NREL
Transforming ENERGY

WETO Software Stack User Workshops
OpenFAST ecosystem

June 20, 2024

Rafael Mudafort
Pietro Bortolotti
Garrett Barter
Jason Jonkman
Derek Slaughter
Dan Zalkind

Agenda

Section	Duration	Time	Speaker
Intro	5’	0:00 - 0:05	Rafael Mudafort
WETO Stack Overview	10’	0:05 - 0:15	Rafael Mudafort
Poll on workshop & WETO Stack	**5’**	**0:15 - 0:20**	**You**
OpenFAST	25’	0:20 - 0:45	Jason Jonkman
ACDC	10’	0:45 - 0:55	Derek Slaughter
ROSCO	10’	0:50 - 1:00	Dan Zalkind
Polls / open-ended questions	**2’**	**1:00**	**You**
Community discussion	**30’ - 40’**	**1:05 - 1:40**	**You**
Wrap up	5’	1:50 - end	Rafael Mudafort

Holistic Modeling Project

WETO Software Portfolio Coordination

US DOE & Lab-based Wind Research Projects

WETO invests in wind energy **software** that enables and accelerates the innovations needed to advance wind energy.

NREL's active WETO projects

Study on the Potential Application of Additive Manufacturing in Wind Turbine Components and Tooling
Enabling Larger Rotors Through Modular, Customizable, Inflatable Blades
Eagle Topic Area 3 Funding Opportunity Announcement (FOA) Support
Co-Simulation Study and Control of a Wind Farm for Conversion Services
Continental-Scale Transmission Modeling Methods for Grid Integration Analysis
Atmosphere to Electrons to Grid (A2e2g)
Fusion Joining of Thermoplastic Composites Using Energy Efficient Processes (TCF)
Automating In-Situ Grinding and Repair for Thermoplastic Blades
Codesign and Intelligent Approaches for Cost-Effective Operation and Maintenance of Generators and Power Converters
Modeling and Validation for Offshore Wind
Wind Power as Virtual Synchronous Generation (WindVSG)
Technology Development and Innovation to Address Operational Challenges
Evaluating Deterrent Stimuli for Increasing Species-Specific Effectiveness of an Advanced Ultrasonic Acoustic Deterrent
North American Renewable Integration Study
High-Fidelity Modeling
Wind Turbine Drivetrain Reliability Assessment and Remaining Useful Life Prediction (TCF)
Enabling Autonomous Wind Plants through Consensus Control (TCF)
North American Energy Resiliency Model (NAERM)
Big Adaptive Rotor
Energy Sector Modeling and Impacts Analysis
Floating Downwind Turbines: A Conceptual System-Level Design and Feasibility Study for U.S. Waters
Wind Standards Development
Multiscale Integration of Control Systems (EMS/DMS/BMS)
Advanced Modeling, Dynamic Stability Analysis, and Mitigation of Control Interactions in Wind Power Plants
Wind Grid Integration Stakeholder Engagement
Atmosphere to Electrons (A2e) Performance Risk, Uncertainty and Finance (PRUF) Analysis Support
Working Together to Resolve Environmental Effects of Wind Energy (WREN)
High-Fidelity Modeling Toolkit for Wind Farm Development

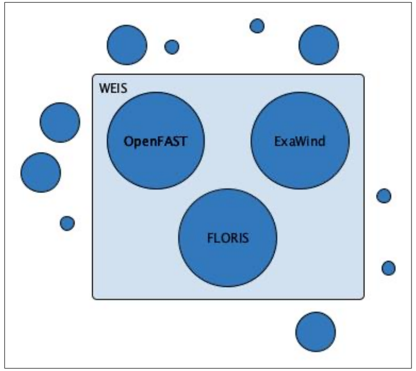
Argonne National Laboratory | Berkeley Lab, Lawrence Berkeley National Laboratory | Lawrence Livermore National Laboratory | NREL National Renewable Energy Laboratory | Pacific Northwest National Laboratory | Sandia National Laboratories

https://www.energy.gov/eere/wind/wind-energy-technologies-office-projects-map

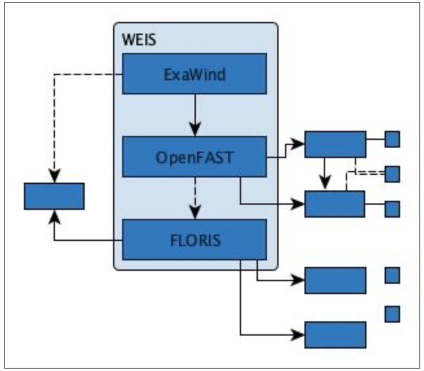
Holistic Modeling Project

Objective

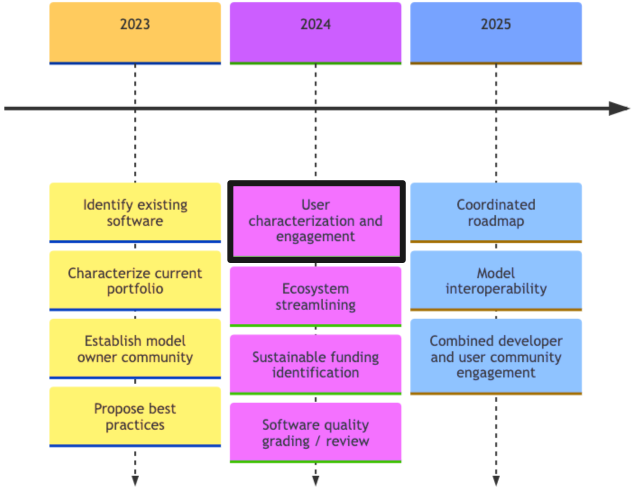
Past: Loose collection of software



Future: Cohesive software stack



Project Timeline



WETO Software Stack

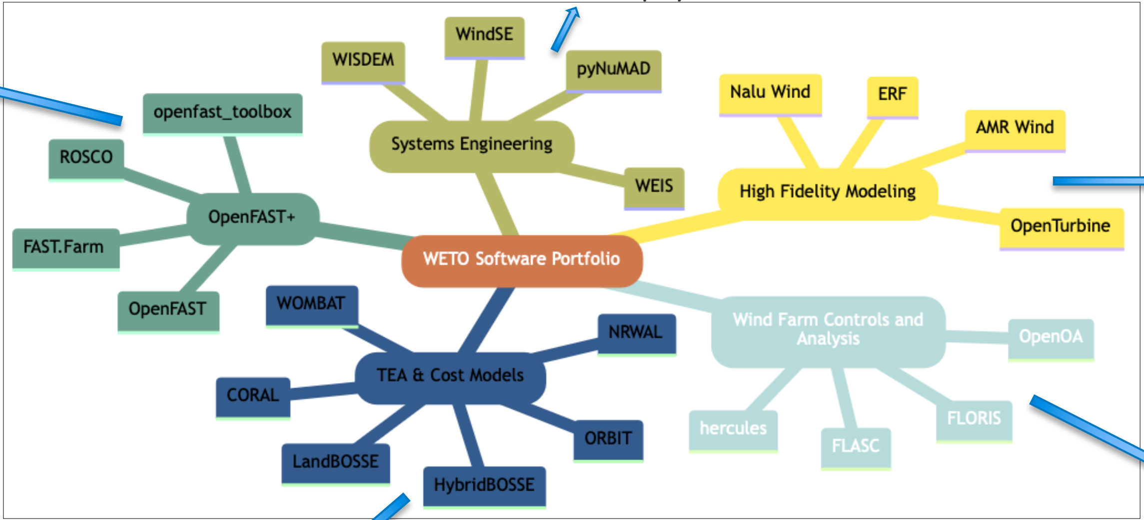
Overview

WETO Software Stack

Grouped by how its used

System-level optimizations with multi-physics and multi-fidelities

Wind turbine and wind farm mid-fidelity physics



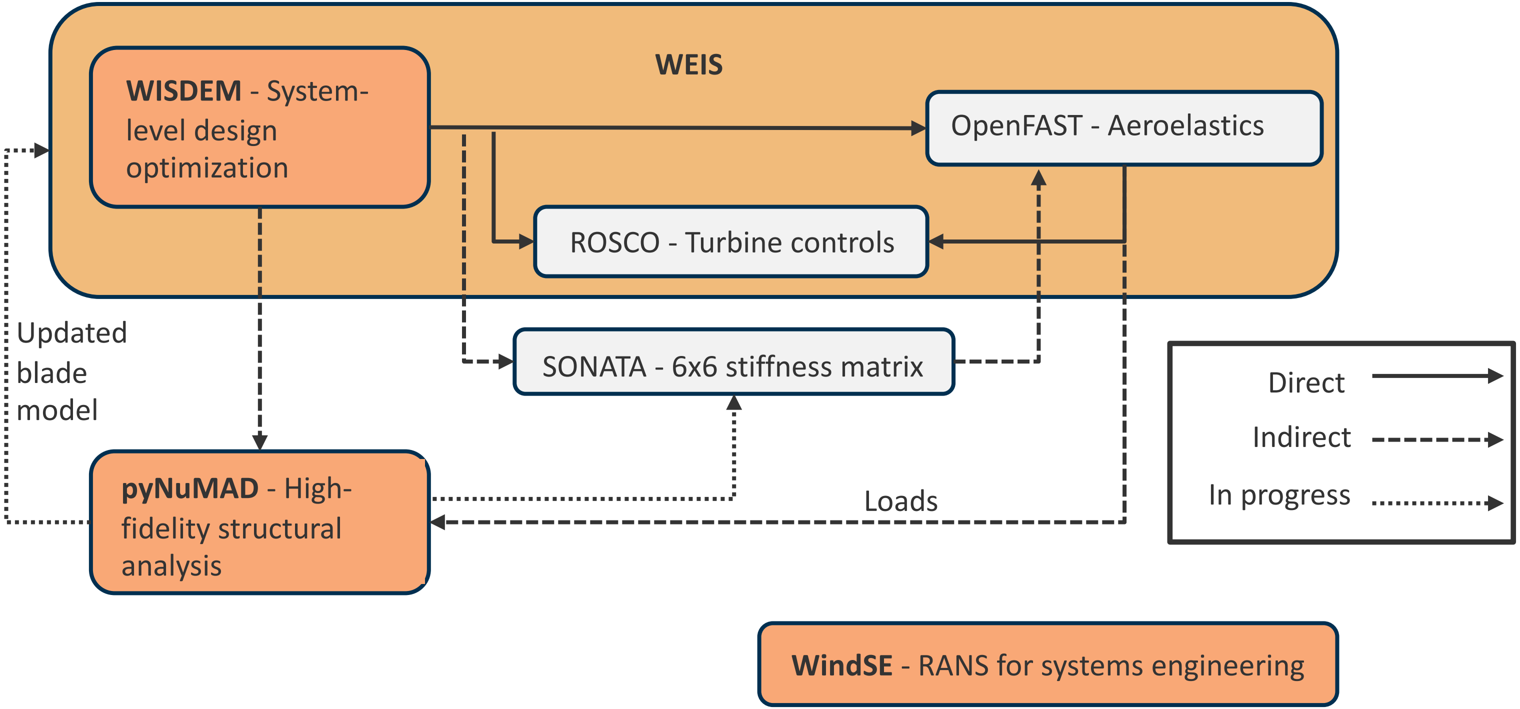
Detailed aerodynamics and structural dynamics

Wind turbine and wind plant costs for installation and operation, cost forecasting

Wind farm energy production, energy loss identification, and loss reduction through farm-level controls

Systems Engineering

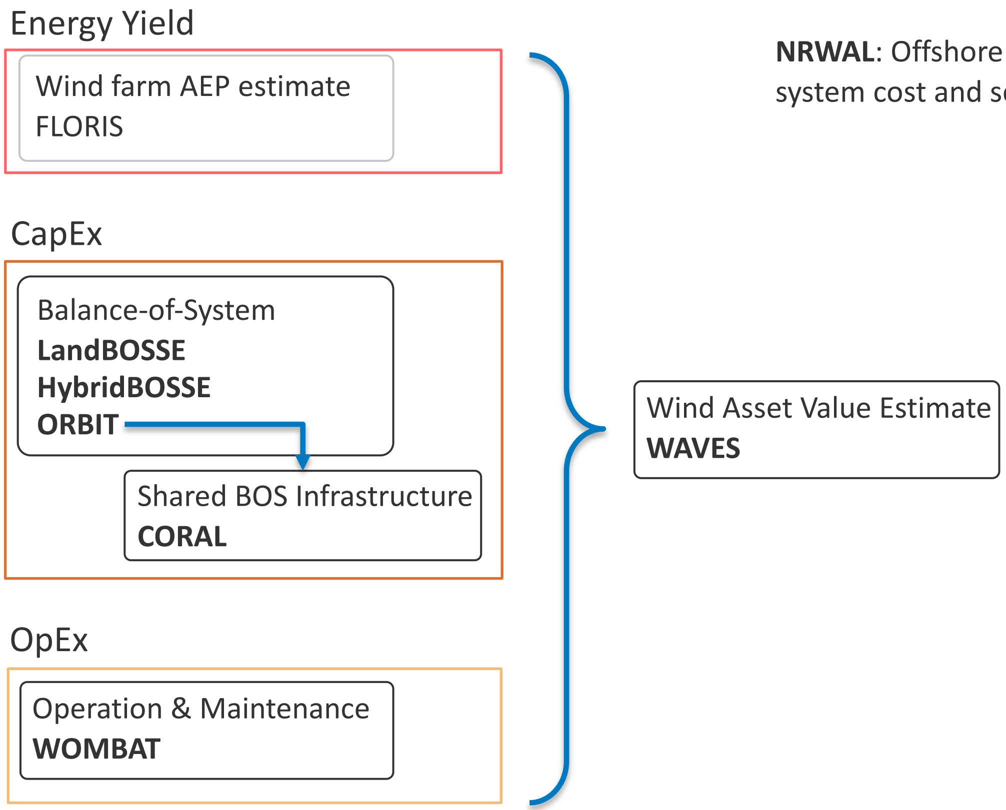
Workshop: June 10



Adapted from Big Adaptive Rotor (BAR) project

Technoeconomic Analysis / Cost Modeling

Workshop: June 12

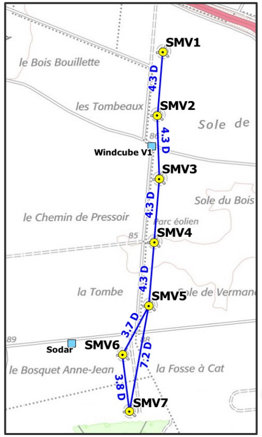


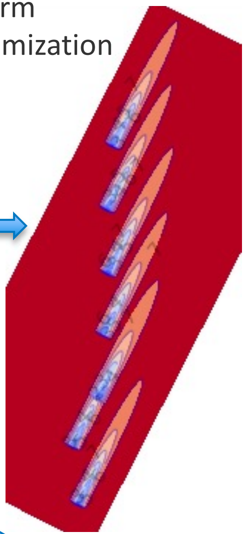
NRWAL: Offshore wind system cost and scaling model

Wind Farm Controls and Analysis

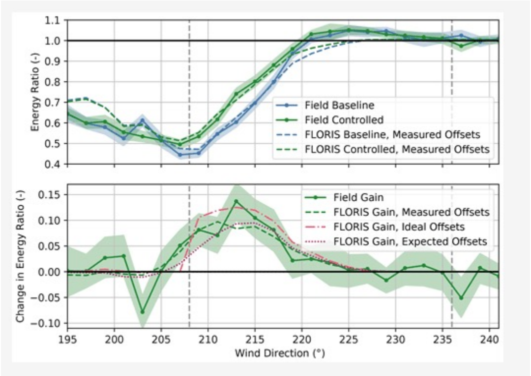
Workshop: June 18

FLORIS: Steady-state modeling, farm controls optimization

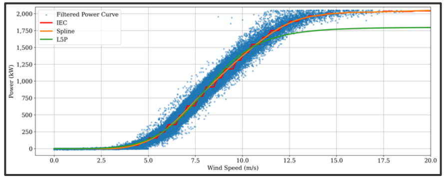




FLASC: Validate FLORIS model with SCADA, compare control methods



Hercules: Realtime high-fidelity simulator for hybrid power plants with a specific focus on wind farm controls.

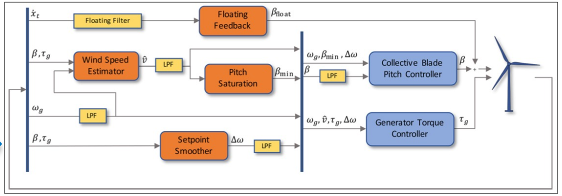


OpenOA: Characterize plant performance and quantify sources of operational loss

OpenFAST+

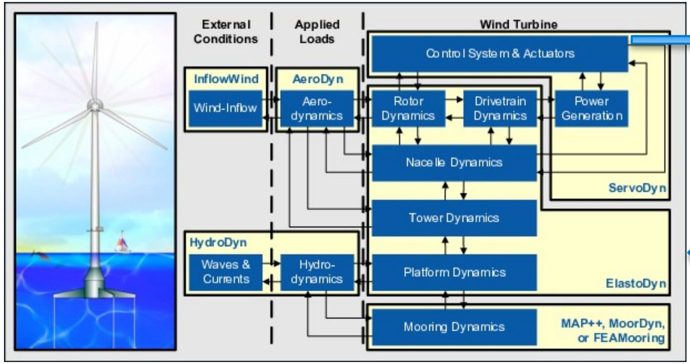
Workshop: June 20

ROSCO



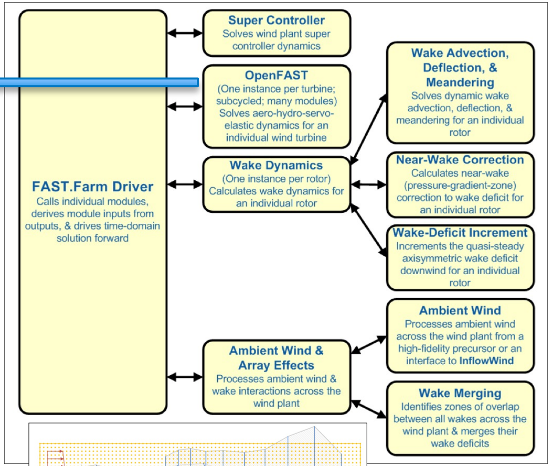
N. J. Abbas et al.: A reference controller for wind turbines

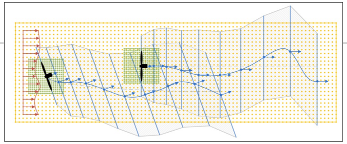
OpenFAST



OpenFAST v3.5.3 documentation

FAST.Farm





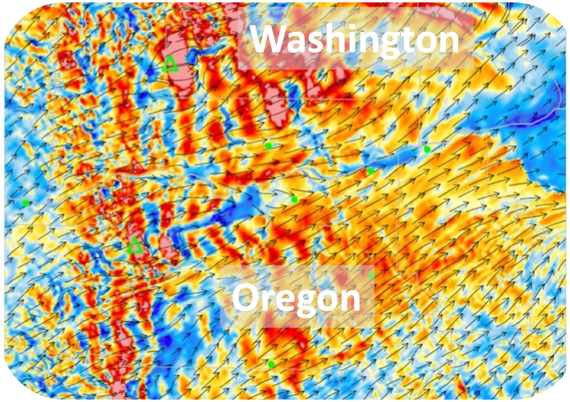
FAST.Farm User's Guide and Theory Manual

openfast_toolbox

High Fidelity Models

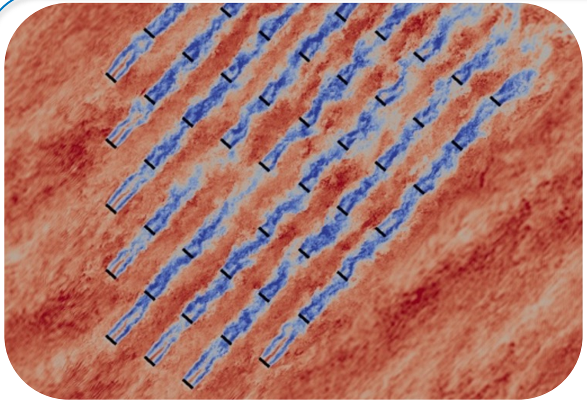
Workshop: TBD

ExaWind



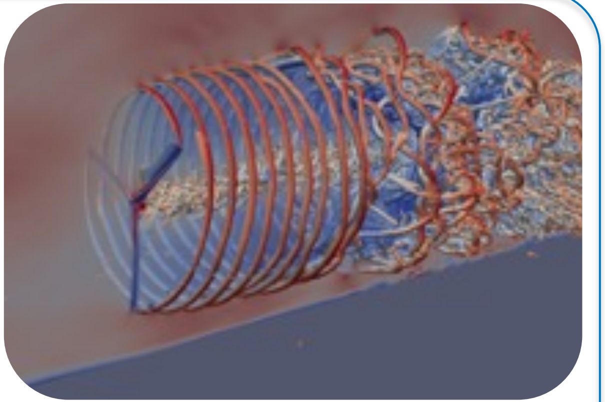
Mesoscale: ERF

- Regional scale weather
- **Scales 10 km to 1000 km**
- WRF numerics & models, built on AMReX
- GPU compatible
- Compressible



Microscale: AMR-Wind

- Atmospheric boundary layer
- **Scales less than 10 km**
- Large Eddy Simulation built on AMReX
- GPU compatible
- Structured grid with refinement zones
- Incompressible



Turbine scale: NALU-Wind

- Turbine, rotor, tower, nacelle
- **Scales less than 1 km**
- Unsteady Reynolds Averaged Navier Stokes
- GPU compatible
- Unstructured grid, geometry resolving
- Incompressible

WETO Software Stack

Polls

OpenFAST Toolchain

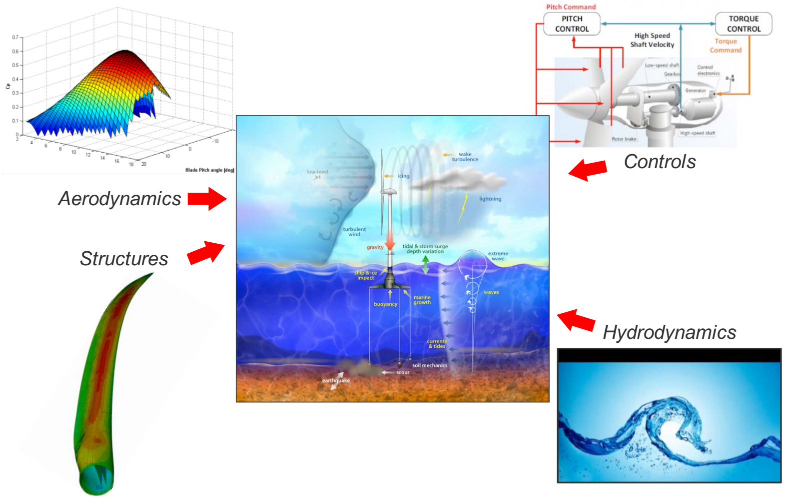
Jason Jonkman

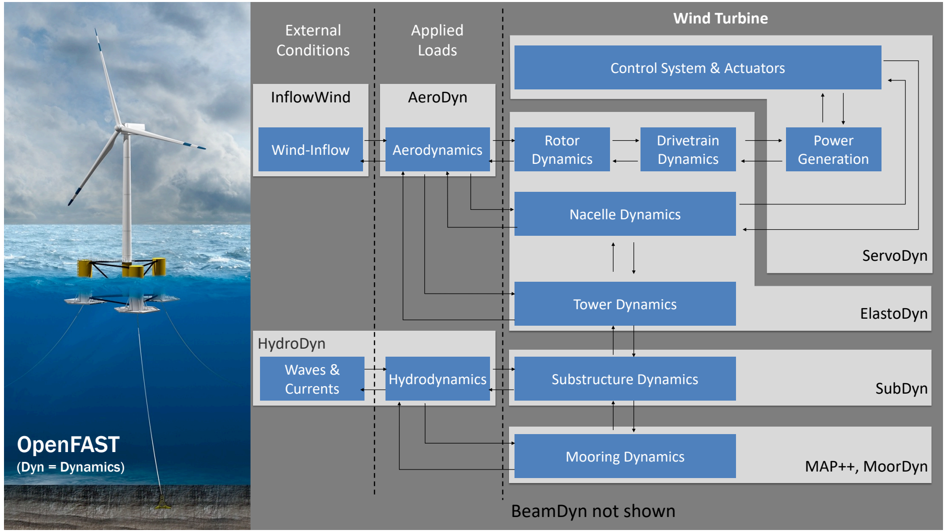
OpenFAST Overview

OpenFAST provides state-of-the-art coupled aero-hydro-servo-elastic simulation of individual land-based, fixed-bottom offshore, and floating offshore wind turbines with the ability to:

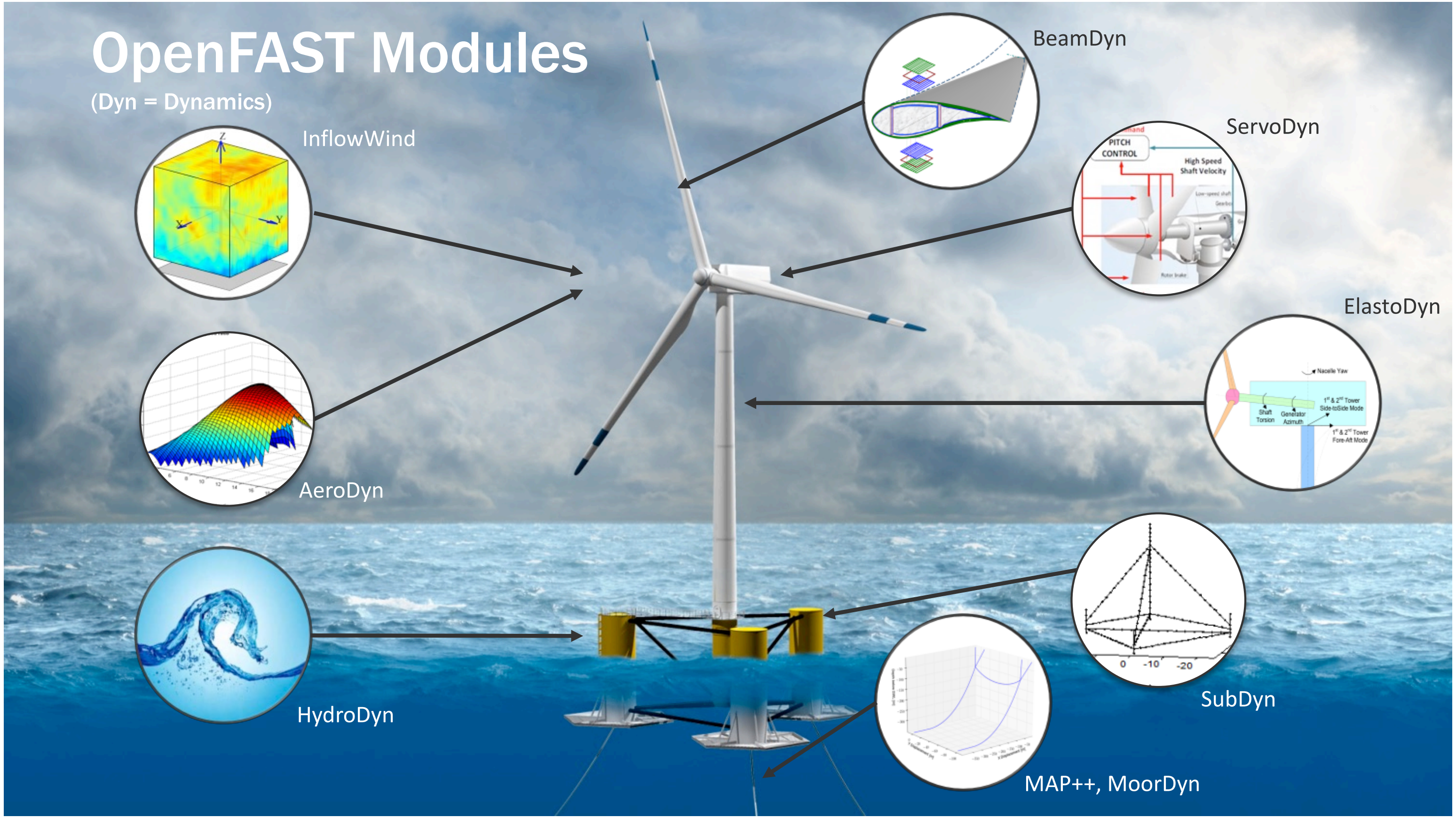
- Run large numbers of nonlinear time-domain simulations in real time to enable standards-based loads analysis for predicting wind system ultimate and fatigue loads
- Linearize the underlying nonlinear model about an operating point to understand the wind system response and enable modal analysis; controls design; and aero-elastic instability studies

OpenFAST Couples the Physics of Fluids, Structures, and Controls



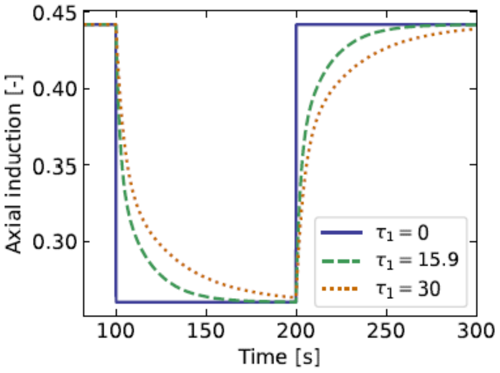


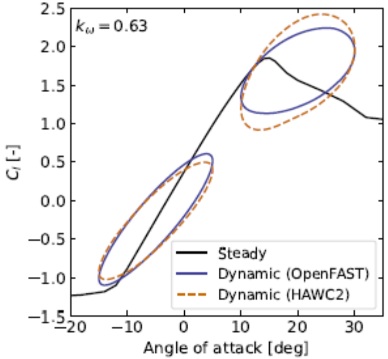
OpenFAST Modular Coupling



Recent/Ongoing OpenFAST Developments – Aero.

Linearization of Dynamic Wake and Unsteady Airfoil Aerodynamics for Aero-Elastic Stability Analysis

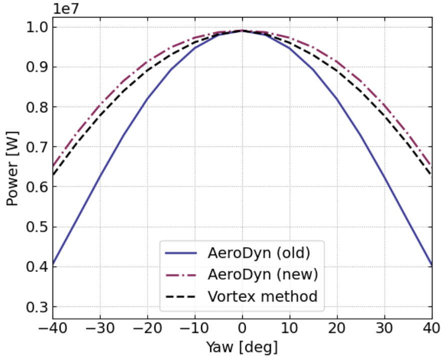


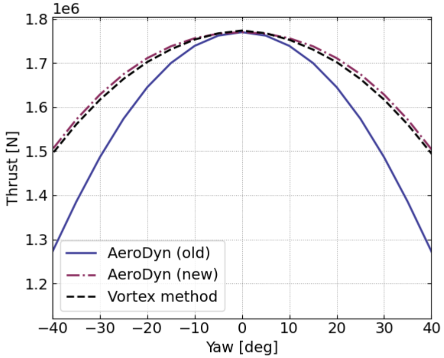


$$\dot{x} = X(x,u,t)$$
$$y = Y(x,u,t)$$

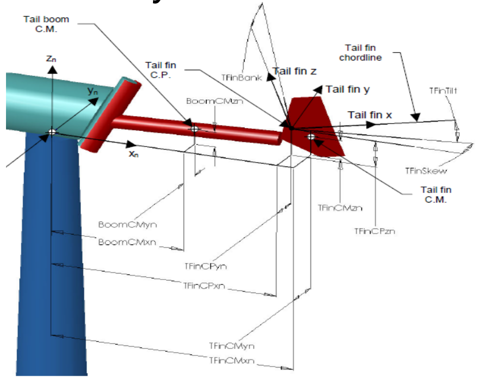
$$\Delta\dot{x} = A\Delta x + B\Delta u$$
$$\Delta y = C\Delta x + D\Delta u$$

Improved BEM for Skewed and Sheared Inflow



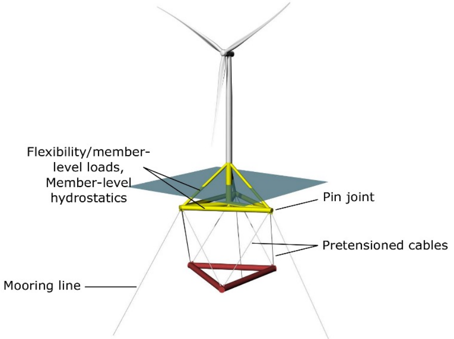


Tail-Fin Aerodynamics for Small Wind

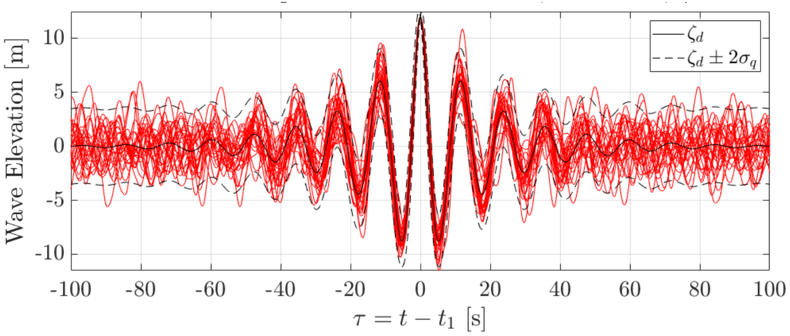


Recent/Ongoing OpenFAST Developments – Hydro.

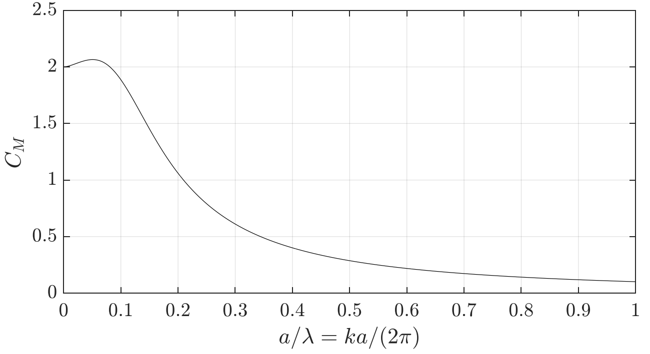
Substructure Flexibility and Member-Level Loads



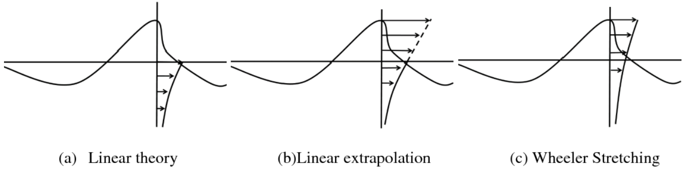
Constrained New Waves



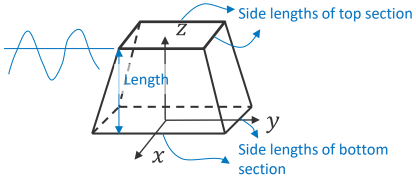
MacCamy-Fuchs Diffraction for Strip-Theory Members



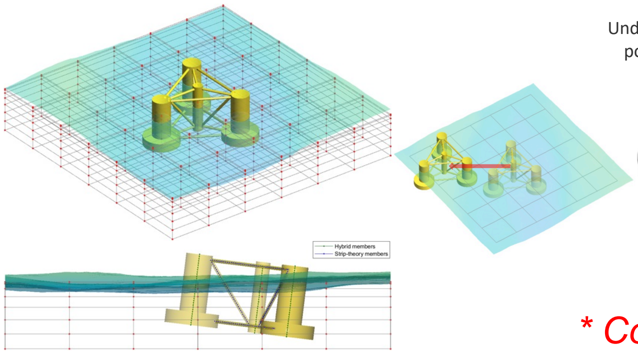
Wave Stretching with Load Smoothing

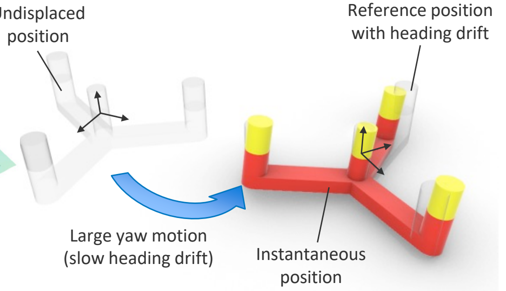


*Strip-Theory Members With Rectangular Cross Sections**



*Wave Loads at Displaced Position and Large Yaw**

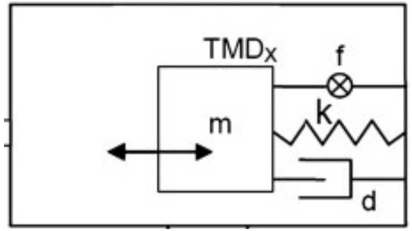


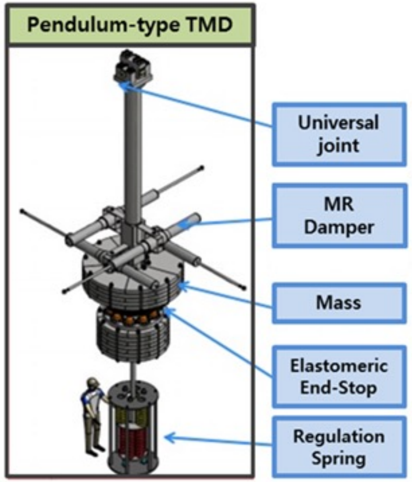


* Coming soon

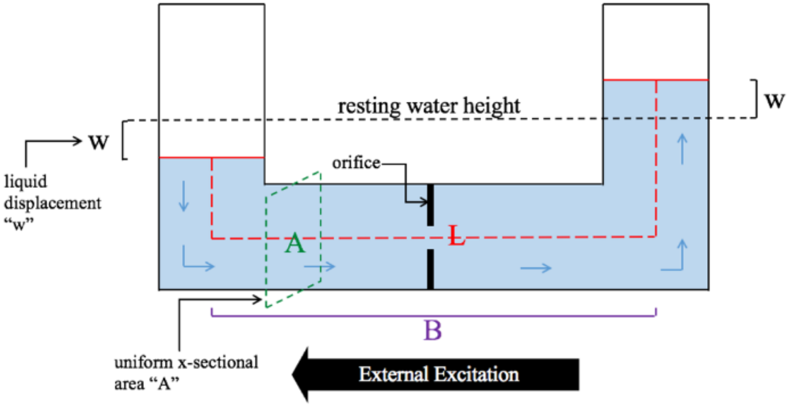
Recent/Ongoing OpenFAST Developments – Servo.

Tuned Mass Dampers (TMDs)

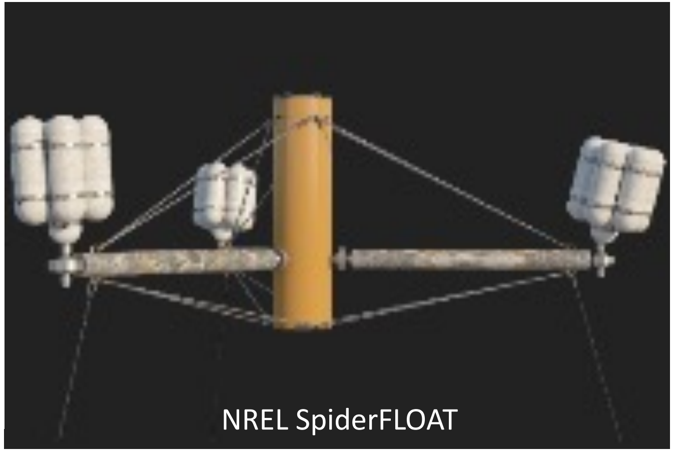




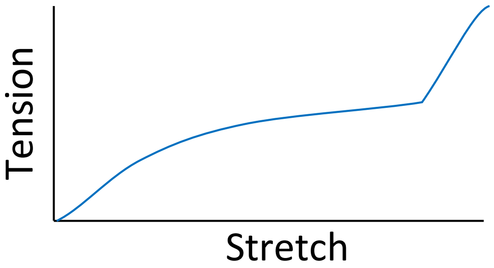
Tuned Liquid Column Dampers (TLCDs)



Buoyancy Cans



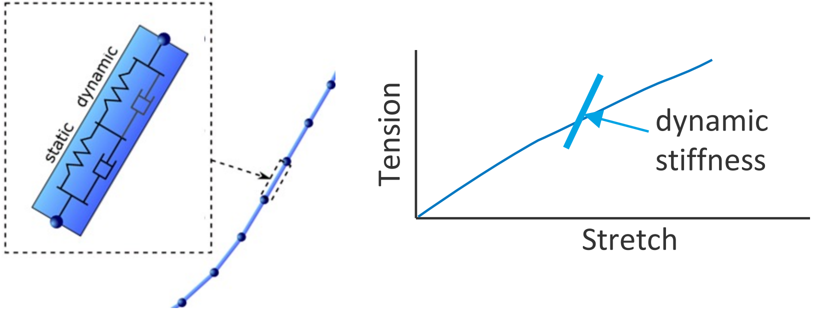
Nonlinear Stiffness Elements



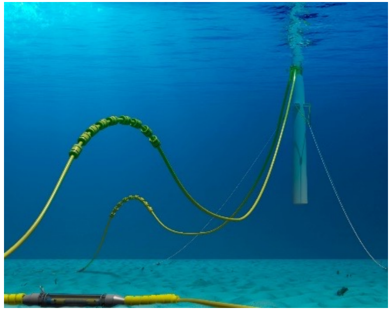
Active Cable Tensioners

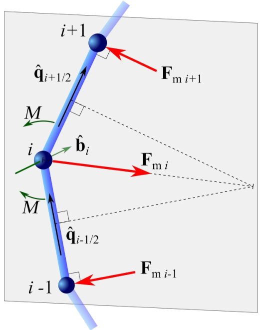
Recent/Ongoing OpenFAST Developments – Mooring

Synthetic Rope Viscoelastics

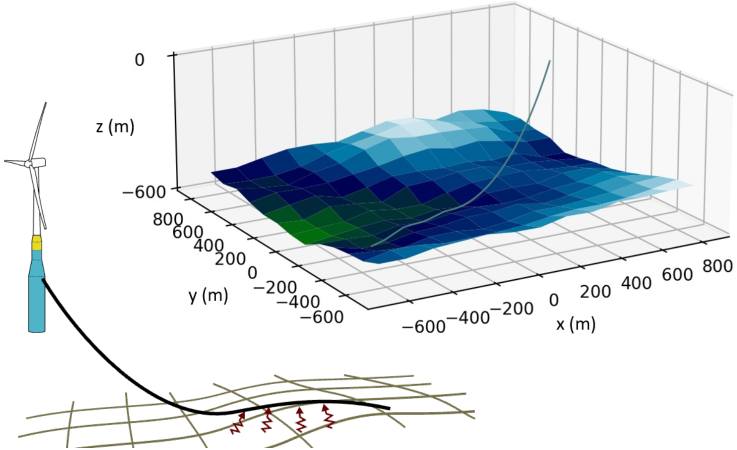


Bending Stiffness for Dynamic Power Cables

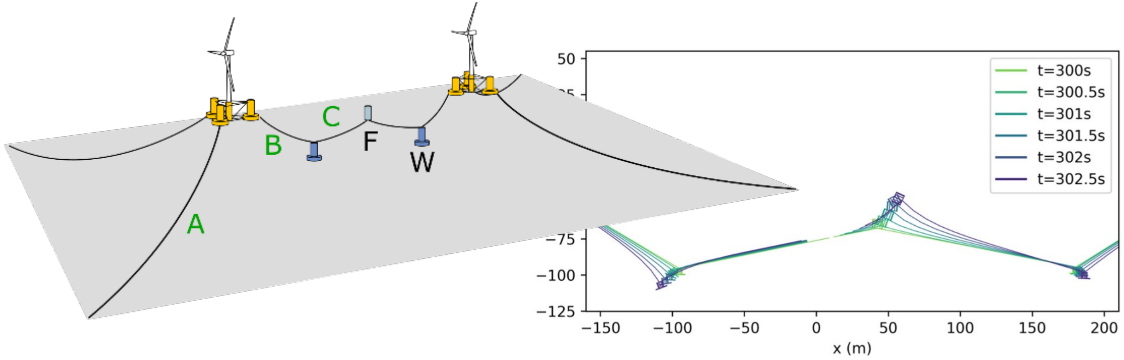




Seabed Bathymetry and Friction



*Mooring Line Failure**

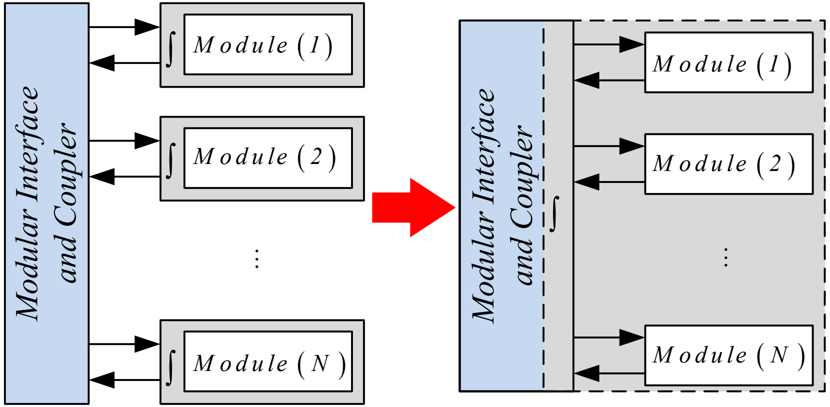


** Coming soon*

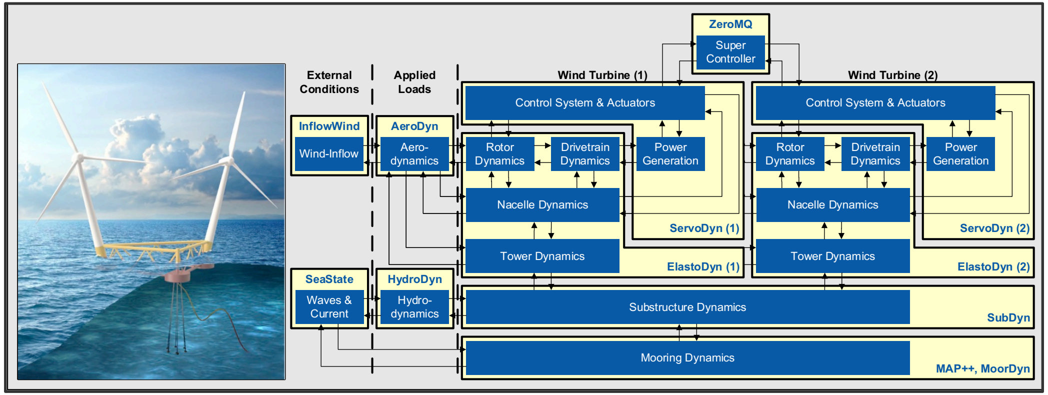
Recent/Ongoing OpenFAST Developments – Coupling

New Tight Coupling Algorithm for Improved Computational Performance (10x-100x Speed Up)*

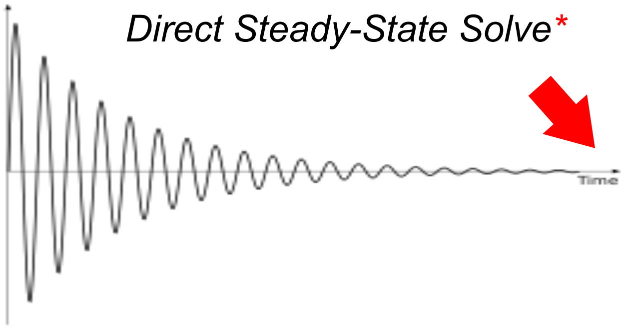
** Coming soon*



*Support for Multiple Turbines on the Same Support Structure**



*Direct Steady-State Solve**

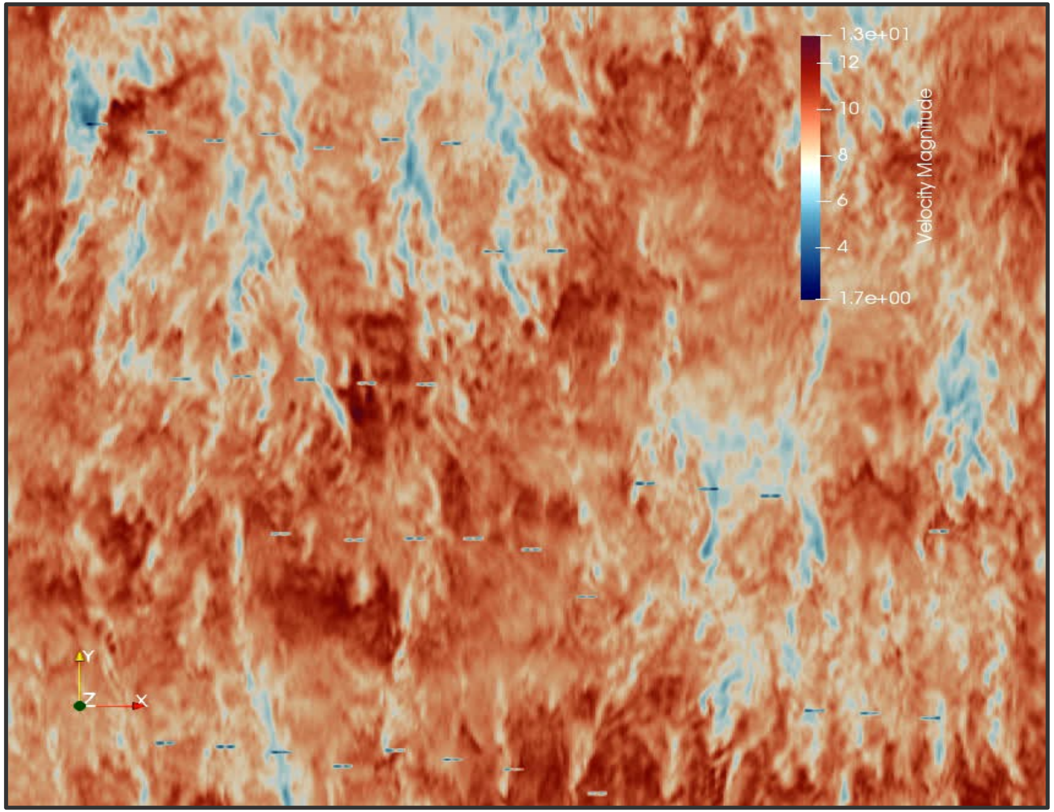


FAST.Farm Overview

FAST.Farm extends the capabilities of OpenFAST to provide physics-based engineering simulation of multi-turbine land-based, fixed-bottom offshore, and floating offshore wind farms with the ability to:

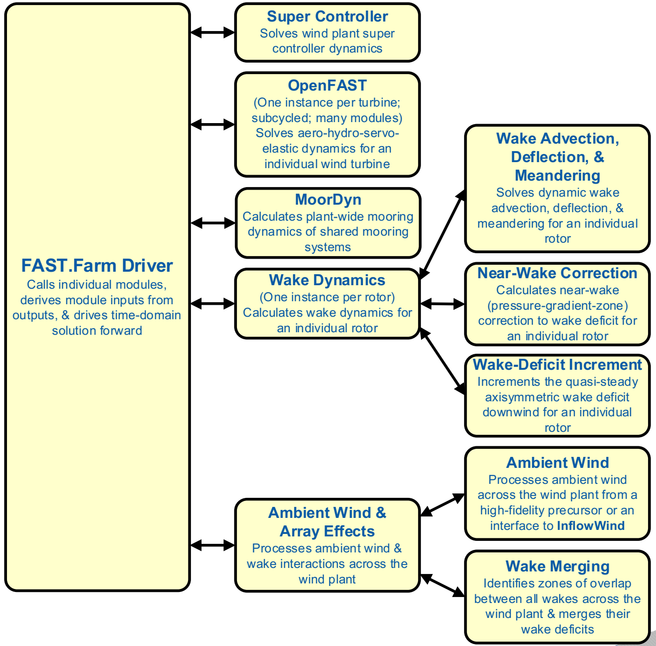
- Simulate each wind turbine in the farm with an OpenFAST model
- Capture relevant physics for prediction of wind farm power performance and structural loads, including wind farm-wide ambient wind, super controller, and wake advection, meandering, and merging
- Maintain computational efficiency through parallelization to enable loads analysis for predicting the ultimate and fatigue loads of each wind turbine in the farm

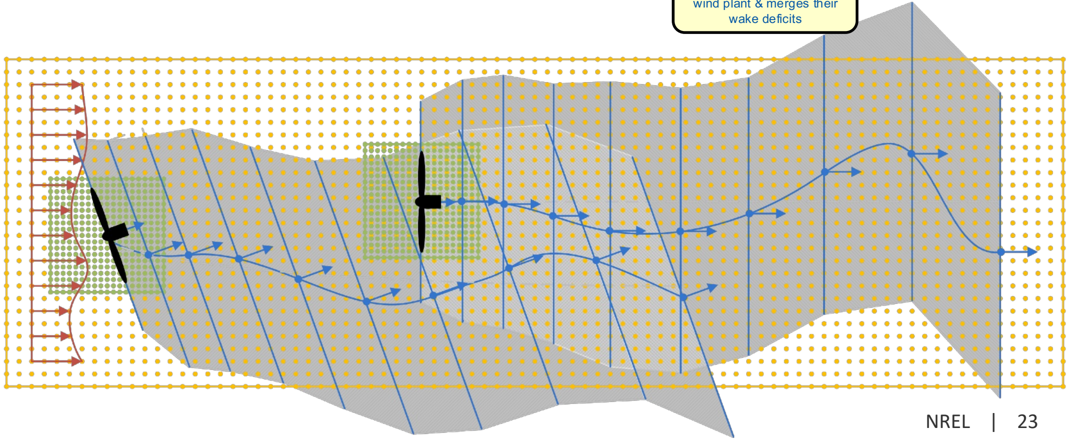
36 Turbine FAST.Farm Simulation of the King Plains Wind Farm within AWAKEN



FAST.Farm Innovations

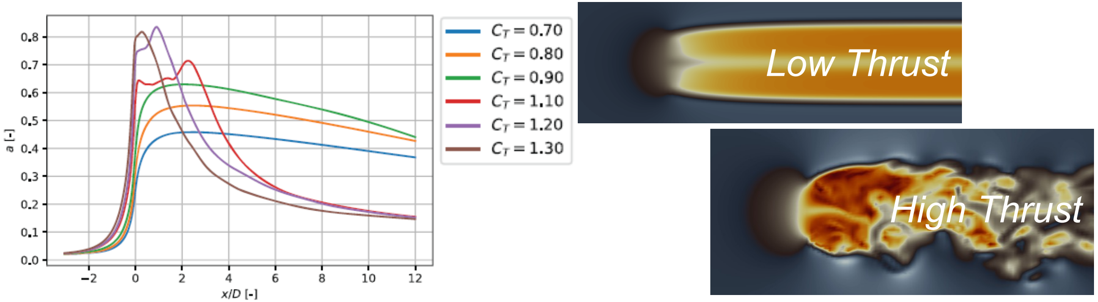
- Modular, following requirements of OpenFAST modularization framework
- Use of LES-generated or synthetic precursor for ambient wind
- Improvement of wake advection, deflection, and merging compared to past DWM-implementation
- Optional inclusion of wind-farm-wide super controller
- Optional inclusion of shared mooring systems
- Ability to solve entire wind farm in serial or parallel
- Calibration of wake-related model parameters against high-fidelity simulations



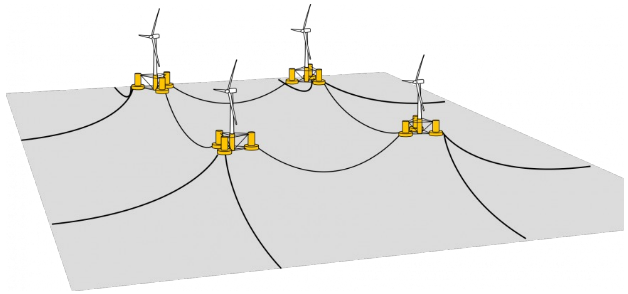


Recent/Ongoing FAST.Farm Developments

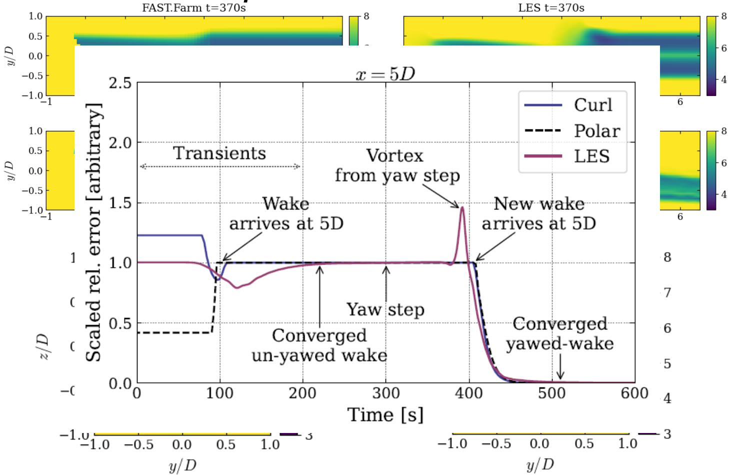
Improved Near-Wake Correction at High Thrust



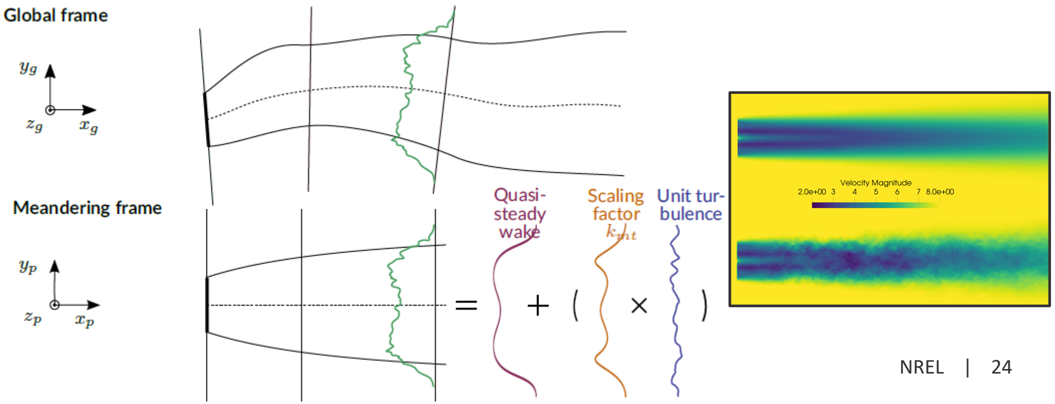
Shared Moorings



Curled Wake Implementation for Wake-Steering

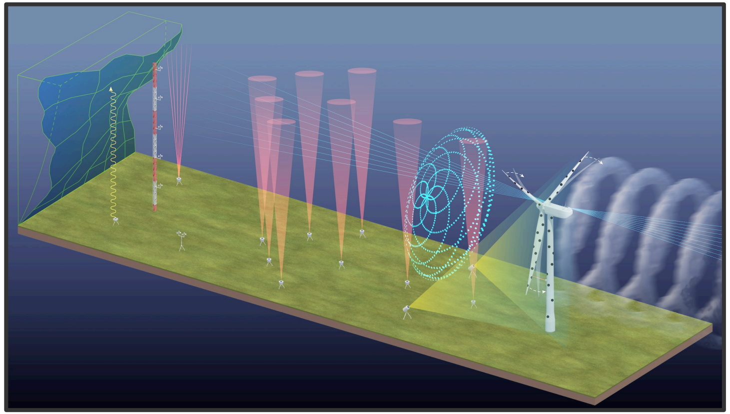


Wake-Added Turbulence, Especially Important at Low TI and Stable Atmospheric Stability

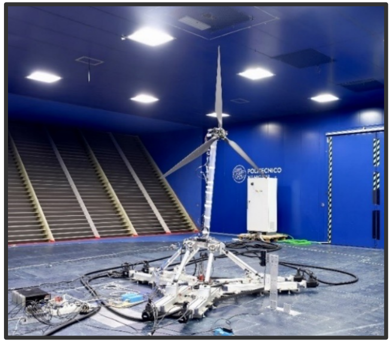


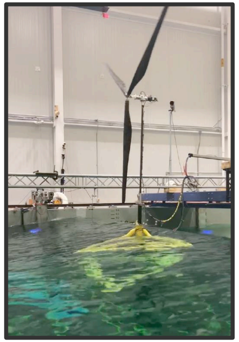
Model Verification and Validation

OpenFAST Versus RAAW Experiment

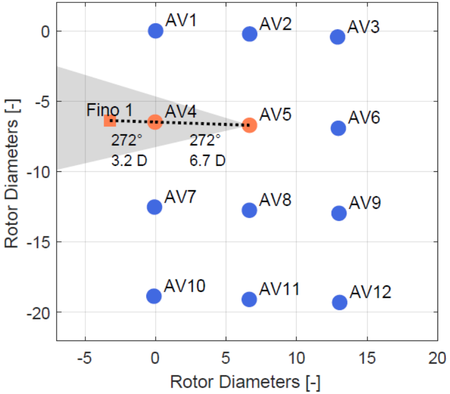


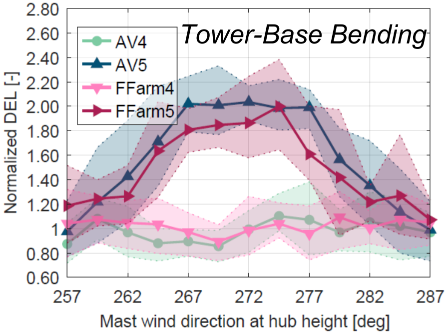
OpenFAST V&V in IEA Wind Task 30 OC6



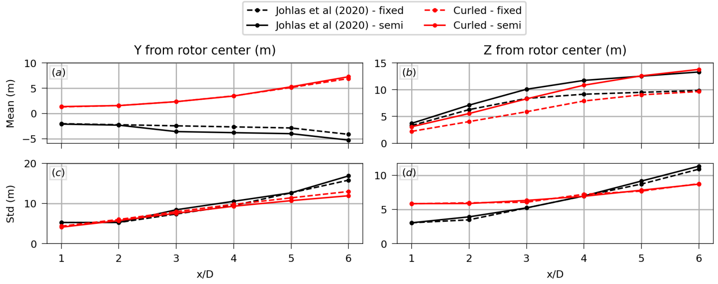


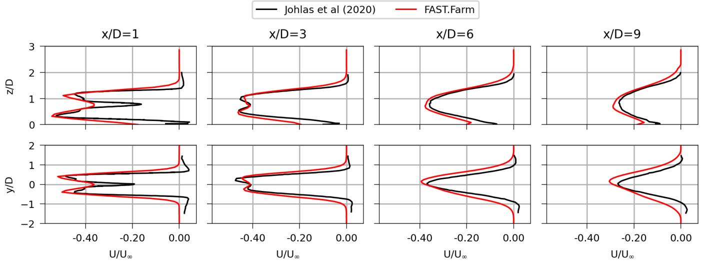
FAST.Farm Versus Data from alpha ventus





FAST.Farm Versus SOWFA for FOWT

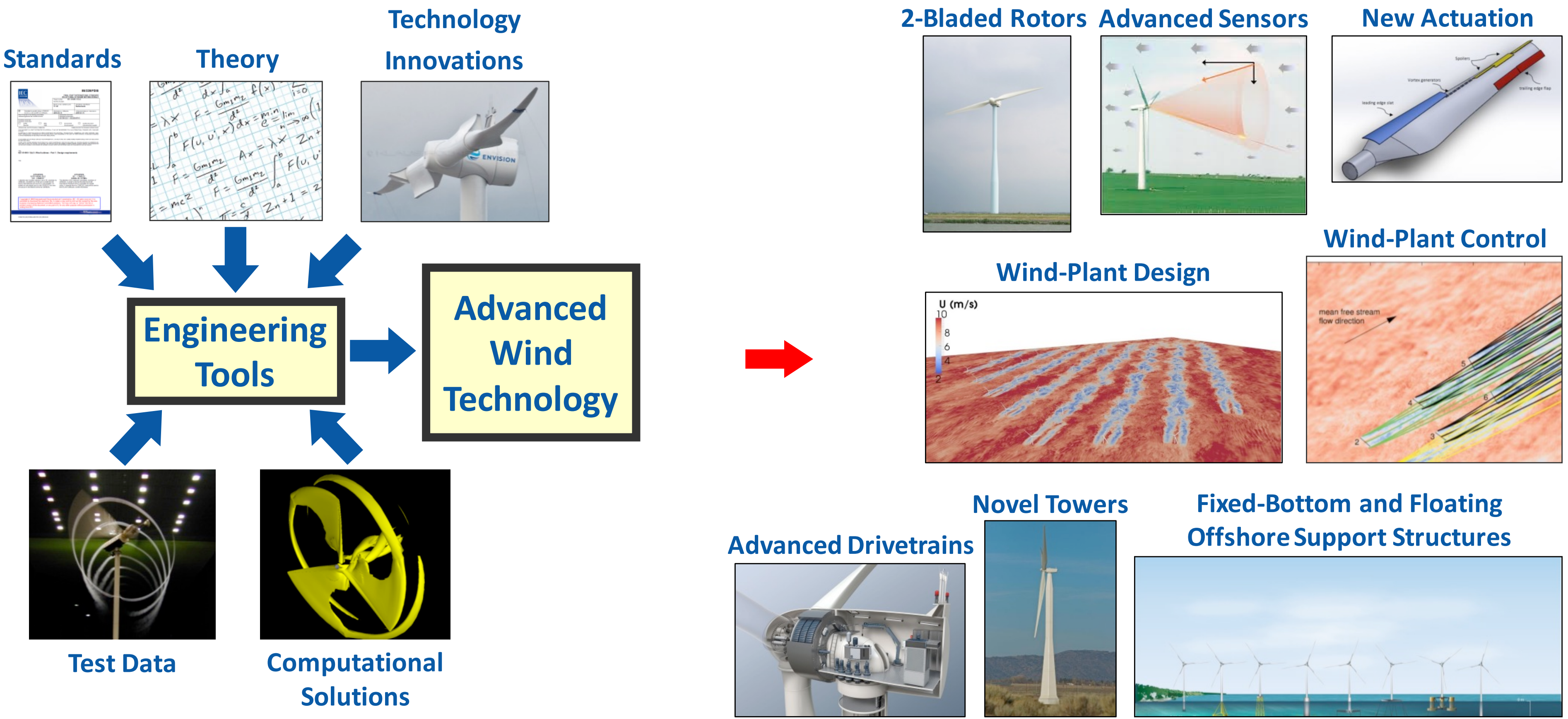




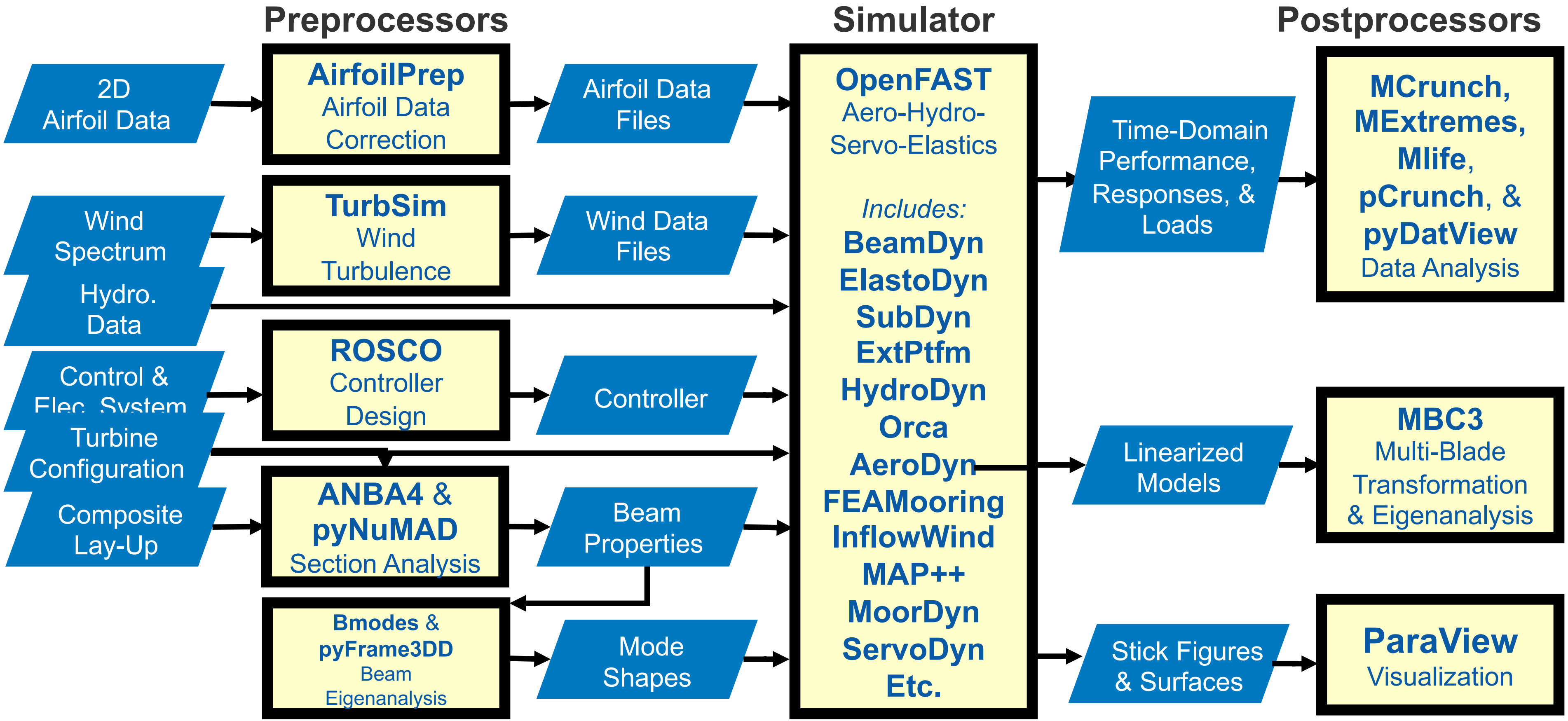
OpenFAST Workflows

Jason Jonkman

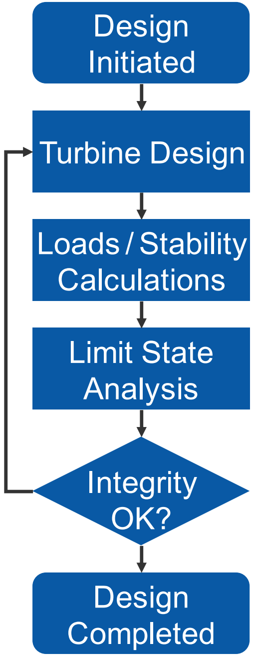
Engineering Tools Enable Technology Advancement



Workflow Overview



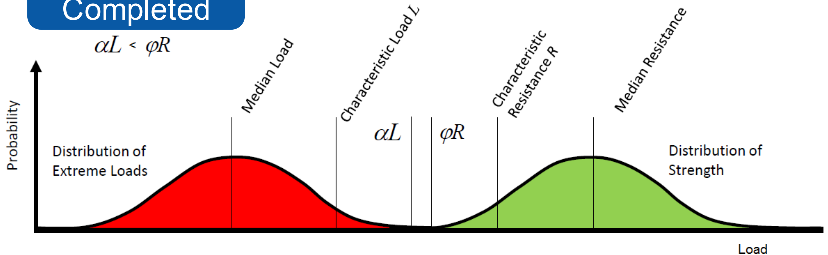
Nonlinear Time-Domain Analysis

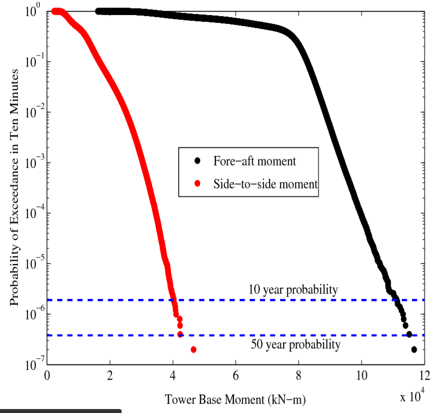


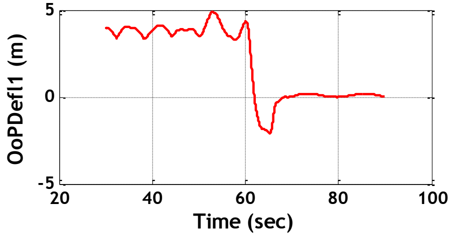
Land: $\mathcal{O}$(1,000) simulations
Offshore: $\mathcal{O}$(10,000) simulations

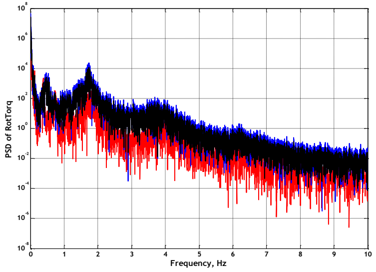
Design Situation	DLC	Wind Condition	Other Conditions	Type of Analysis
Power production	1.x			
Power production plus occurrence of fault	2.x			
Start up	3.x			
Normal shut down	4.x			
Emergency shut down	5.x			
Parked	6.x			
Parked with fault	7.x			
Transport, assembly, and maintenance	8.x			

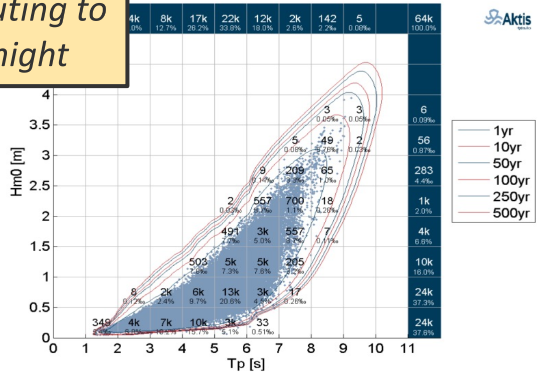
Use high-performance (HPC) or cloud computing to run simulations overnight

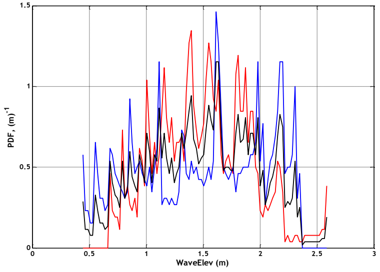










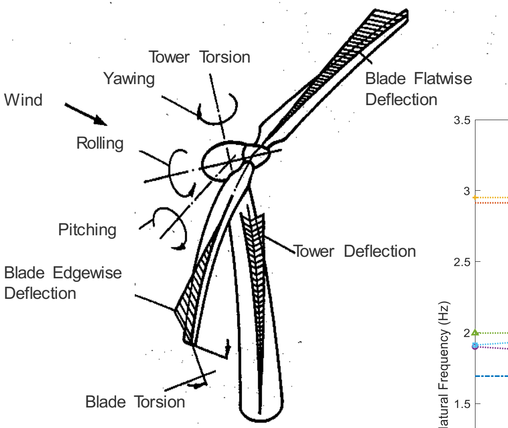


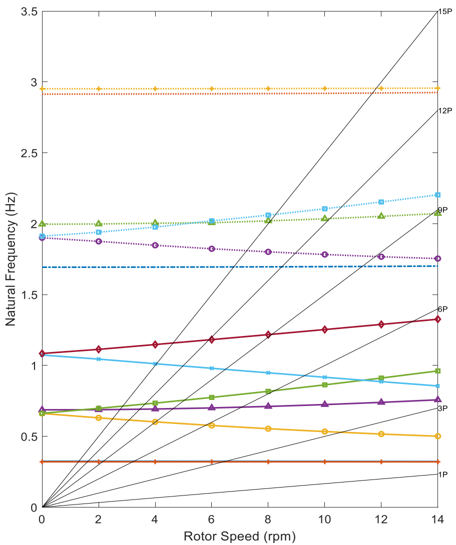
Linearization Analysis

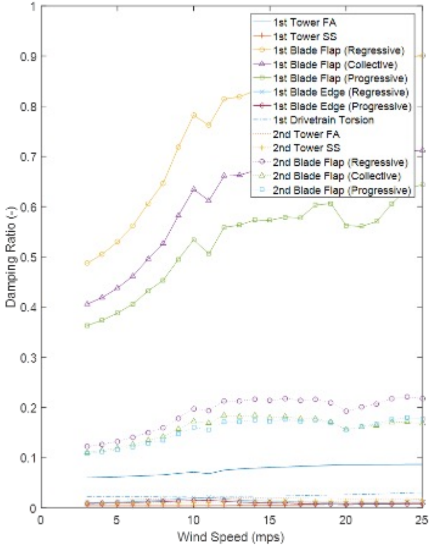
$$\dot{x} = X(x,u,t)$$
$$y = Y(x,u,t)$$

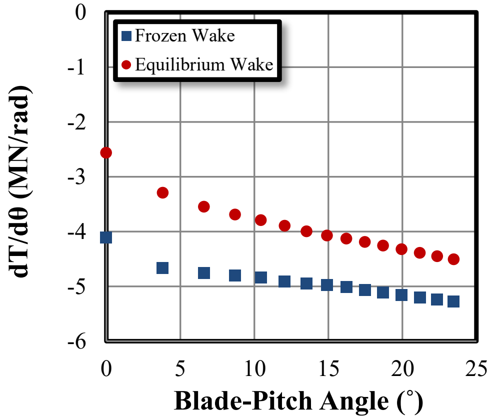
$$u = u\big|_{op} + \Delta u \quad etc.$$

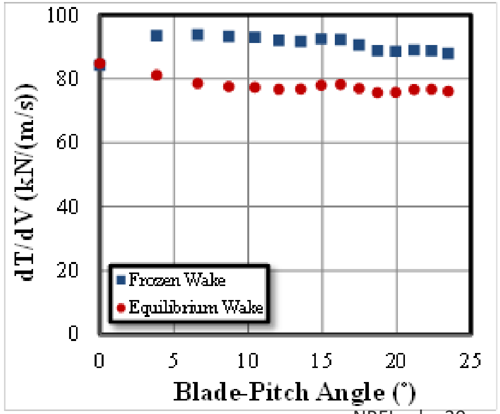
$$\Delta\dot{x} = A\Delta x + B\Delta u$$
$$\Delta y = C\Delta x + D\Delta u$$





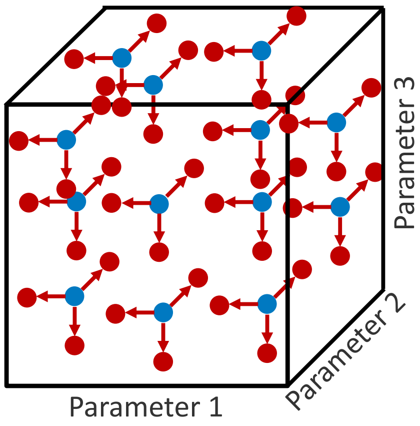




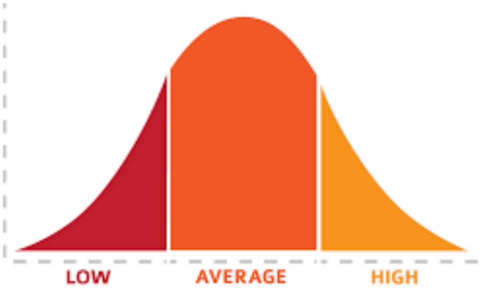


Other Analyses

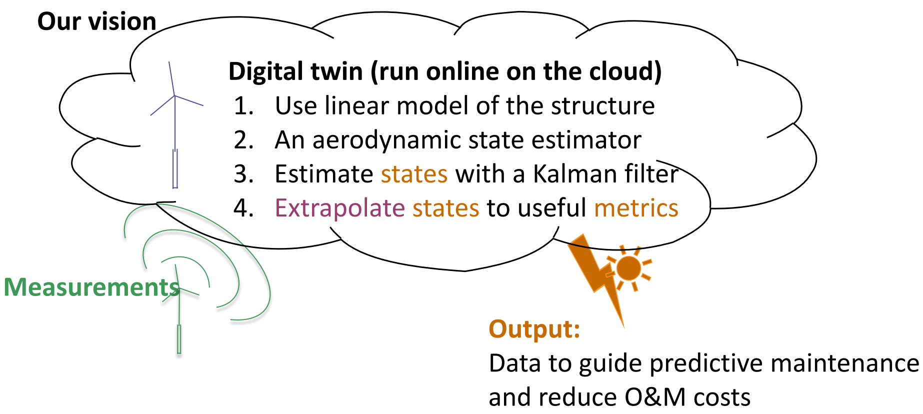
Sensitivity Analysis to Identify Input Parameters Most Influencing Loads/Response



$$EE = \frac{\partial Y}{\partial U}\Delta U$$



Use of OpenFAST Within a Digital Twin



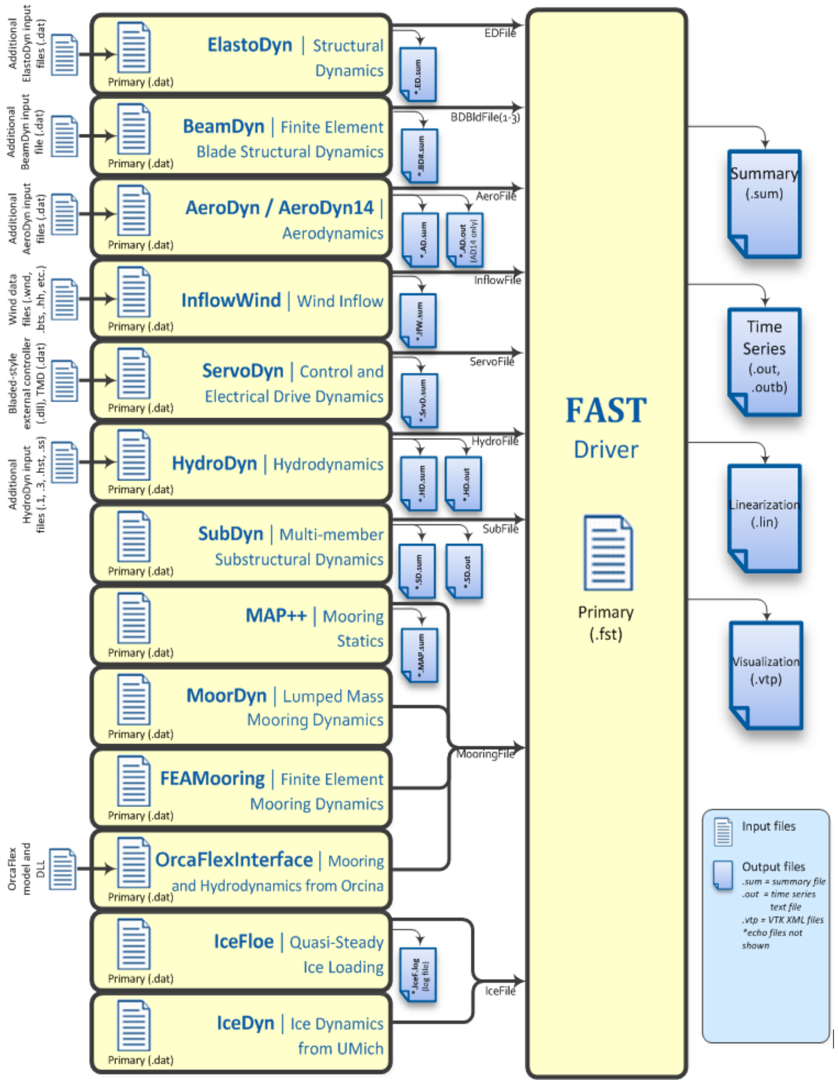
Running OpenFAST

After installing / compiling OpenFAST, to run from a Windows® command prompt, the syntax is:

```
<name of executable>
         <name of input file>
```

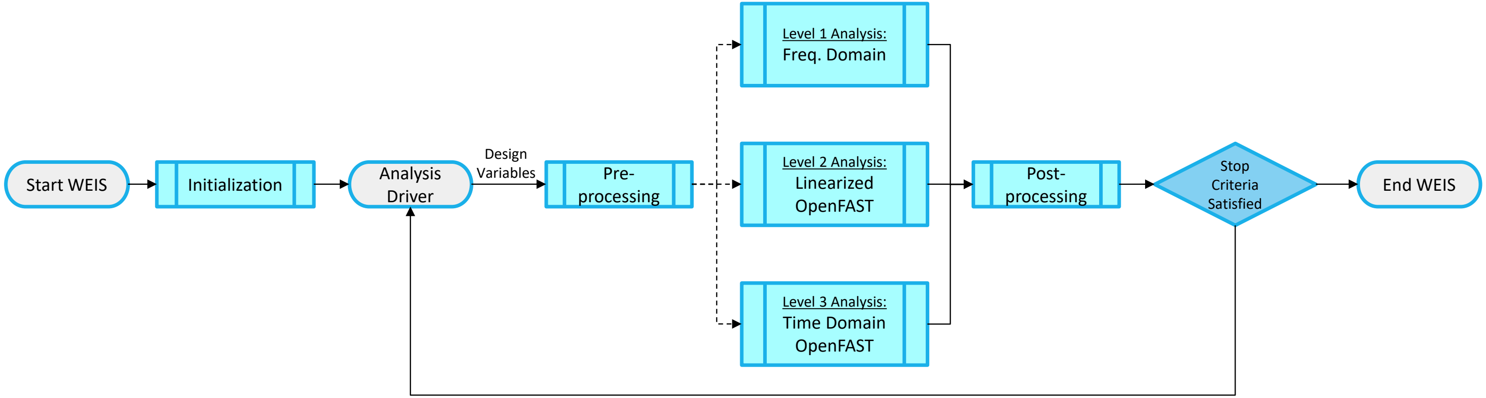
E.g., if you have a primary input file named "*Input.fst*", along with "*OpenFAST_x64.exe*", stored in "*C:\FileLocation*", type:

```
C:\>cd FileLocation
C:\FileLocation>
OpenFAST_x64.exe Input.fst
```

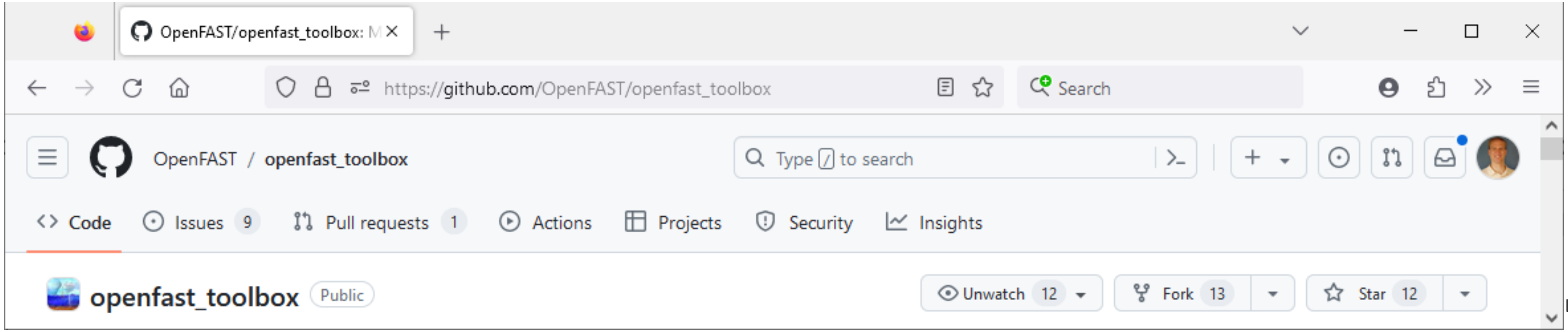


Scripting

Wind Energy with Integrated Servo-Control (WEIS) – Enables Optimization / CC of Physical Plant with Controller



OpenFAST Toolbox – Python Scripts to help Users Setup Models, Run Simulations and Postprocess Results

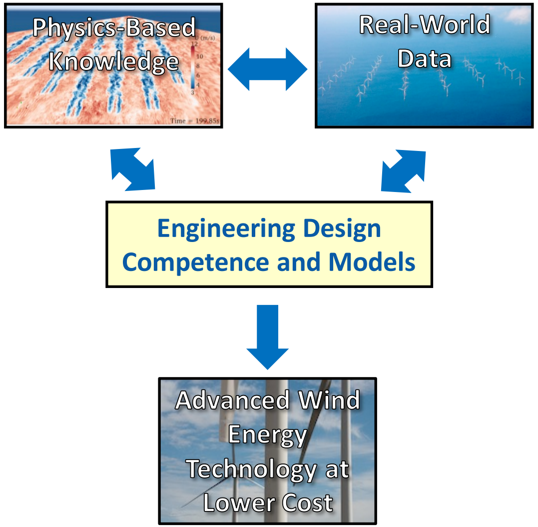


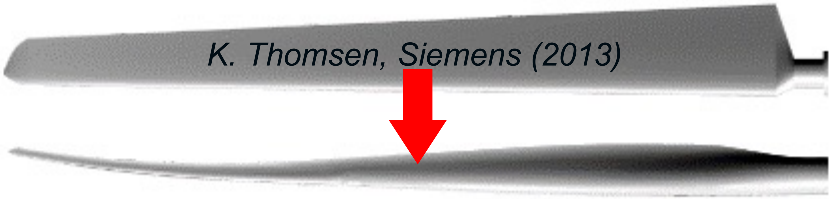
OpenFAST Roadmap

Jason Jonkman

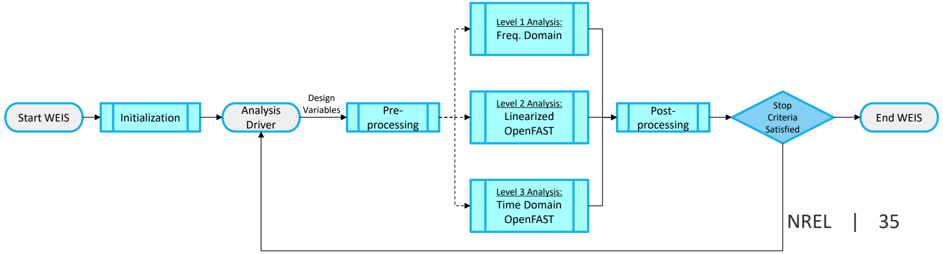
Software Development Roadmap

- *Improve Accuracy* – Use knowledge, data, and results based on HFM, experiments, and research to improve accuracy, reduce uncertainty, address limitations, and increase applicability
- *Advance Technology* – Develop functionality to support wind technology advancement, including upscaling to larger sizes, novel architectures, and innovative controls
- *Improve Design Process* – Improve the ability to use the tools in an iterative, multi-fidelity, and probabilistic design process
- *Support Developer and User Communities* – Support the broad wind industry and research communities in applications to advance technology and in further development and V&V



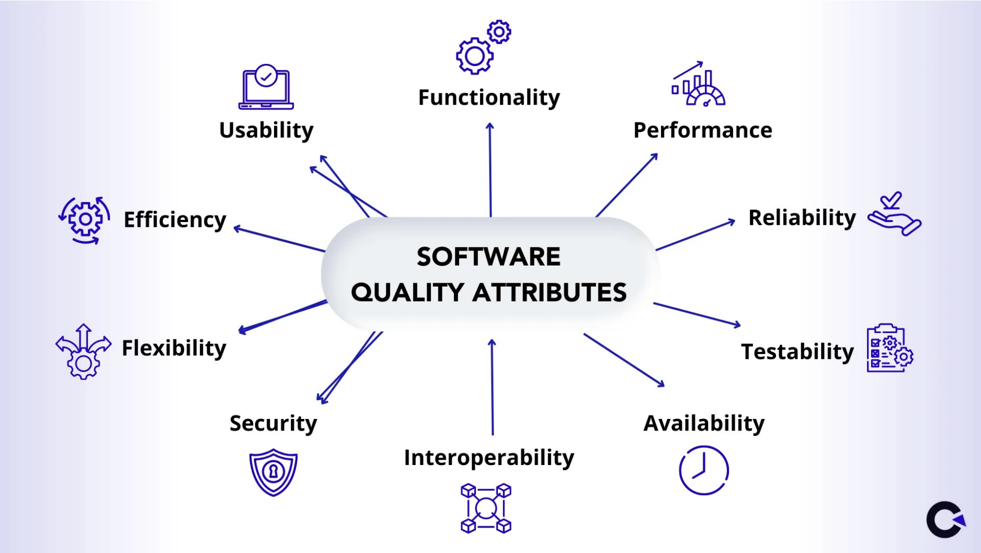


Advancement in Blade Design



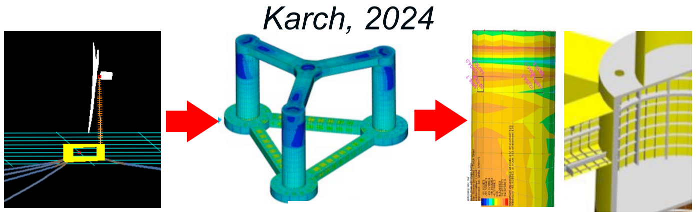
Software Quality

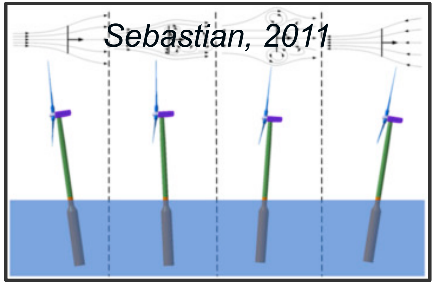
- *Accessibility* – Objectives, use cases, scope, distribution/installation, platforms, licensing, 3rd party libraries
- *Usability* – Interface, input files, stability, error messages, logging, terminal, GUI, learning curve, versioning
- *Documentation* – Pre-requisites, getting started, installation, theory, inputs, best practices, common mistakes, roadmap, validation, funding
- *Extendibility* – Style, architecture, contributor, connection to theory, versioning, review
- *Verification* – Installation tests, continuous integration, framework, documentation, unit tests, regression tests
- *Community Health* – Forum, response time, recency, traffic, engagement, funding diversity

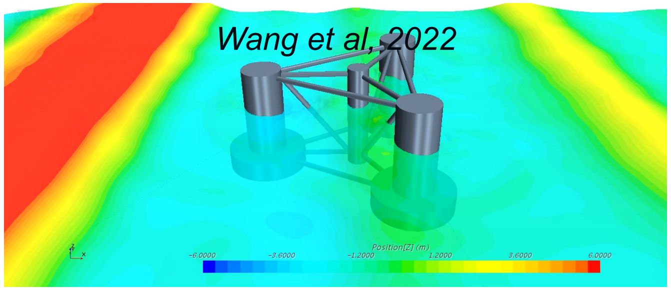


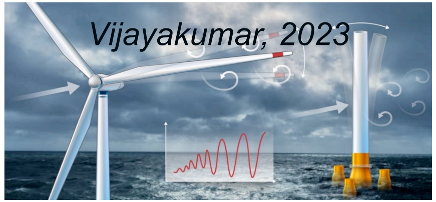
Kew Future Modeling and V&V Focus Areas

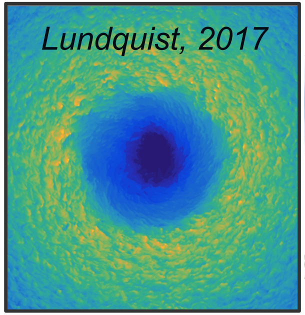
- Global to local structural coupling
- Viscous hydrodynamics
- Steep and breaking waves
- Floater motion-induced aerodynamics
- Combined rotational augmentation and unsteady airfoil aerodynamics
- High Reynolds number
- Stall- and vortex-induced vibration
- Complex terrain
- Air-sea interaction
- Atmospheric stability
- Tropical cyclones
- Blockage / deep array effects
- Cluster wakes

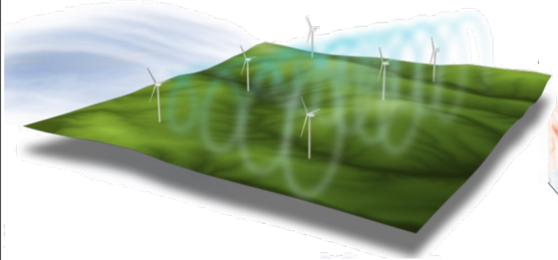

Karch, 2024

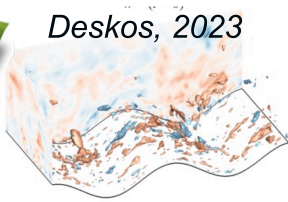

Sebastian, 2011

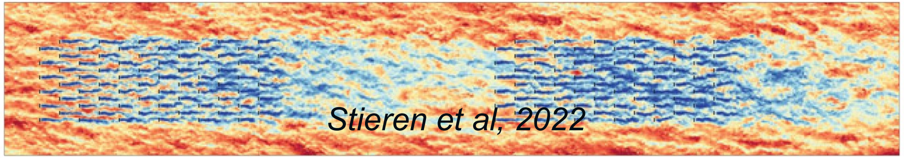

Wang et al, 2022


Vijayakumar, 2023


Lundquist, 2017



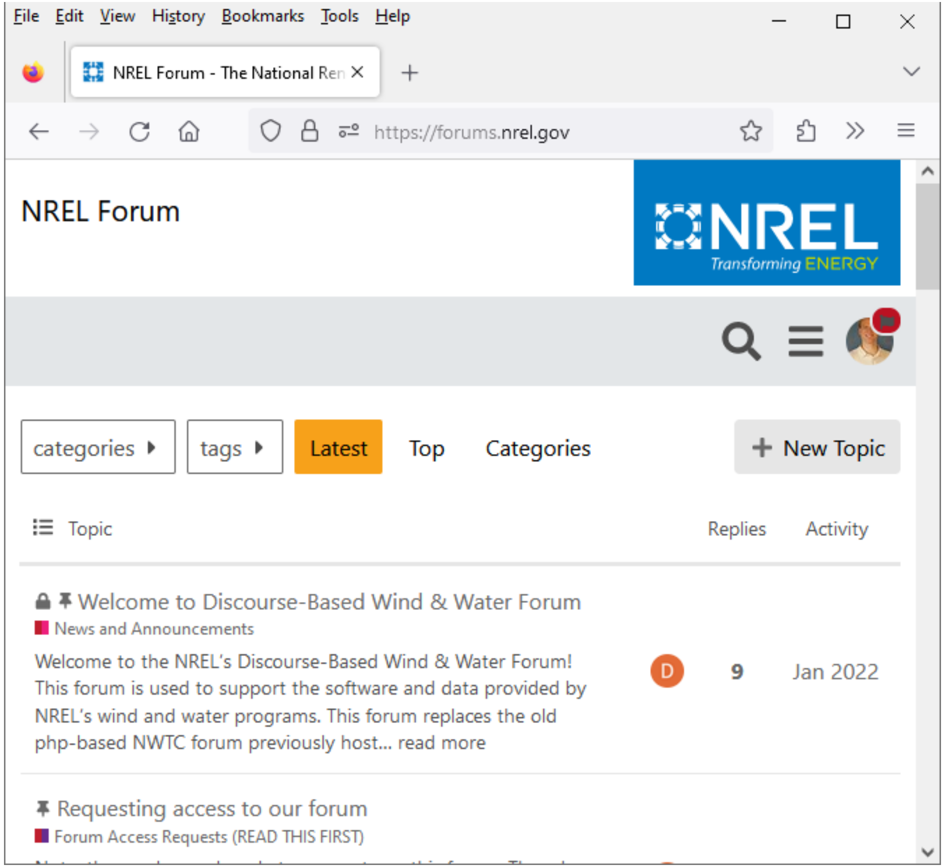

Deskos, 2023

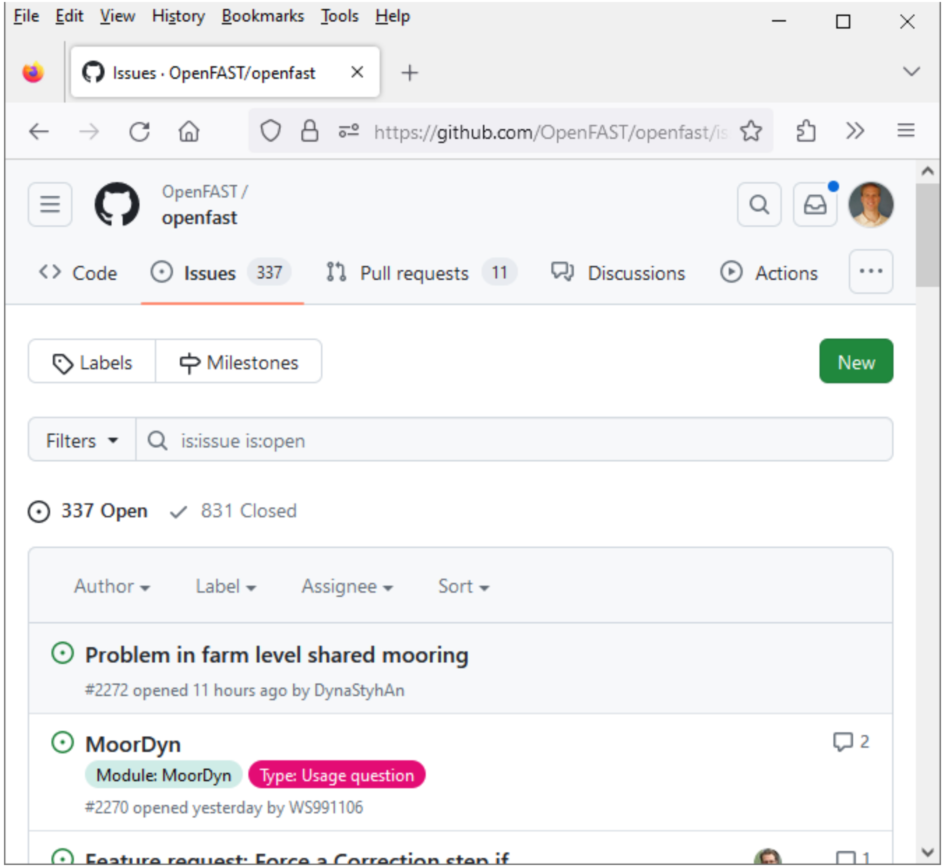

Stieren et al, 2022

OpenFAST Community Engagement

Jason Jonkman

User and Developer Support





Funding Pathways

- Directed funding through U.S. DOE WETO
- Competitive solicitations (WETO FOA, ARPA-E FOA, NOWRDC, BSEE, etc.)
- Technical support services to industry (TSA, FIA, ACT, CRADA)
- Back-end services to front-end consultants (TSA, FIA, ACT, CRADA)

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

arpa·e
Advanced Research Projects Agency • ENERGY

BSEE
Bureau of Safety and Environmental Enforcement

NATIONAL OFFSHORE WIND
RESEARCH & DEVELOPMENT CONSORTIUM

Current Industry-Funded Work

ENVISION
sener
Shell
TotalEnergies
TODA
equinor

ACDC

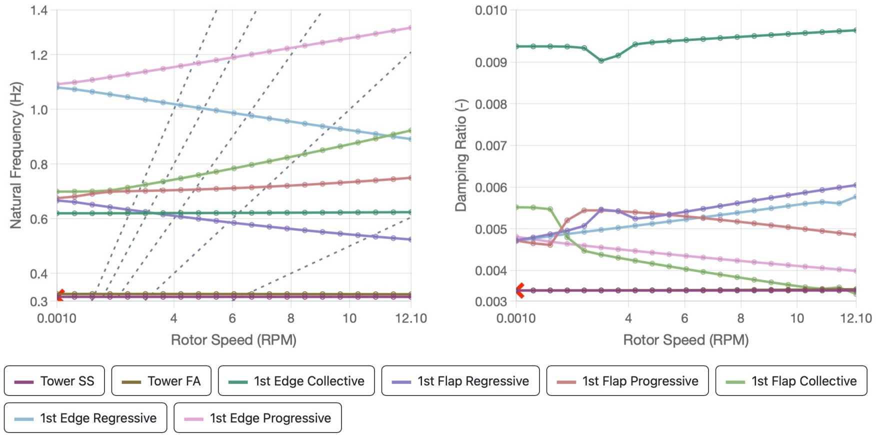
Derek Slaughter

ACDC: Automated Campbell Diagram Code

ACDC is a GUI app that automates the generation of Campbell Diagrams

What is a Campbell Diagram?

A CD graphically relates rotational speed of the rotor to the turbine's natural frequencies and damping



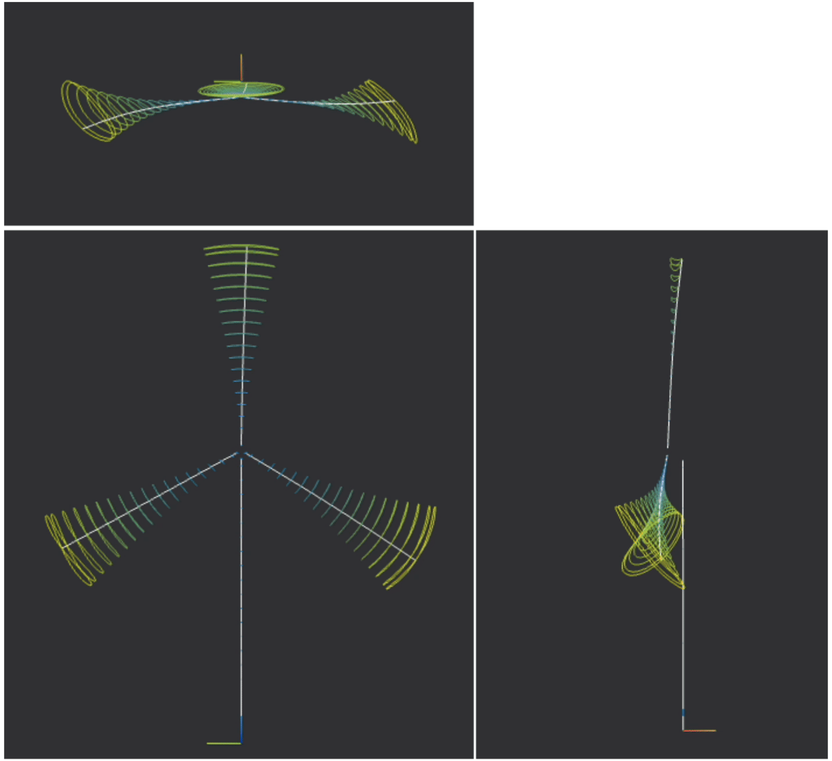
What is the ACDC workflow?

- Import OpenFAST model & setup linearization
- User defines range of operating points (OP)
  - Wind Speed, Rotor Speed, Blade Pitch
- Generates OpenFAST input files for each OP and runs simulations in parallel
- ACDC Processes results
  - Loads linearization files
  - Runs Eigenanalysis to get natural frequencies, damping, and mode shapes
  - Connects similar modes across OPs
- Generates and displays diagram

ACDC: Automated Campbell Diagram Code

What are the advantages of ACDC?

- User friendly graphical interface
- New methods for connecting modes
- Interactive diagram to explore mode information and label lines
- 3D visualization of mode shapes



How do I get ACDC?

Executables for Windows, MacOS, and Linux

https://github.com/openfast/acdc/releases

Where are the docs?

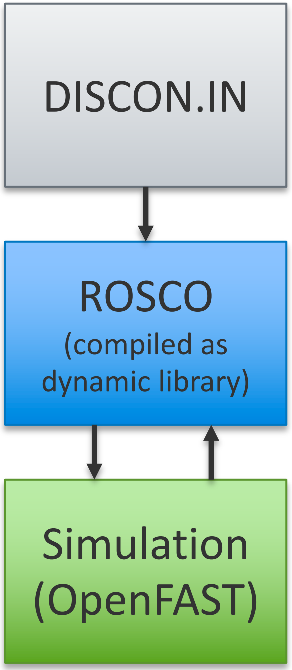
https://openfast.github.io/acdc/

ROSCO

Dan Zalkind

Reference Open-source Controller (ROSCO) Goals

- Provide a flexible, open-source reference controller to mimic the common functionalities to modern OEM controllers. Users include
  - Controls researchers to compare their designs against
    - Include floating control modules
  - Non-control designers to use in engineering studies for a variety of turbines
    - Developers and platform designers have used ROSCO on 500 kW to 15 MW models

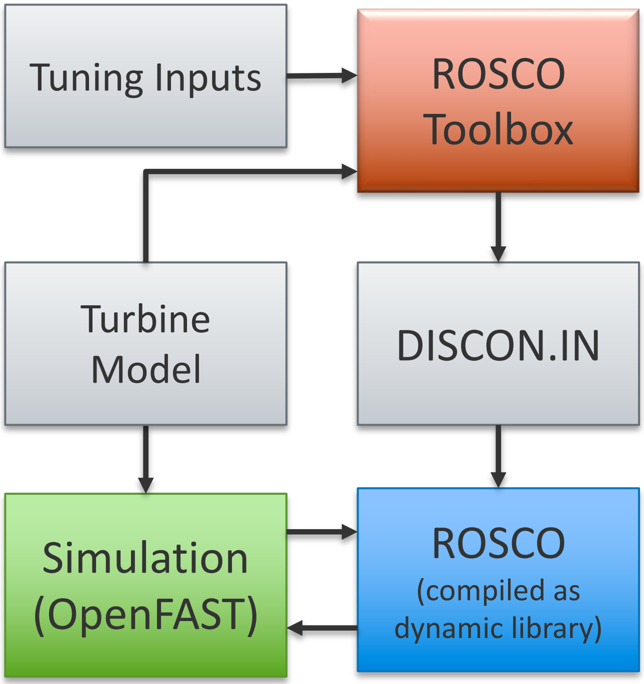


ROSCO Toolbox

- Python-based tool for tuning controllers

- Inputs:
  - Turbine parameters:
    - Rated power, actuator limits, C_P & C_T tables, etc.
  - Control parameters:
    - Pitch control bandwidth, peak thrust, etc.

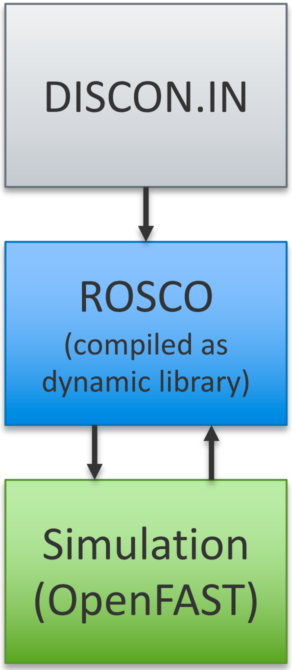
- Output:
  - Input file (DISCON.IN) with ROSCO parameters:
    - Gains & setpoints,
    - Saturation limits, etc.



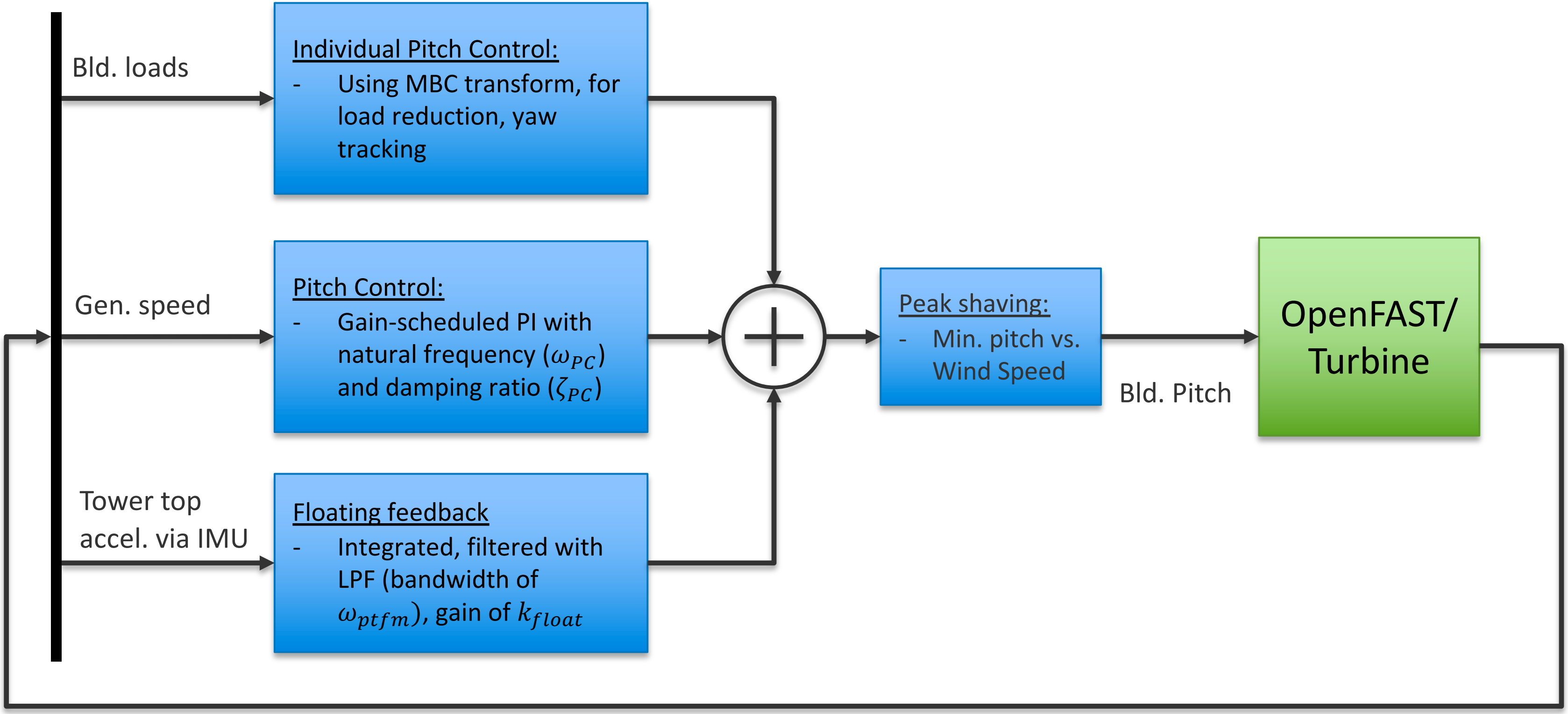
ROSCO Software

- Fortran-based code that can be compiled into Bladed-style dynamic library
  - https://github.com/NREL/ROSCO

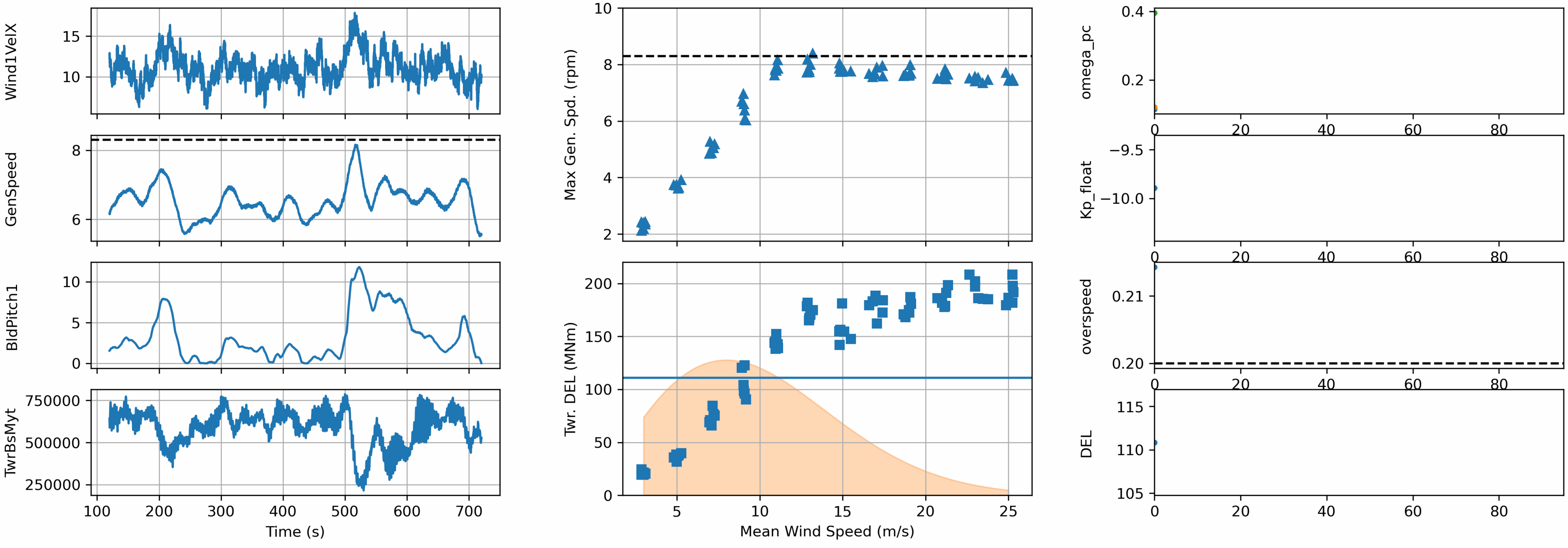
- Control Modules
  - Collective and individual pitch control
  - Floating platform motion feedback
  - Pitch saturation/peak shaving
  - Setpoint smoothing control
  - Variable speed torque control
  - Extended Kalman filter wind speed estimator
  - Shutdown control
  - Yaw control
  - Distributed aerodynamic control
  - Open-loop control
  - External DLL and ZeroMQ inputs
  - Cable and structural control
  - Variable speed setpoints
  - Tower resonance avoidance



Floating Control Modules



Controller Optimization



Roadmap

- Near term (next versions, v2.10 …)
  - Power reference control
  - Additional floating feedback configurations
  - Support all IEC DLCs
- Medium term (next few years, v3.x)
  - Testbench for controller performance quantification/comparison
  - Support for wind farm control simulations
- Long term
  - Identifying and reducing gaps with OEM controllers
  - Modularity for community solutions and improvements

OpenFAST Ecosystem

Mentimeter

Open Discussion

OpenFAST+

Raise your hand and we'll call your name to ask a question.

- **Discussion topics**
  - What modeling capabilities are missing?
  - Where can accessibility be improved?
  - How would you like to engage with the OpenFAST team differently than you already do?

Thank you for your time today!

- How to engage:
  - GitHub Issues or Discussions
  - NREL User Forum: forums.nrel.gov
- Software repositories:
  - OpenFAST: https://github.com/OpenFAST/OpenFAST
  - ACDC: https://github.com/OpenFAST/ACDC
  - ROSCO: https://github.com/NREL/ROSCO
  - OpenFAST Toolbox: https://github.com/OpenFAST/openfast_toolbox
- Workshop materials: https://nrel.github.io/WETOStack/
- Feedback: Rafael.Mudafort@nrel.gov