_2^2+\theta_3^2\right)+\theta_1\theta_3\left(\sqrt{1+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

Correction for Orthogonality

Structural Dynamics

ElastoDyn – Blade & Tower Modeling Assumpt'ns

- 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: $\theta \approx \frac{\partial u}{\partial h} \quad \kappa \approx \frac{\partial^2 u}{\partial h^2}$
    - 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

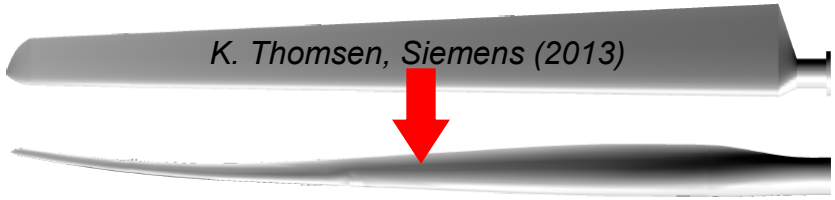


Modal Representation

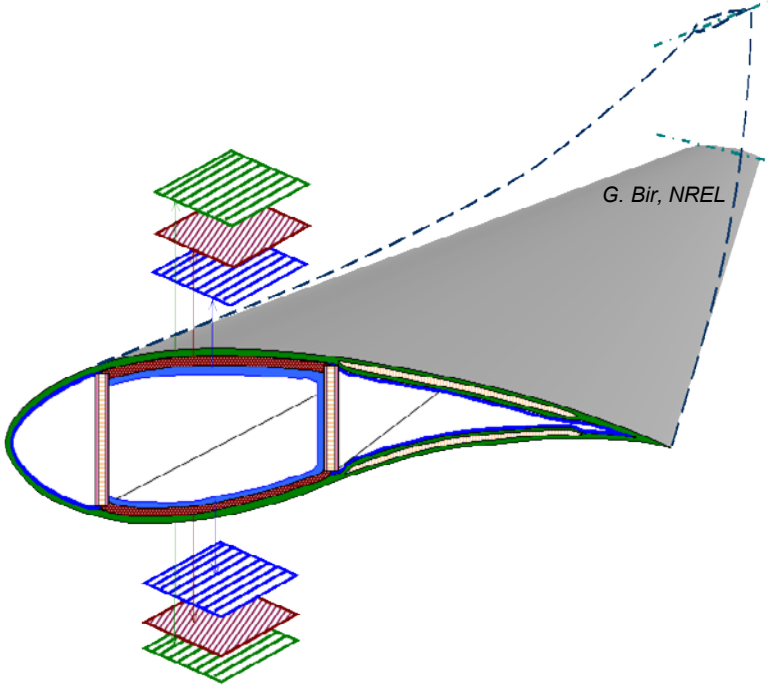
Structural Dynamics

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



Advancement in Blade Design



Blade Twist Induced By Anisotropic Layup

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

Inputs:
- Aerodynamic loads
- Root motion

→

BeamDyn

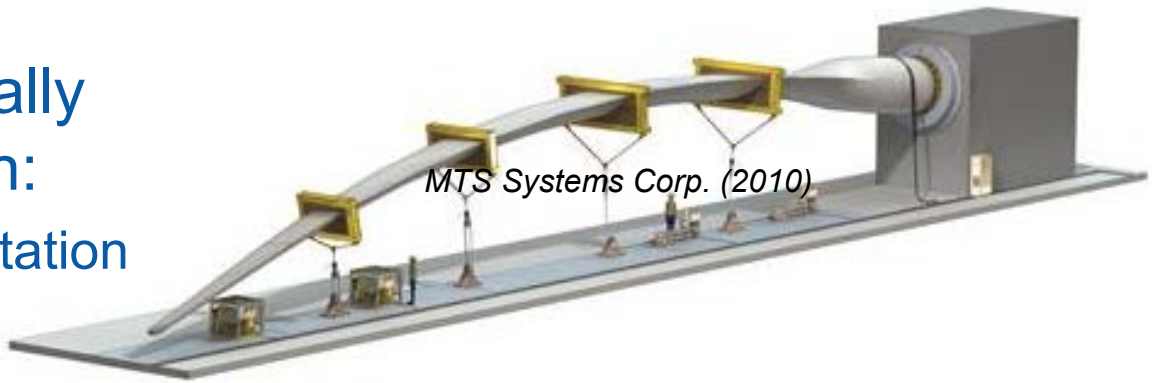
Continuous States:
- Displacements
- Velocities

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

→

Outputs:
- Blade motion
- Root reaction loads

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

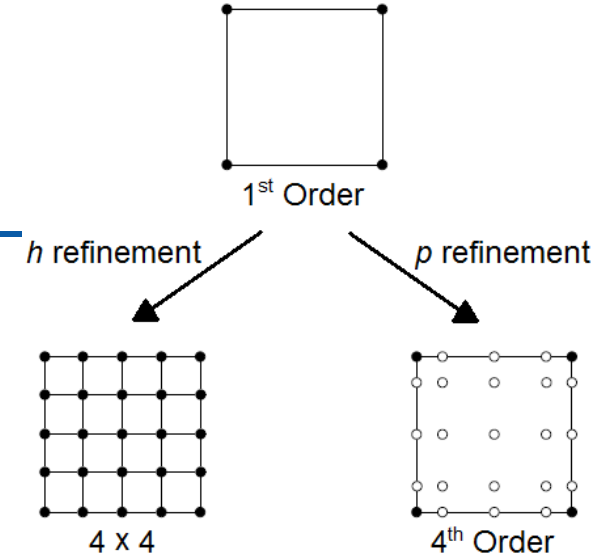


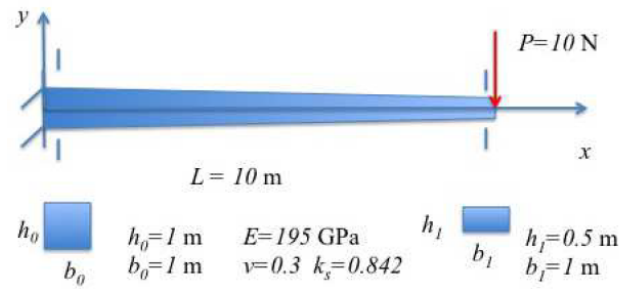
Structural Dynamics

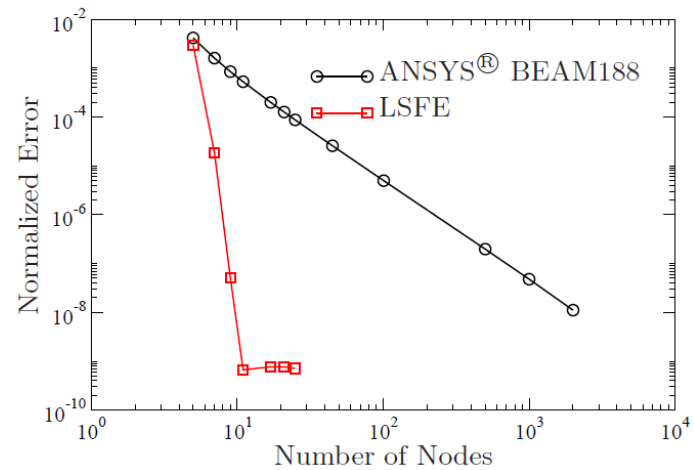
BeamDyn – LSFE

- 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



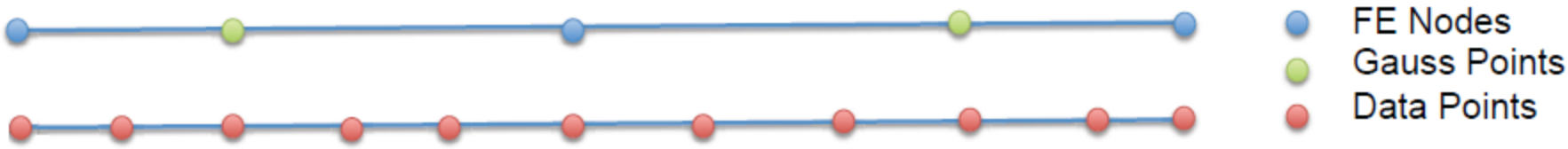


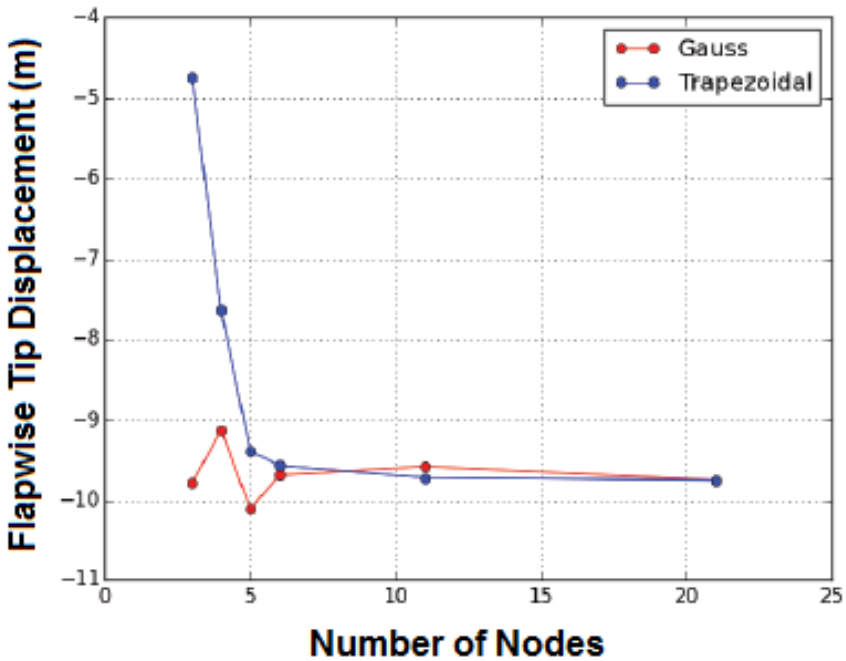


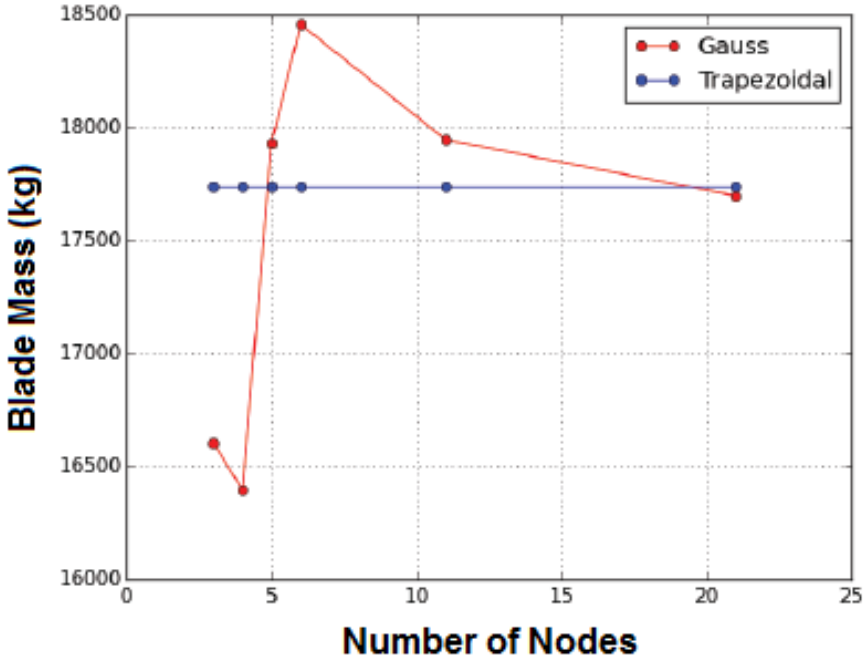
Structural Dynamics

BeamDyn – Spatial Integration

- Both Gauss & Trapezoidal-Rule spatial integration







***BeamDyn** Analysis of NREL 5-MW Blade w/ 49 Cross-Sectional Stations*

NATIONAL RENEWABLE ENERGY LABORATORY

Aerodynamics (AeroDyn & InflowWind)

NAWEA 2017 Symposium

September 26, 2017

Ames, IA (USA)

Jason Jonkman, Ph.D.
Senior Engineer, NREL

Aerodynamics

Inputs, Outputs, States, & Parameters

AeroDyn

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

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

InflowWind

Inputs:
- Positions

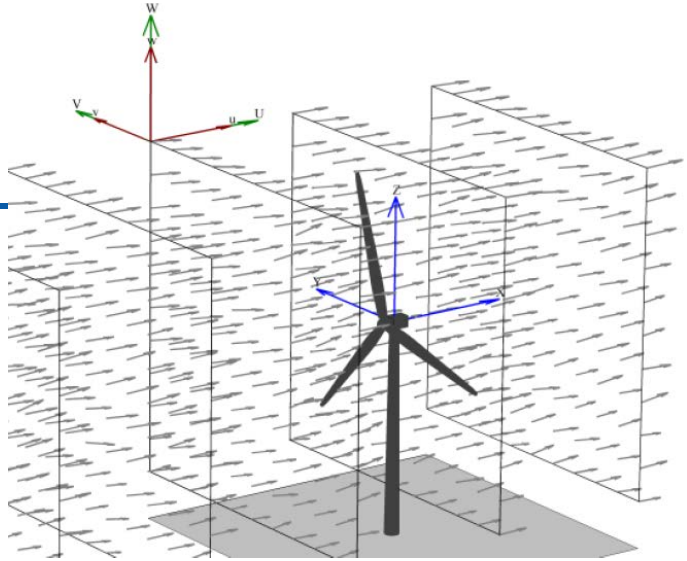
States:
- None

Parameters:
- Undisturbed wind inflow

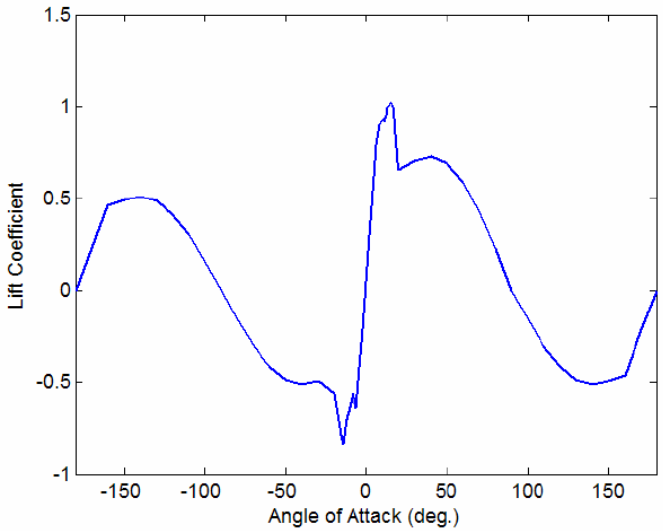
Outputs:
- Wind @ input positions

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



FF Wind Treated with Taylor's Frozen Turbulence Hypothesis

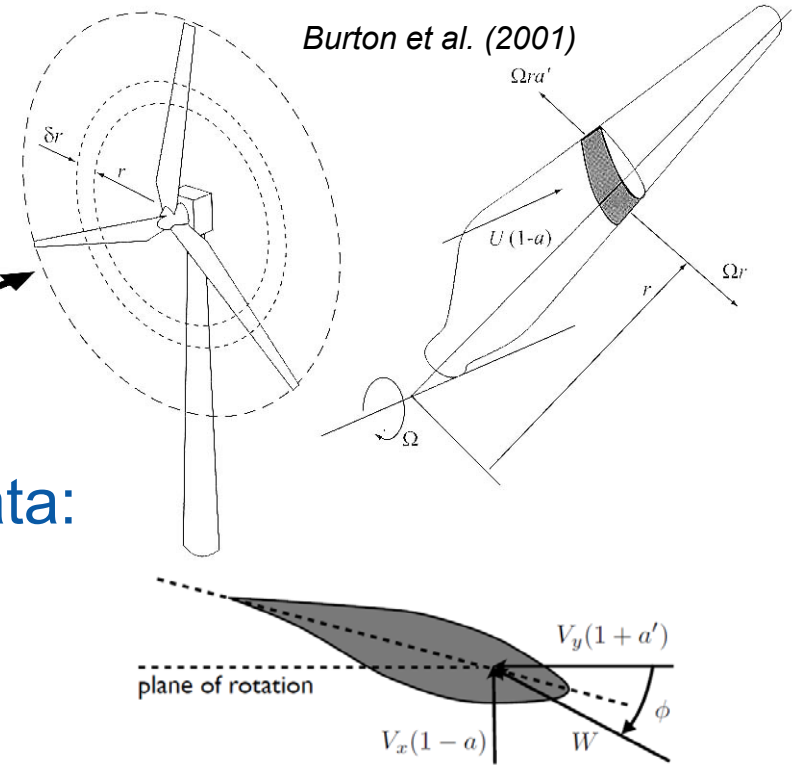


S809 Airfoil Data @ Re=750M

Aerodynamics

Wake – Blade-Element/Momentum Theory (BEMT)

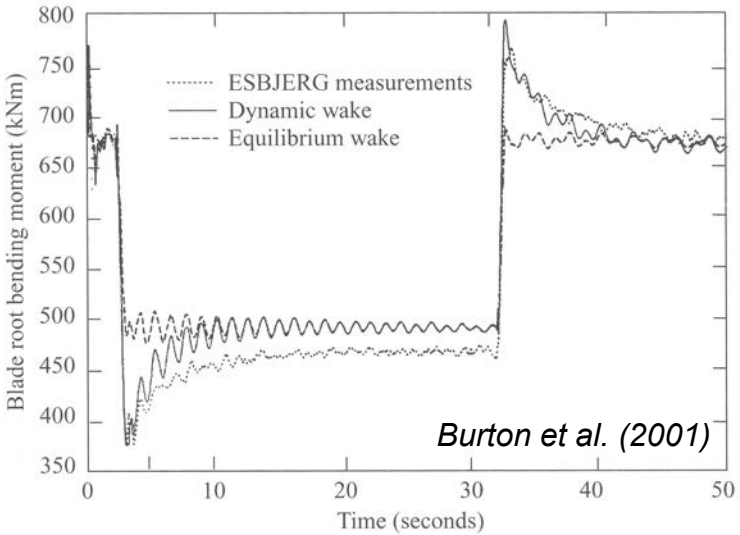
- Blades discretized into elements
- Momentum balance in annuli:
  - Linear → axial induction (*a*)
  - Angular → tangential induction (*a'*)
  - Implemented per element per blade
  - Nonlinear solve requires iteration
- Blade-element loads from airfoil data:
  - Drag terms can optionally be used in 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)*

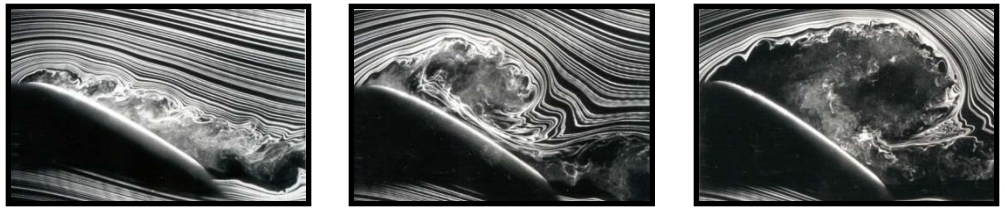
- Transient loading leads to a dynamic wake:
  - Turbulence/gusts
  - Skewed flow
  - Pitch control
- DBEMT models time- & spatial-varying induction across the rotor
- Based on Stig Øye:
  - Low-pass time-filtered BEMT
  - Applied both to axial & tangential inductions
- Replaces old Generalized Dynamic 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



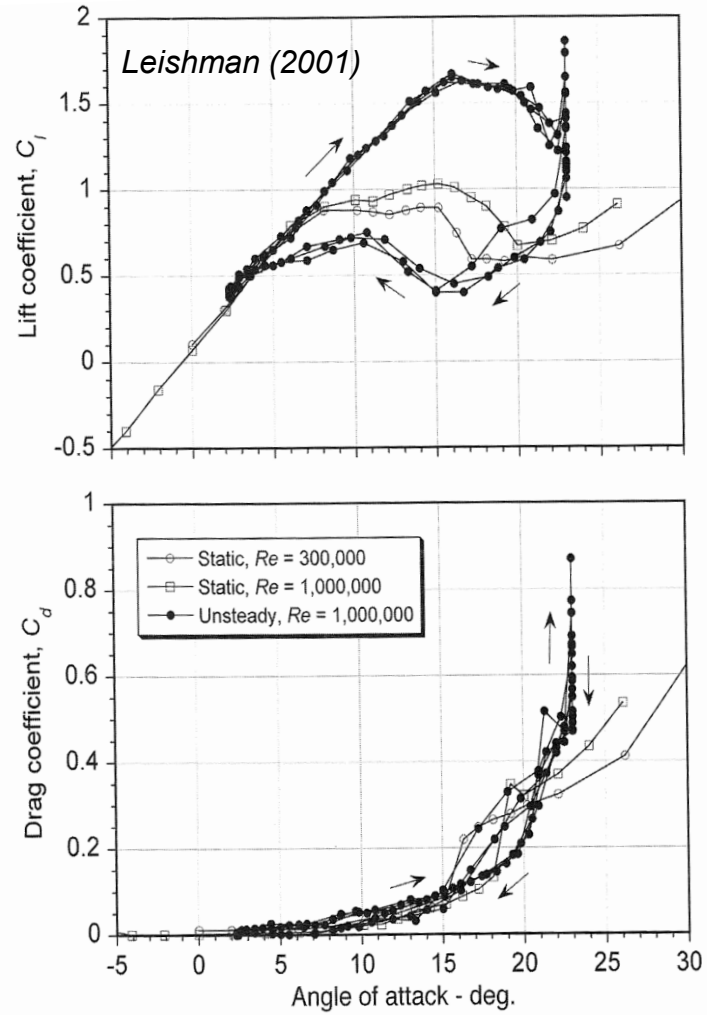
Blade Loading During Rapid Pitch Events

**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

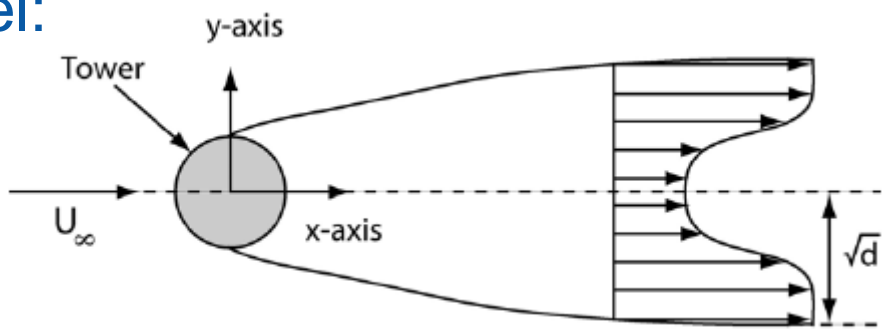


Dynamic Stall of S809 Airfoil

Aerodynamics

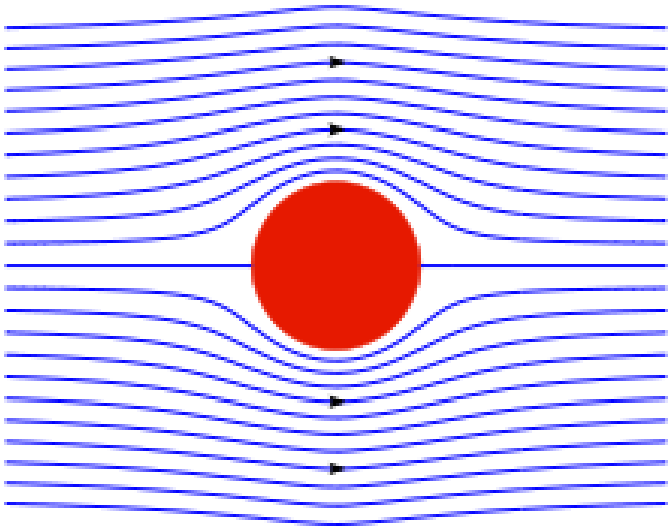
Tower Influence & Drag Load

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



Tower Shadow

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



Potential Flow Around a Cylinder

- Tower drag model:
  - Drag load @ each tower node proportional to square of undisturbed relative wind speed

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Control & Electrical-Drive Dynamics (ServoDyn)

NAWEA 2017 Symposium

September 26, 2017

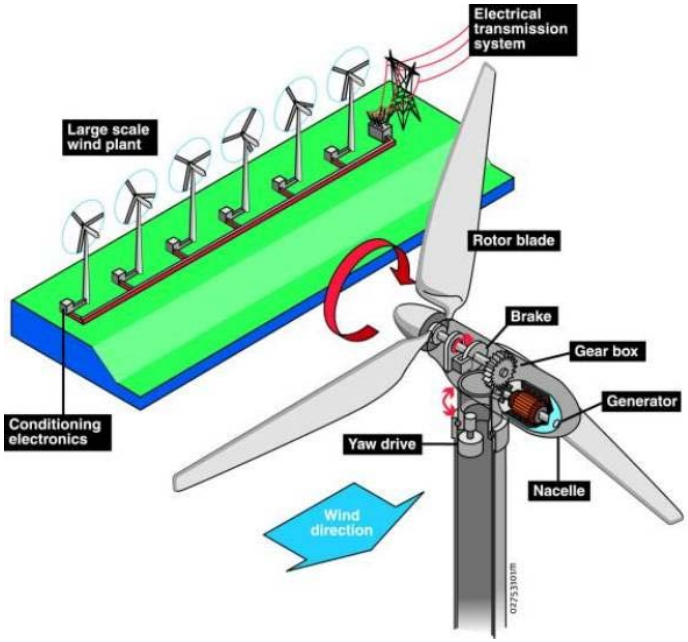
Ames, IA (USA)

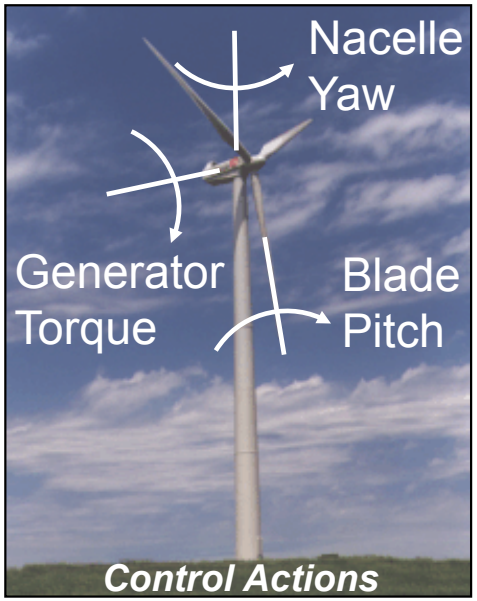
Jason Jonkman, Ph.D.
Senior Engineer, NREL

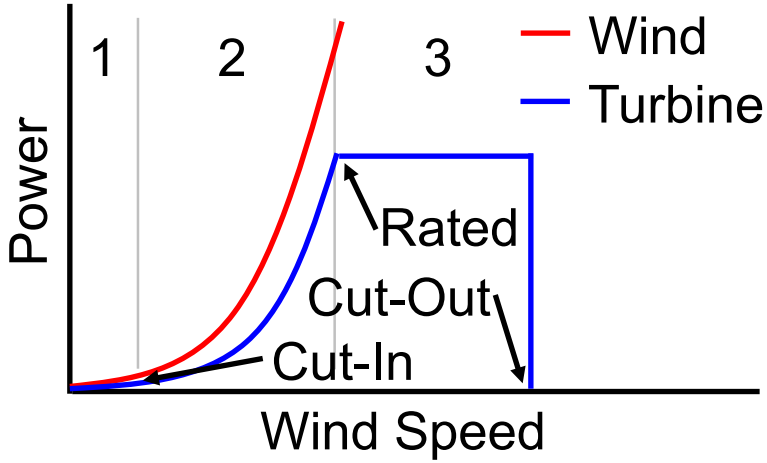
Control & Electrical Drive (ServoDyn)

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







Control & Electrical-Drive (ServoDyn)

Inputs, Outputs, States, & Parameters

Inputs:
- Structural motions
- Reaction loads
- Wind measurements

ServoDyn

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

Discrete States:
- Digital control signals

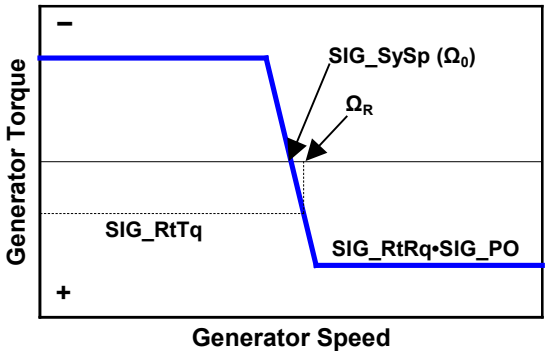
Parameters:
- Controller gains
- Control limits
- TMD configuration
- TMD mass, stiff., & damp

Outputs:
- Controller commands
- TMD reactions

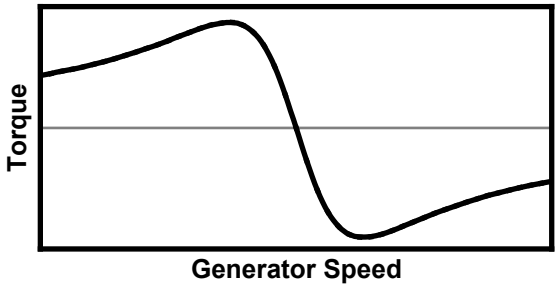
Control & Electrical-Drive (ServoDyn)

Active Control Methods

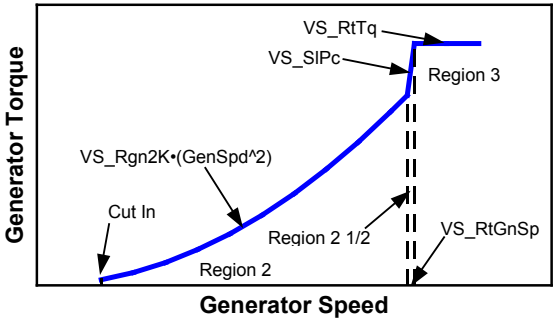
- Blade pitch:
  - Collective or independent
  - To feather or to stall
  - Command the angle
  - No actuator dynamics
  - Override maneuvers available
- Generator torque:
  - Fixed (w/ or w/o slip of induction generator) or variable speed
  - Command the torque
  - Indirect electrical power
  - Default models built in
  - Enable for startup or disable for shutdown
- HSS brake:
  - Command the deployment



Simple Induction Generator (SIG)



Thevenin-Equivalent Circuit (TEC) Generator

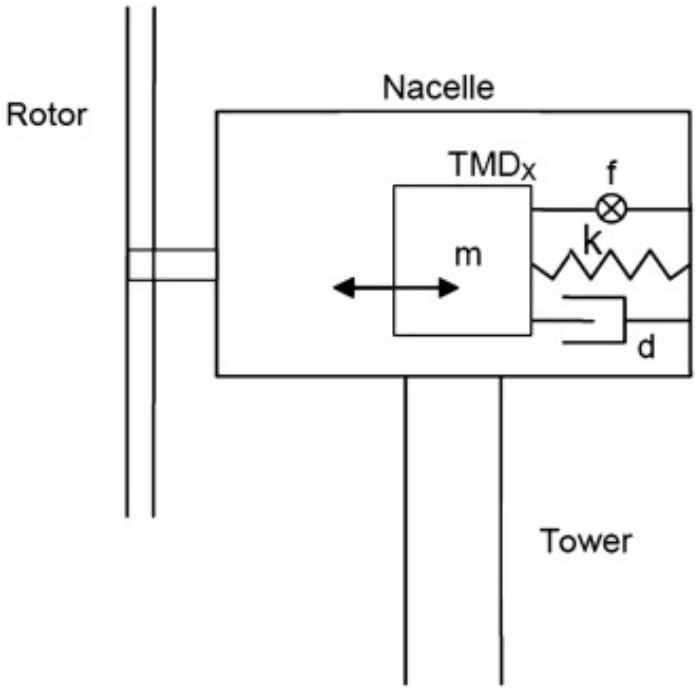


Simple Variable-Speed Controller

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



Nacelle-Based TMD

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

Control & Electrical-Drive (ServoDyn)

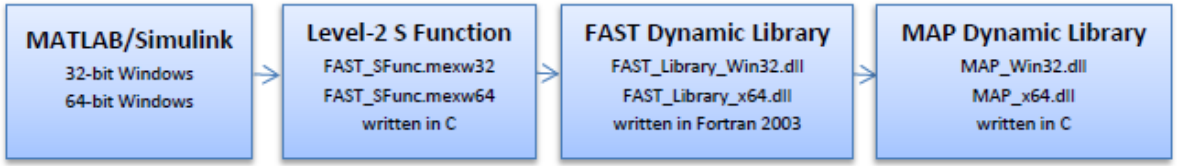
Interfacing Active Controllers – 5 Options (cont)

4) **MATLAB/Simulink**:

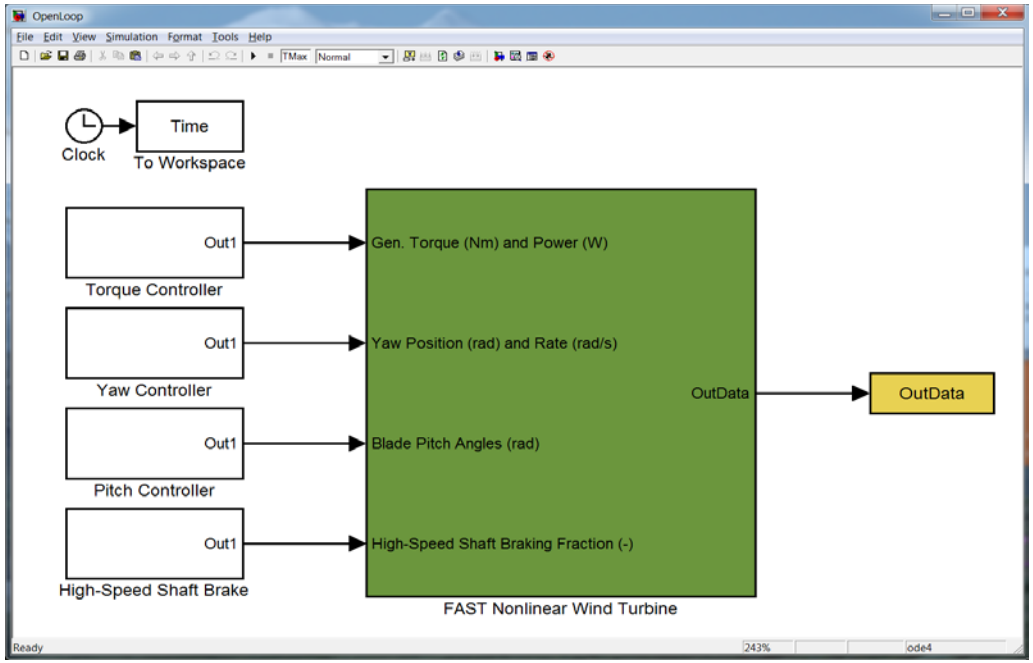
- **FAST** implemented as S-Function block
- Controls implemented in block-diagram form
- **SimPowerSystems** toolbox for detailed electrical drive

5) **LabVIEW***:

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



*Libraries in **FAST-Simulink** Interface*



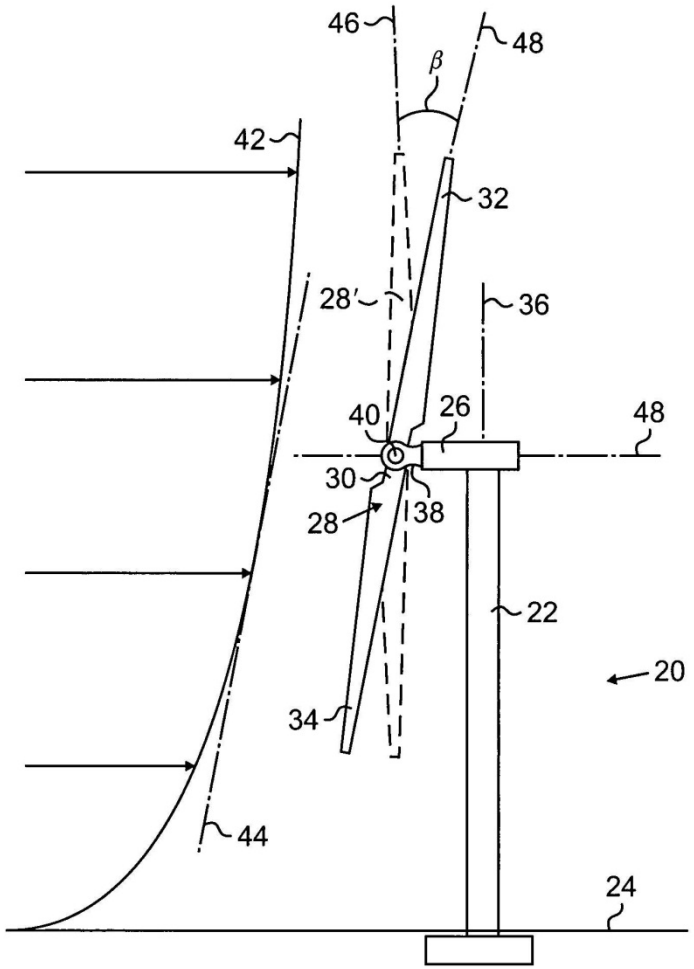
*Open-Loop **Simulink** Model*

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



2-Bladed Turbine with Teeter

Available in **FAST v7, but not yet in v8*

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

NAWEA 2017 Symposium

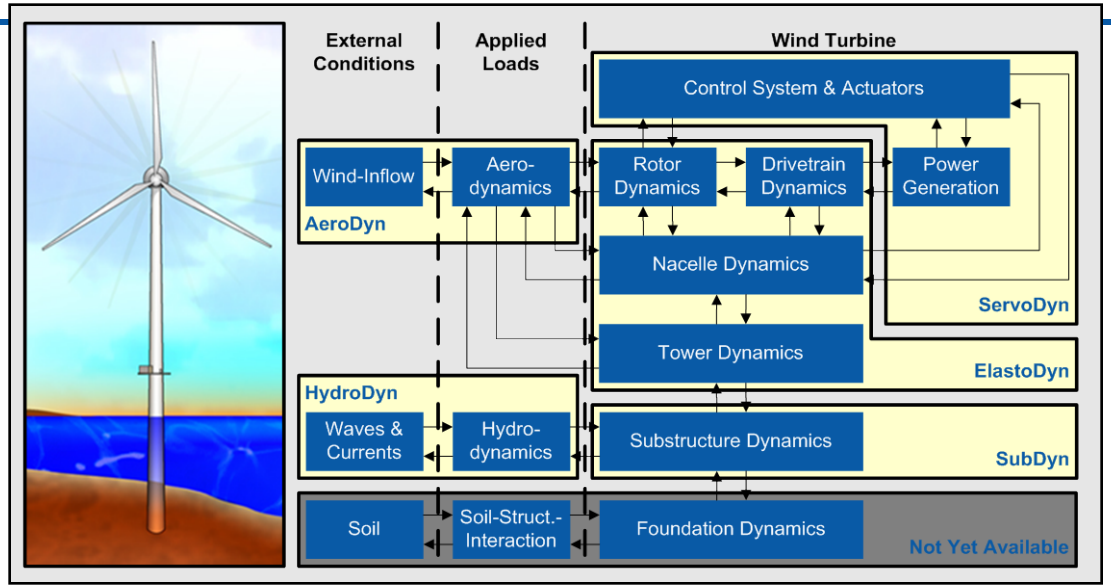
September 26, 2017

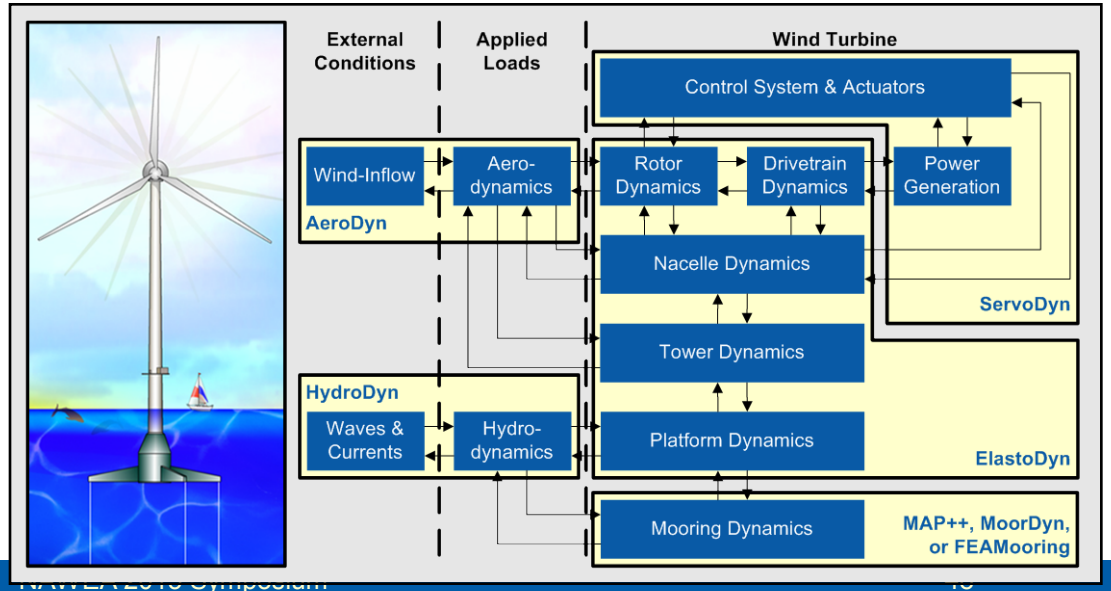
Ames, IA (USA)

Jason Jonkman, Ph.D.
Senior Engineer, NREL

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.

→

HydroDyn

Continuous States:
- State-space-based radiation "memory"

Discrete States:
- Convolution-based radiation "memory"

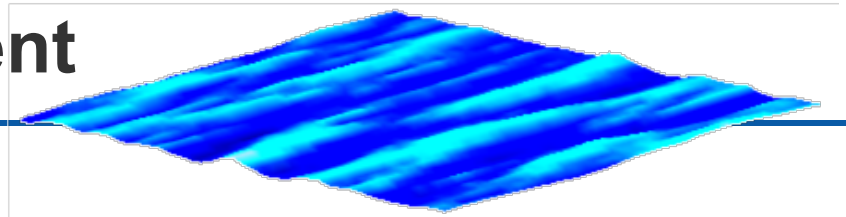
Parameters:
- Geometry
- Hydrodynamic coefficients
- Undisturbed incident waves
- Water Density
- Gravity

→

Outputs:
- Hydro. loads

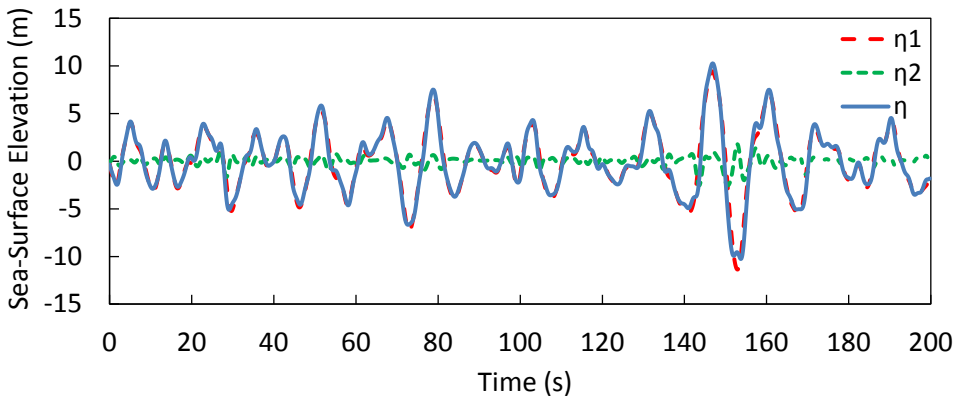
Hydrodynamics & Offshore Features

HydroDyn – Waves & Current

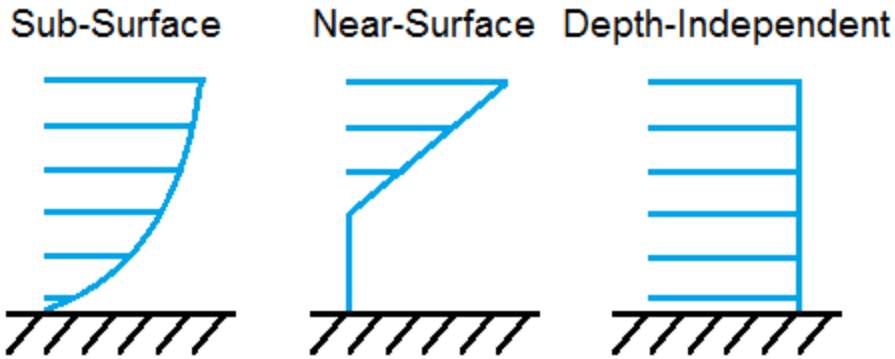


Multi-Directional Sea State

- 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



Sea-Surface Elevation (η) from the Summing of 1st- (η_1) & 2nd- (η_2) Order Waves

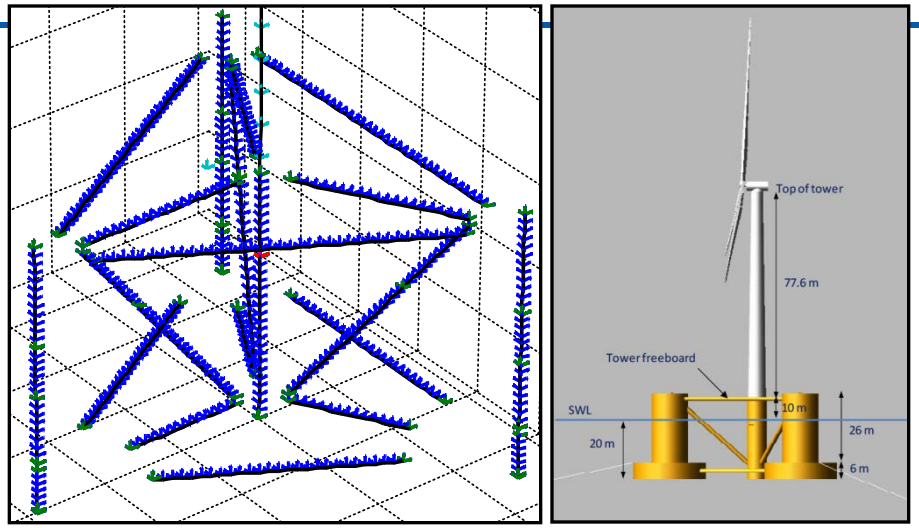


IEC Sea Currents

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
  - 1st- (RAO) & 2nd-order (QTF)
  - 2nd-order via Newman's approximation or full QTF
- Hybrid combination of these two



Strip-Theory Nodes for the OC4-DeepCwind Semisubmersible

$$u \longrightarrow \boxed{y(t) = \int_0^t K(t-\tau)u(\tau)\,d\tau} \longrightarrow y$$

$$u \longrightarrow \boxed{\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned}} \longrightarrow y$$

Reformulation of Radiation Convolution to Linear SS Form

Hydrodynamics & Offshore Features

SubDyn – Inputs, Outputs, States, & Parameters

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

SubDyn

Continuous States:
- Displacements
- Velocities

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

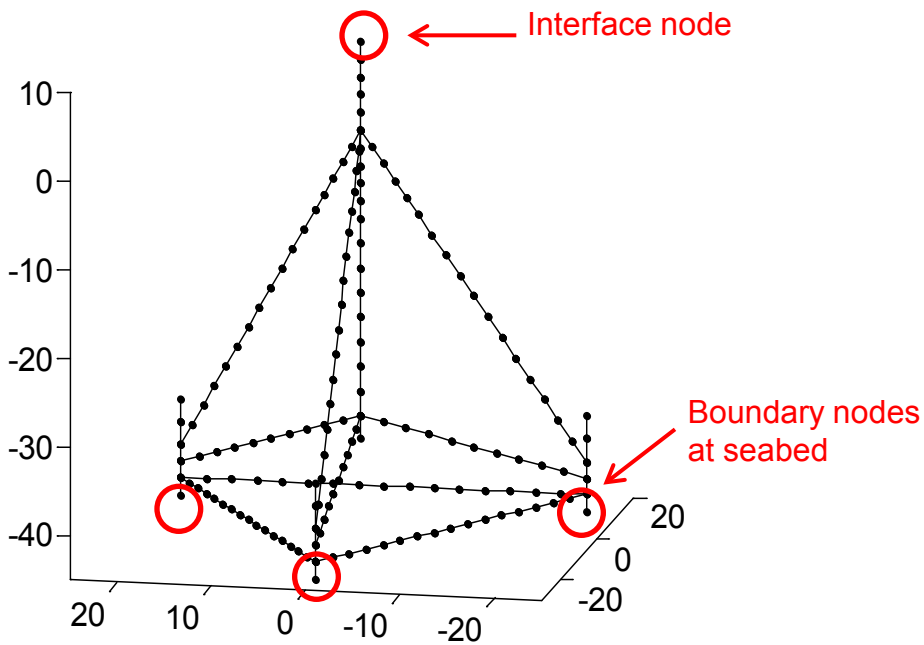
Outputs:
- Displacements
- Velocities
- Accelerations
- Reaction loads

**TP = Transition piece*

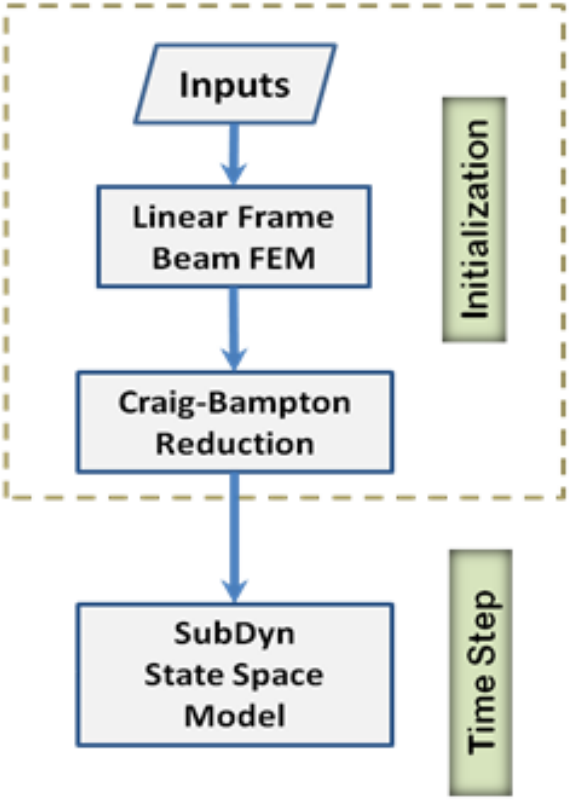
Hydrodynamics & Offshore Features

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

MAP++

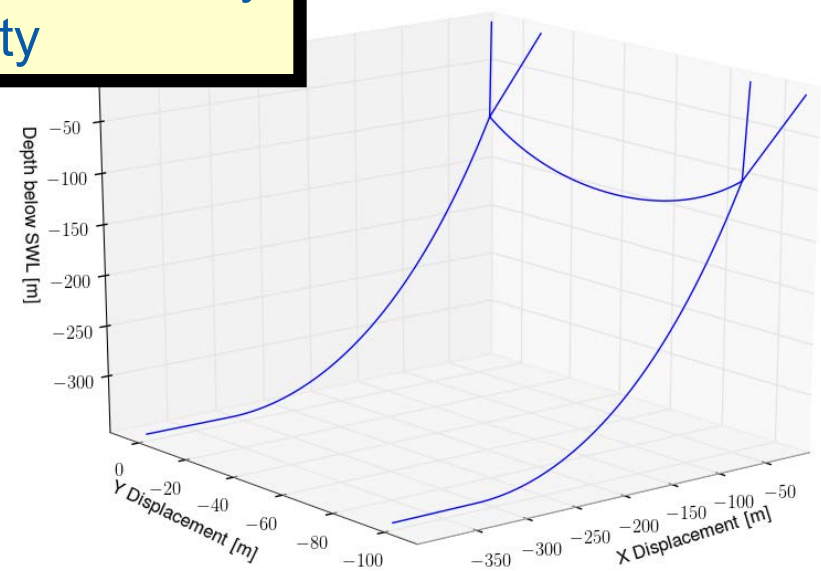
Inputs:
- Platform disp.

Constraint States:
- Line tensions
- Joint locations

Parameters:
- Line properties
- Line connectivity
- Gravity

Outputs:
- Line tensions
- Line disp.

- 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



*Example Multi-Segmented Mooring System Analyzed by **MAP++***

Hydrodynamics & Offshore Features

MoorDyn – Key Features

MoorDyn

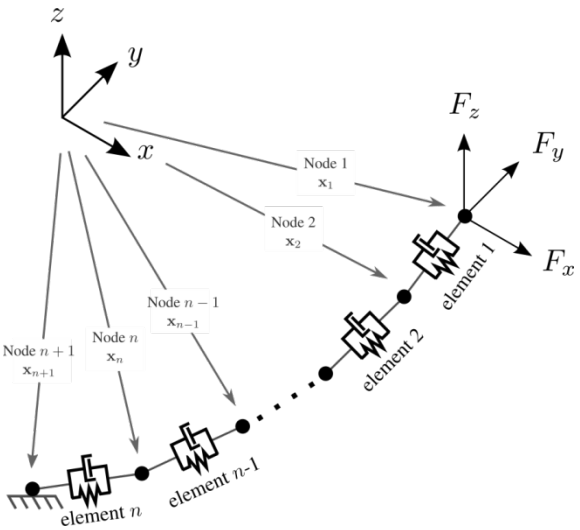
Inputs:
- Platform disp.

Continuous States:
- Displacements
- Velocities

Parameters:
- Line properties
- Line connectivity
- Gravity

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

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Transition to OpenFAST

NAWEA 2017 Symposium

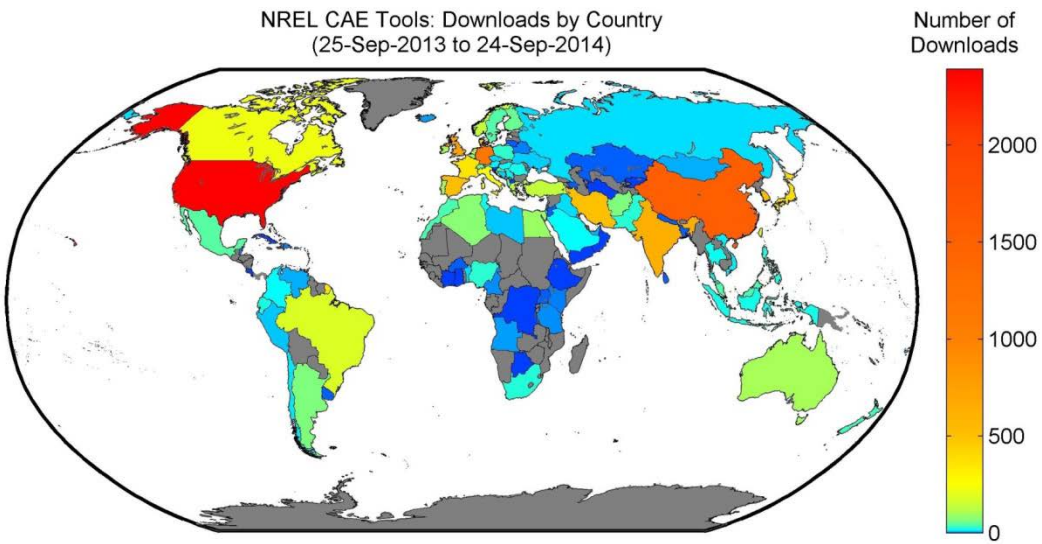
September 26, 2017
Ames, IA (USA)

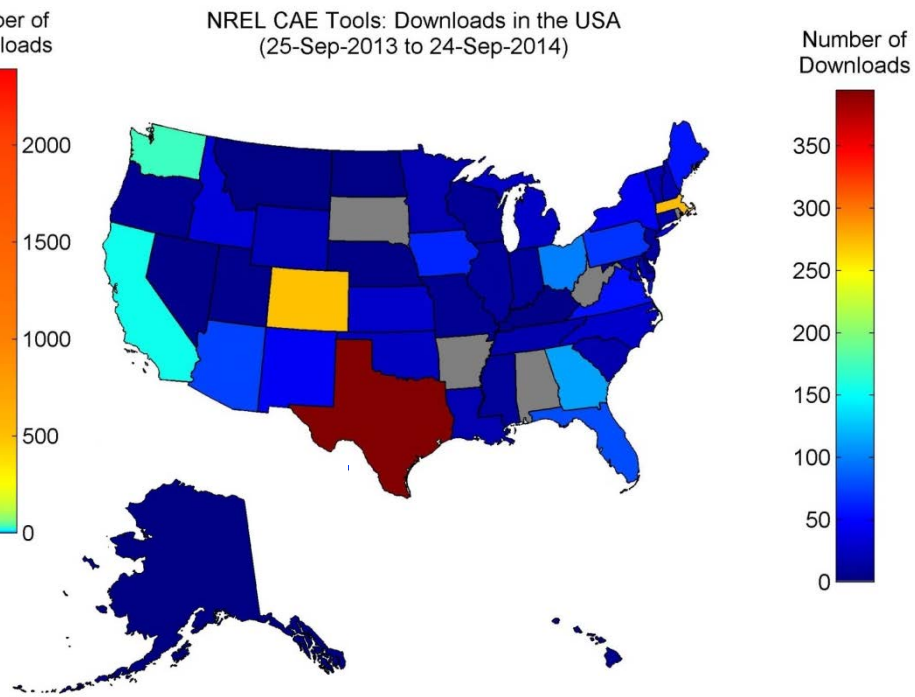
Jason Jonkman, Ph.D.
Senior Engineer, NREL

Transition to OpenFAST

Users of DOE/NREL-Developed Tools

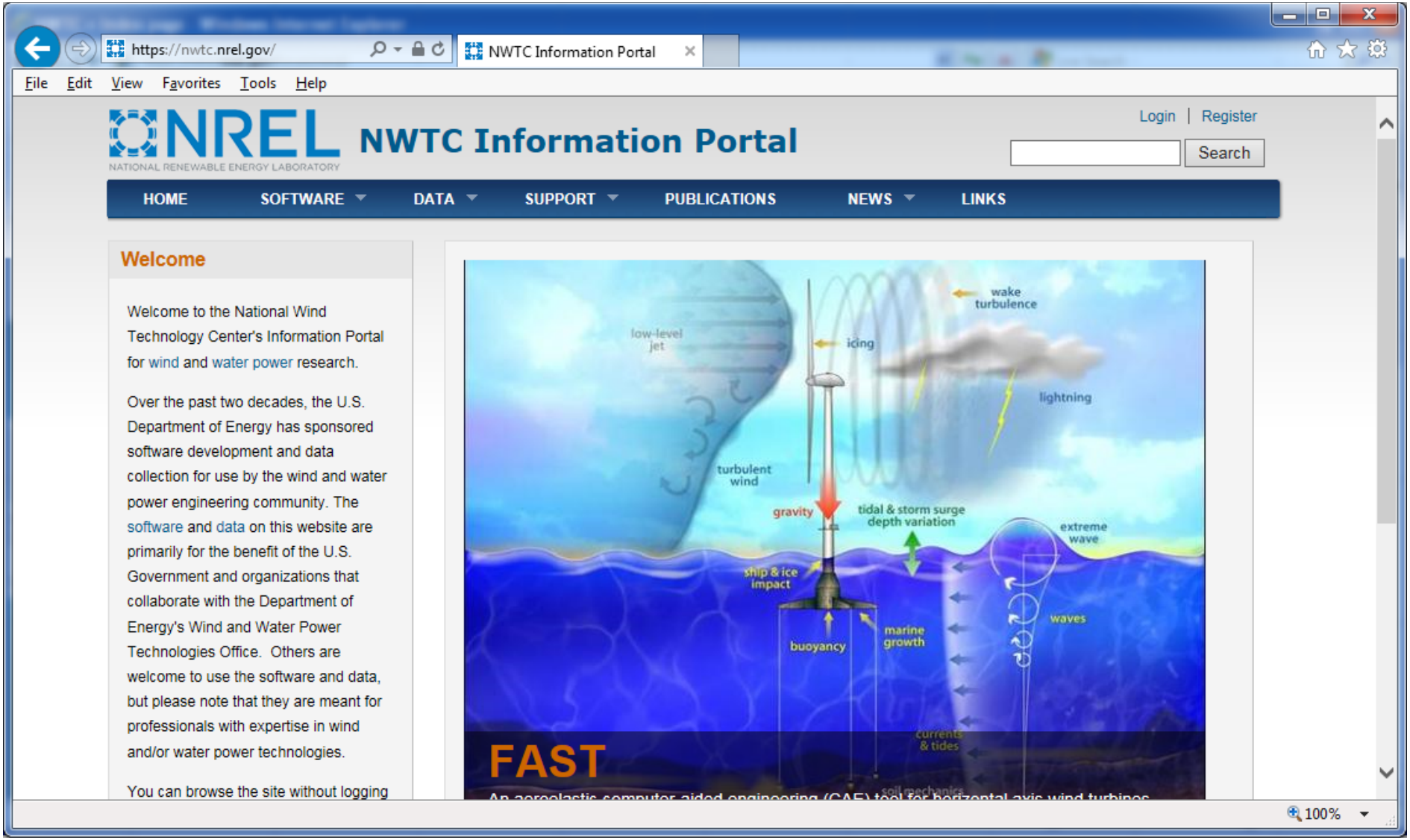
- Used worldwide by designers/manufacturers, consultants, certifiers, researchers, educators, & students:
  - Annually, there are over 10,000 unique downloads by over 4,000 users from 2,000 organizations in 100 countries
- Transitioning from an NREL-centric development to a development community





Transition to OpenFAST

NWTC Information Portal



Transition to OpenFAST

NWTC Forum

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NWTC

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FAQ Members Logout [Jason.Jonkman]

It is currently Thu Jun 04, 2015 4:10 pm

[Moderator Control Panel]

Last visit was: Thu Jun 04, 2015 2:13 pm

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INFORMATION AND ANNOUNCEMENTS	TOPICS	POSTS	LAST POST
Forum Access Requests (READ THIS FIRST BEFORE CREATING AN ACCOUNT) Information on accessing our forums. **Moderator:** Bonnie.Jonkman	2	8	by Bonnie.Jonkman Tue Sep 23, 2014 10:42 am
Answers to Frequently Asked Questions (FAQ) - Read this first before posting Answers to some of the most frequently asked questions can be found here. **Moderator:** Bonnie.Jonkman	1	1	by Marshall.Buhl Tue Jul 02, 2013 9:03 am
News and Announcements Announcements of new or updated CAE and systems engineering software tools, upcoming and past modeling workshops, and other news. **Moderators:** Bonnie.Jonkman, Jason.Jonkman, Katherine.Dykes	3	31	by Bonnie.Jonkman Thu Apr 02, 2015 11:11 am

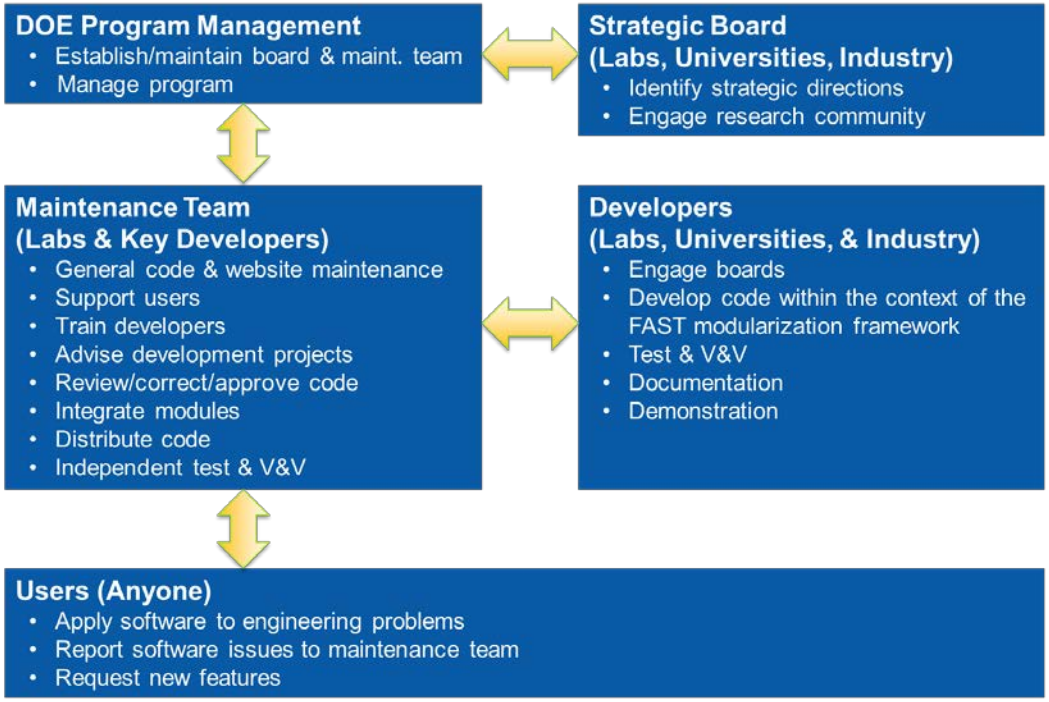
WIND EXTERNAL	TOPICS	POSTS	LAST POST
Computer-Aided Engineering Software Tools Provide feedback, request enhancements, and get help with wind-turbine computer-aided	710	3665	by Jason.Jonkman Thu Jun 04, 2015 2:12 pm

100%

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

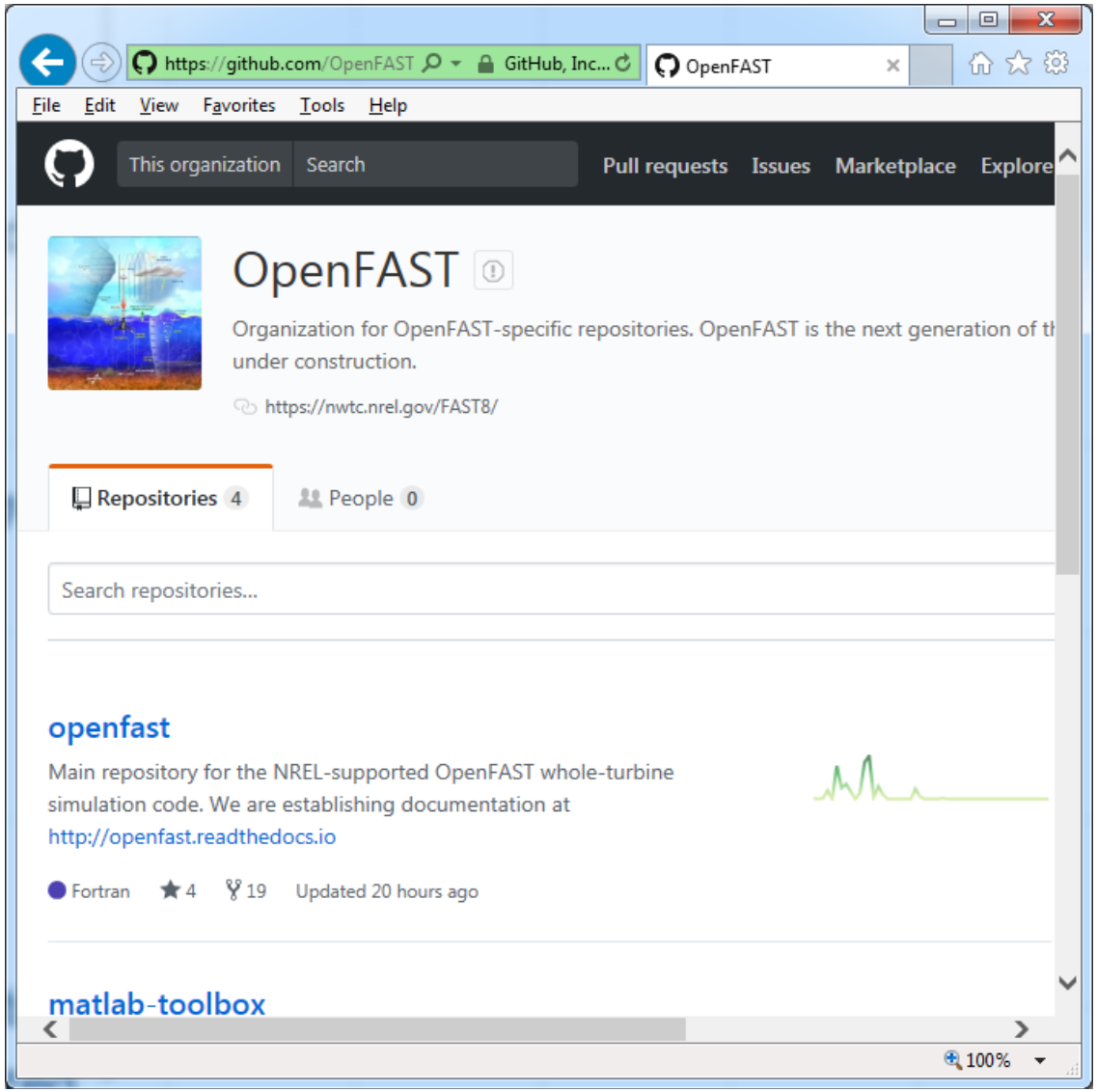


*Vision for a **FAST** Development Community*

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



NATIONAL RENEWABLE ENERGY LABORATORY

Outlook

NAWEA 2017 Symposium

September 26, 2017

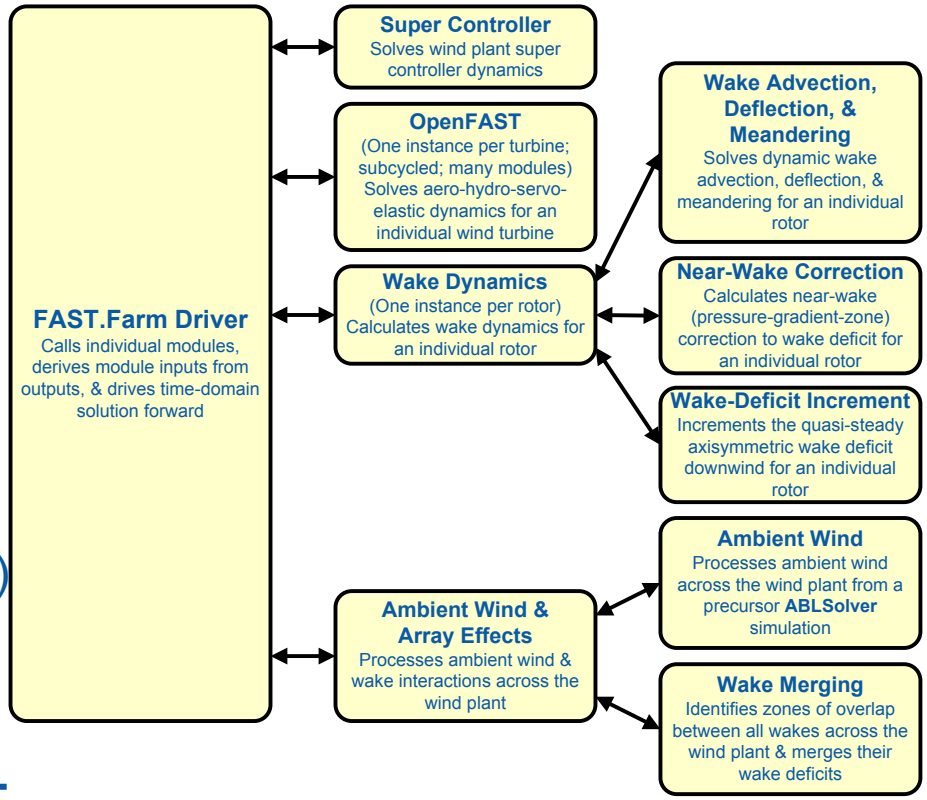
Ames, IA (USA)

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



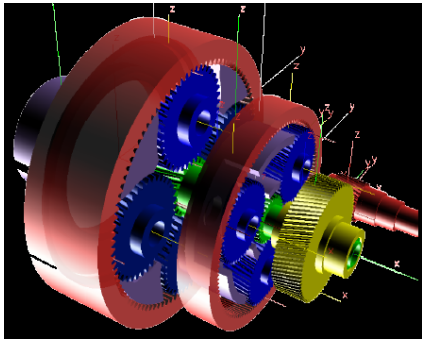
FAST.Farm *Submodel Hierarchy*

Outlook

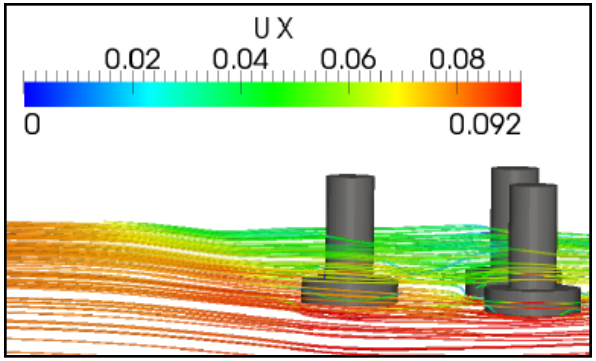
Future Needs

- 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

NASA-Ames Test of UAE



***SIMPACK** Gearbox*



***OpenFOAM** CFD*

Outlook

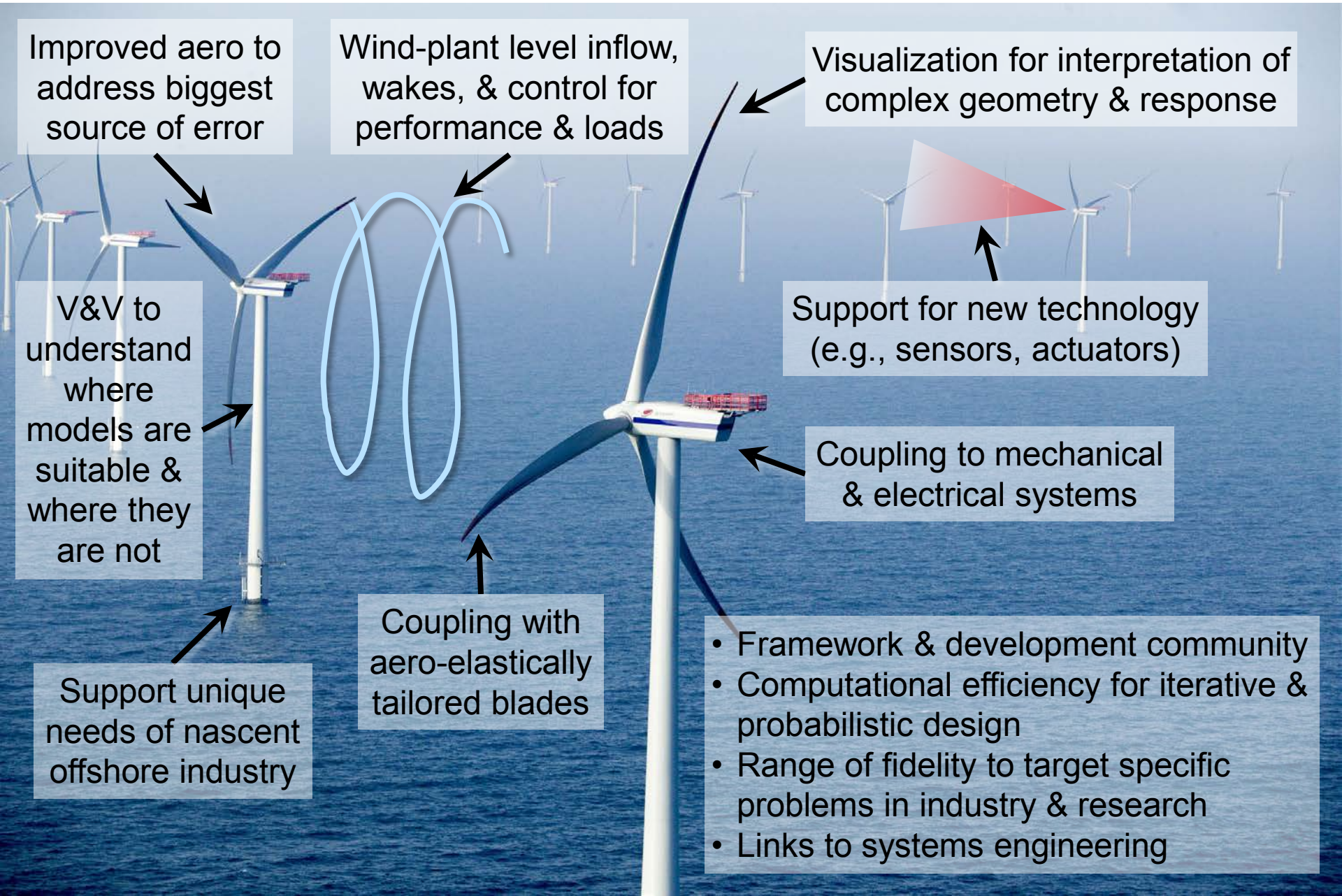
Conclusions

- 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

SWT-6.0-154 with Airbus A380

Horns Rev Wind Farm

Outlook – Vision for Future Engineering Models



Outlook

A Final Thought – Quoting George E. P. Box

"Essentially, all models are wrong, but some are useful."

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More information @: https://nwtc.nrel.gov

Carpe Ventum!

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