OpenFAST Workshop

Windows

Mac/Linux

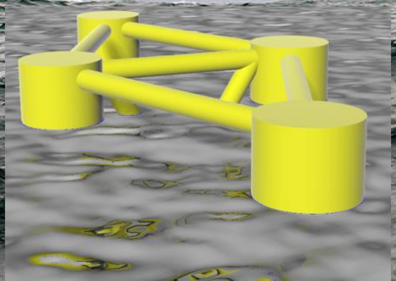
https://github.com/hkross/OpenFAST_UMERC_Demo

NREL Transforming ENERGY

OpenFAST for Marine Turbines

Hannah Ross, Toan Tran, and Will Wiley

August 7, 2024



Workshop Summary

1. 9:30 – 10:00 OpenFAST Overview
2. 10:00 – 10:30 CT-Opt Overview
3. 10:30 – 10:40 Break
4. 10:40 – 11:30 OpenFAST Demonstration

OpenFAST Overview

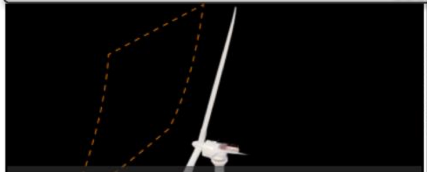
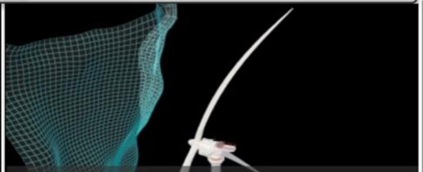
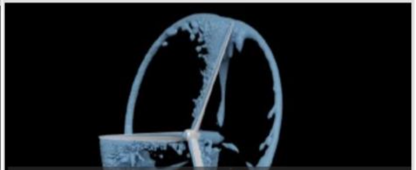
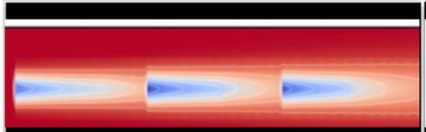
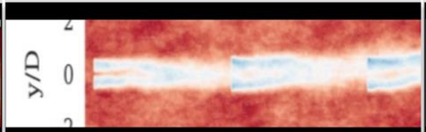
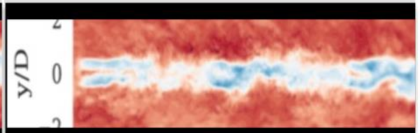
1 OpenFAST Capabilities

2 OpenFAST Structure

3 OpenFAST Modules

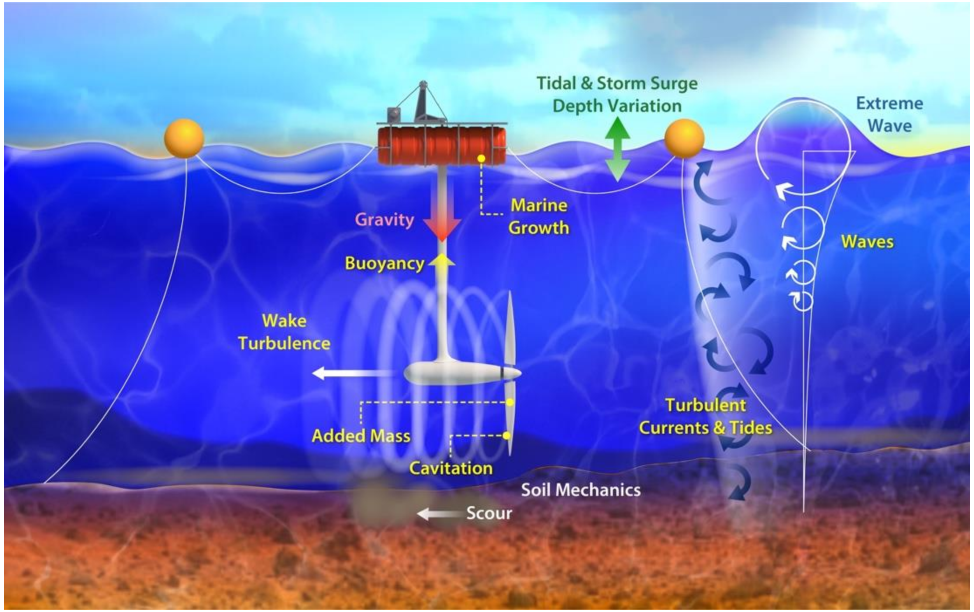
NREL/DOE Open-source Turbine Modeling Tools

Model Fidelity / Computational Intensity

Application	Design Exploration	Detailed Design	Highly Resolving
Single Turbine Performance and Loads	**WISDEM, RAFT** Multidisciplinary design optimization and cost modeling	**OpenFAST** Turbine loads analysis, detailed turbine design, IEC standards	**ExaWind/SOWFA** Understand physics, final turbine design check, calibrate / validate lower fidelity
	WEIS		
			
	Other Tools: Turbine Architect, CpMax, HawtOpt2	**Other Tools:** Bladed, HAWC2, FLEX 5	**Other Tools:** EllipSys3D-HAWC2, STAR-CCM+
Full Wind-Plant Performance and Loads	**FLORIS** Wind-plant controls and siting optimization	**FAST.Farm, WindSE** Turbine siting within plant, wind-plant controls, plant loads analysis, detailed plant design	**ExaWind/ERF/SOWFA** Understand physics, final plant design check, calibrate / validate lower fidelity
			
	Other Tools: WAsP, WindFarmer, Fuga	**Other Tools:** openWind, MeteoDyn WT, DWM	**Other Tools:** EllipSys3D, PALM, WRF-LES, W2A2KE3D, VFS-Wind

OpenFAST Capabilities

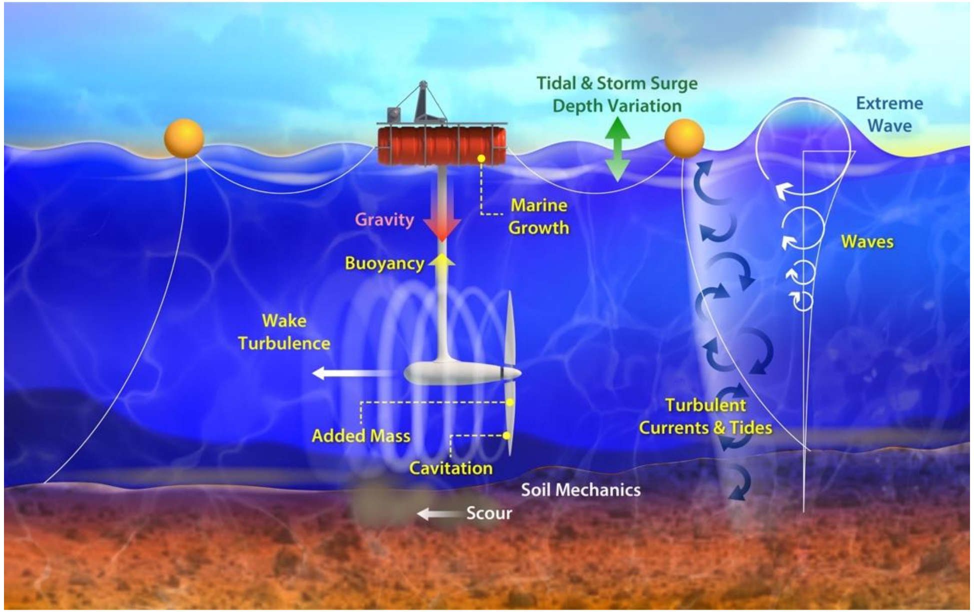
- Models fixed and floating wind and marine turbines
- Engineering model (coupled aero-hydro-servo-elastic dynamics)
- Computes nonlinear dynamics in the time domain
- Enables loads analysis for predicting system ultimate and fatigue loads



Marine turbine physics captured by OpenFAST. *Image by NREL Communications*

OpenFAST Capabilities

- Linearizes nonlinear equations about an operating point
  - Modal analysis
  - Controls design
  - Instability studies
- Glue code couples independent modules
  - Enables data encapsulation for specific physics and components
  - Can run more than one instance of a module simultaneously



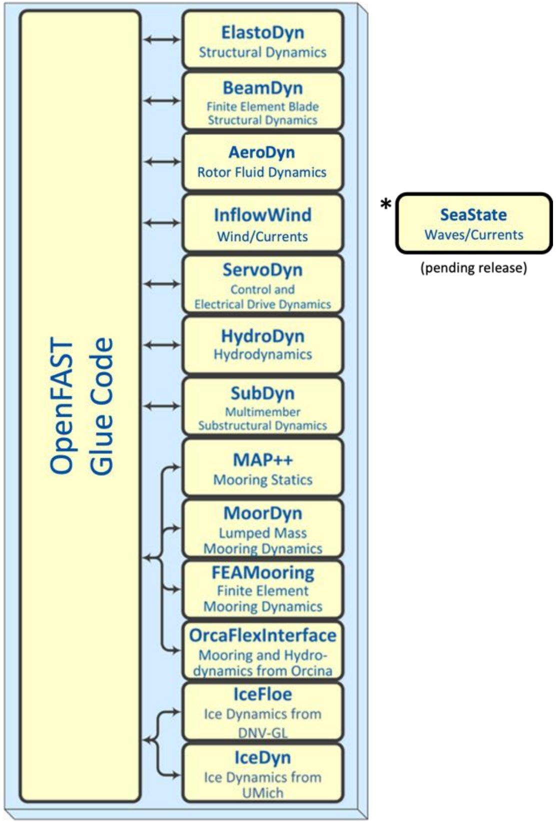
Marine turbine physics captured by OpenFAST. *Image by NREL Communications*

Marine Turbine Features

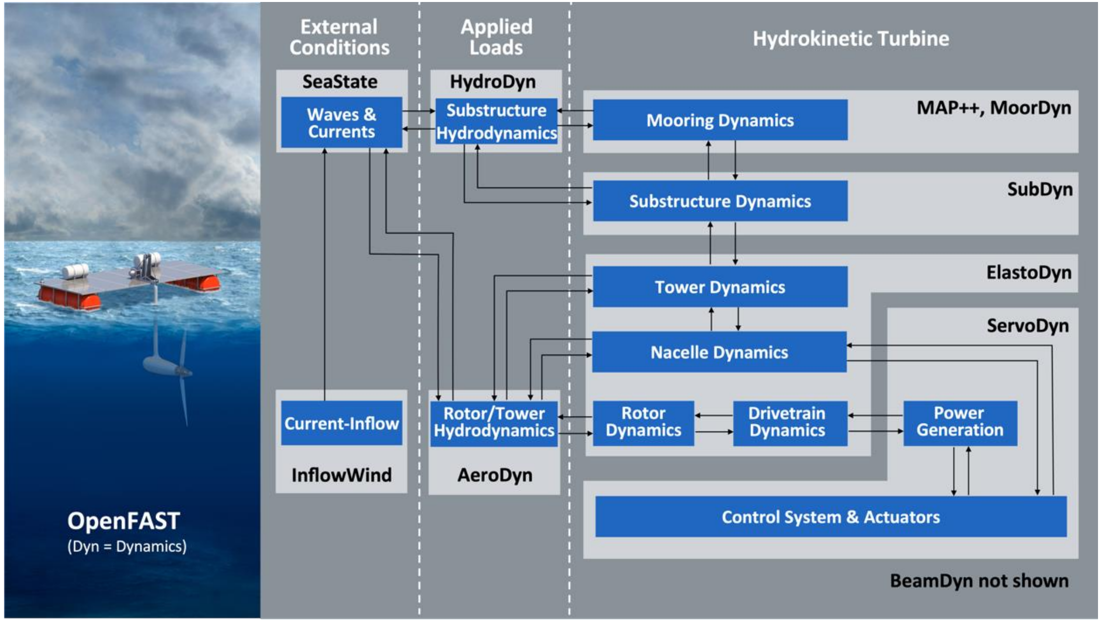
- Buoyancy loads on rotor, nacelle, and tower
- Calculation of inflow accelerations
- Wave and current velocity superposition
- Added mass and fluid inertial loads on blades and tower
- Cavitation check

Fixed-bottom marine turbine. Illustration by Besiki Kazaishvili, NREL

OpenFAST Structure

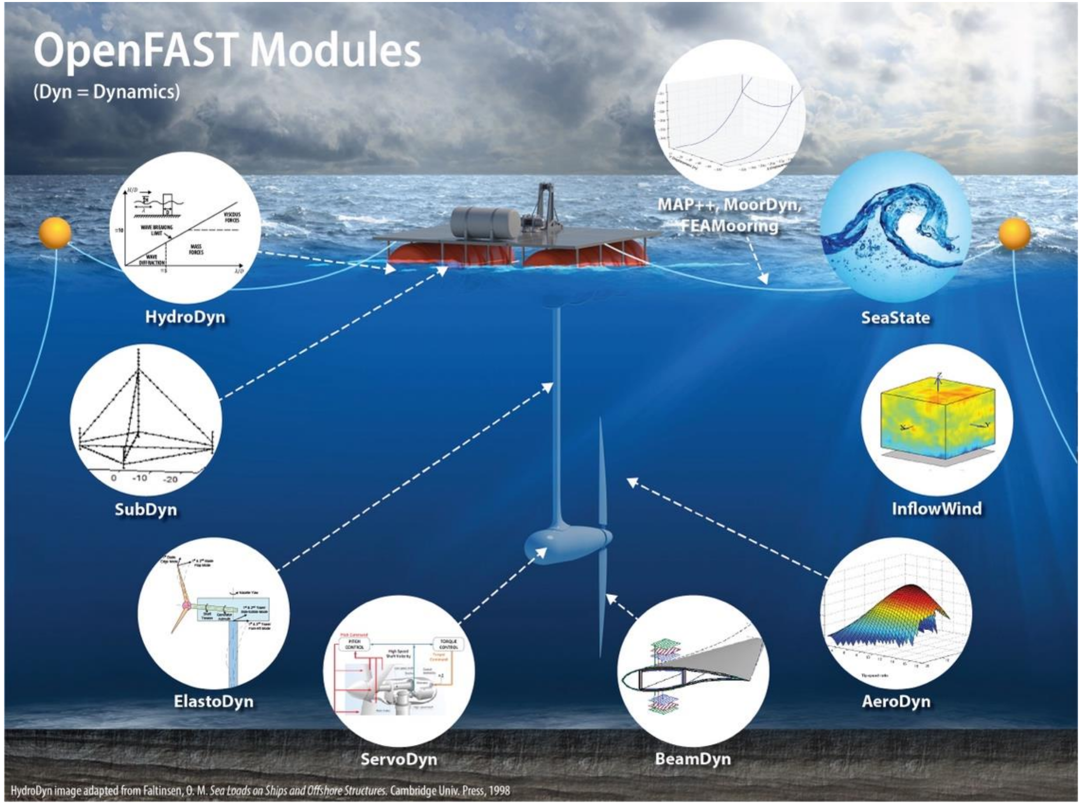


OpenFAST glue code and its modules. *Image by Jason Jonkman, NREL*



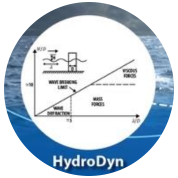
OpenFAST module coupling for a floating offshore wind turbine. *Image by NREL Communications*

OpenFAST Modules

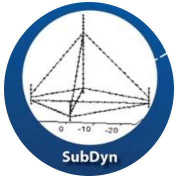


OpenFAST modules for a floating marine turbine. *Image by NREL Communications*

OpenFAST Modules



- HydroDyn: Support structure hydrodynamics
  - Strip theory and potential flow



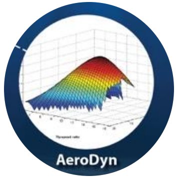
- SubDyn: Support structure structural dynamics
  - Linear FEA with modal reduction

- ElastoDyn: Tower and blade structural dynamics
  - Linear modal
  - Multi-body

OpenFAST Modules

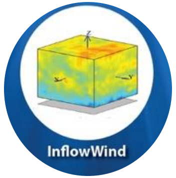
- ServoDyn: Controls and drivetrain dynamics

- BeamDyn: Blade structural dynamics
  - Geometrically exact beam theory



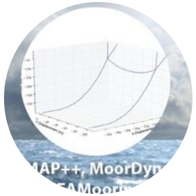
- AeroDyn: Rotor aero/hydrodynamics
  - BEM and free vortex wake

OpenFAST Modules



- InflowWind: Wind or current inflow

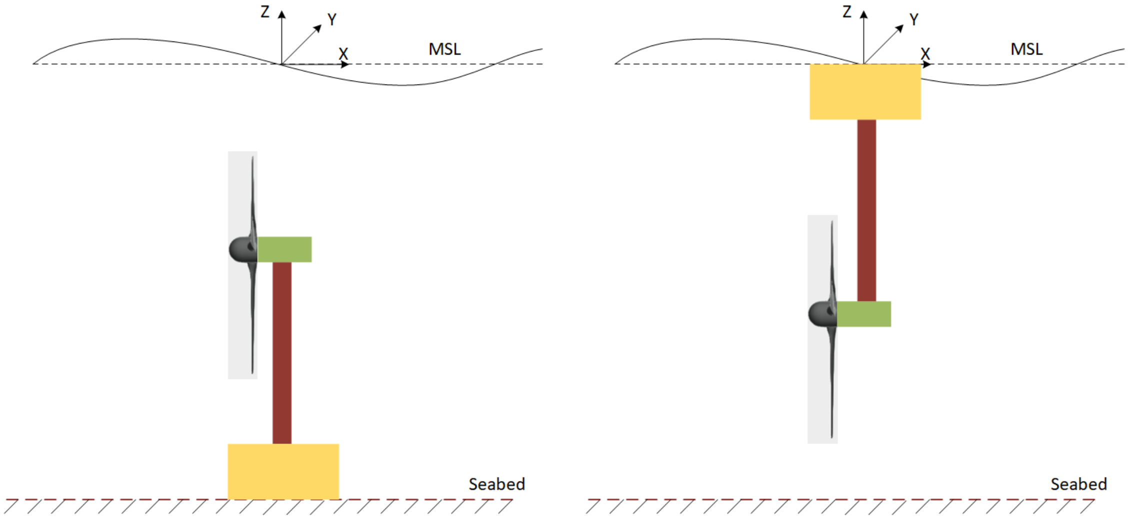
- SeaState: Waves



- MoorDyn: Mooring dynamics
  - Lumped-mass discretization, strip theory

ElastoDyn

- Turbine configuration
  - Axial-flow
  - 2 or 3 bladed rotor
  - Upstream or downstream
  - Fixed or floating
  - Tower attached to a platform



Fixed *Floating*

ElastoDyn

- Multi-body representation
  - Platform, nacelle, hub, generator
  - Platform rotations assume small angle approximation
  - Other multi-body DOFs may exhibit large motions
- Linear modal representation
  - Blades and tower
  - Small angle approximation
  - Depends on user-specified mode shapes
  - Assumes straight and isotropic beams
  - Bending only (no twist)

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

ElastoDyn →

Outputs:
- Displacements
- Velocities
- Accelerations
- Reaction loads

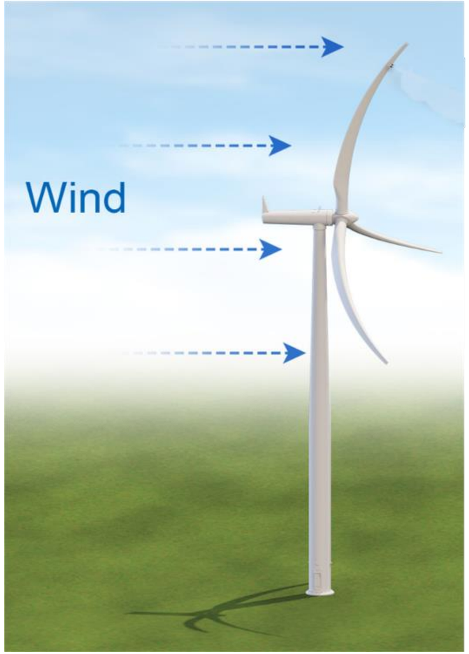
BeamDyn

- Geometrically-exact beam theory
  - Full 6×6 cross-sectional mass & stiffness
  - Stiffness-proportional damping
  - Curved/swept reference axis (spline based)
  - Nonlinear geometrically exact large deflection

Inputs:
- Aerodynamic loads
- Root motion

BeamDyn →

Outputs:
- Blade motion
- Root reaction loads



AeroDyn

- Wake/induction models
  - Blade-element momentum
  - Free vortex wake
- Airfoil aero/hydrodynamics
  - Quasi-steady
  - Unsteady (employs empirical dynamic stall models)
  - Both models rely on user-specified polars
- Tower drag, dam, and shadow models

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

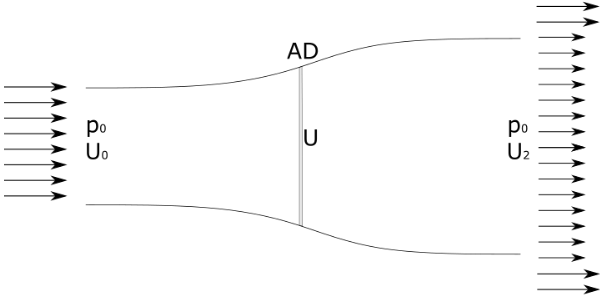
AeroDyn

Outputs:
- Aero. loads

AeroDyn

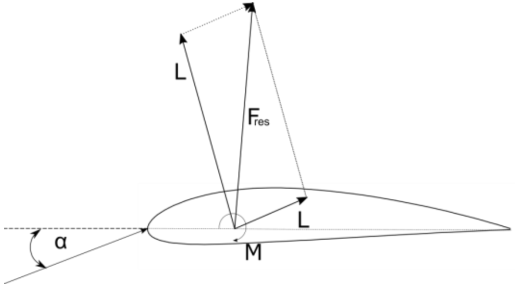
Blade-element momentum model (BEM)

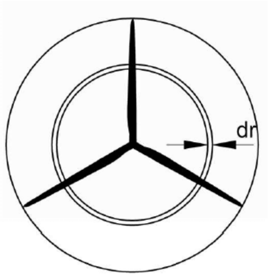
Momentum theory



- Gives expressions for C_P and C_T as functions of *a* (axial induction factor, relates U and U_0)

Blade element theory





- Calculates blade loads at specified radial locations
- Gives an expression for C_T as a function of *a* and *a’* (axial and tangential inductions factors)

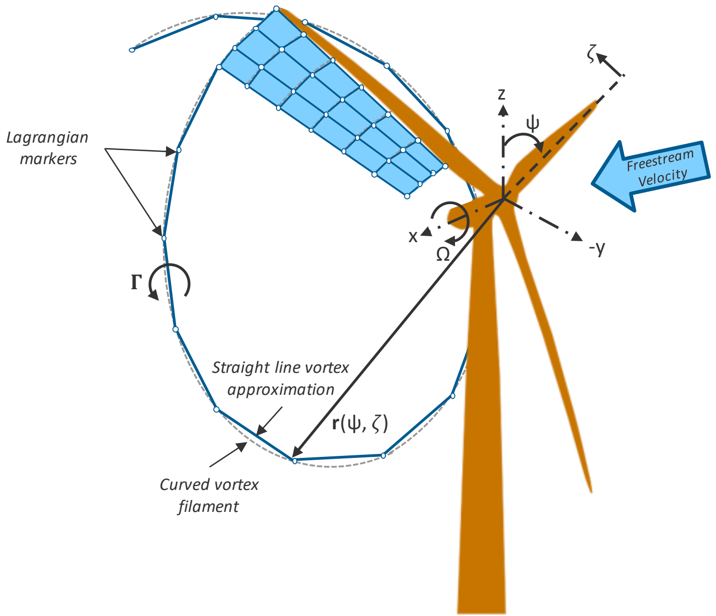
1. Solved iteratively for *a* and *a’*
2. Resulting *a* used to calculate C_T and C_P

AeroDyn

Free vortex wake model (cOnvecting LAgrangian Filaments: OLAF)

- Lagrangian approach
  - Wake discretized into Lagrangian markers connected by vortex filaments

- Hybrid lattice / filament
  - Near wake / tip and root vortices



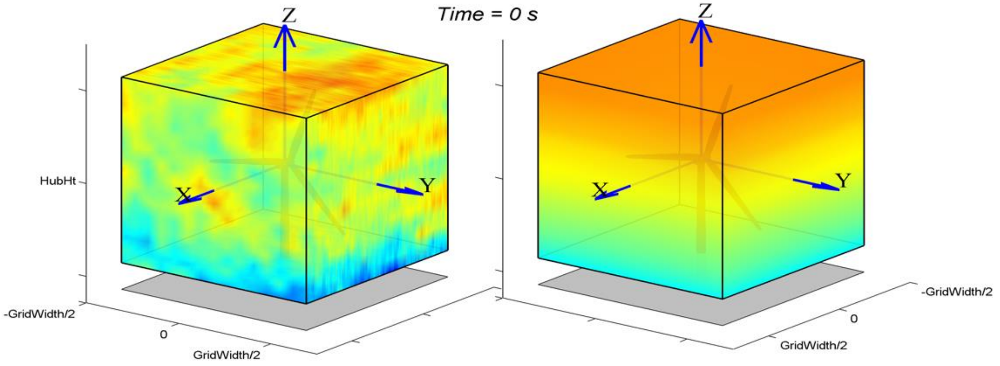
InflowWind

- Precomputes inflow velocities and accelerations
  - Wind or current
- Multiple definitions
  - Steady
  - Uniform, time-varying
  - Full-field turbulence (TurbSim, Bladed, HAWC2)
  - User-defined

Inputs:
- Positions

InflowWind →

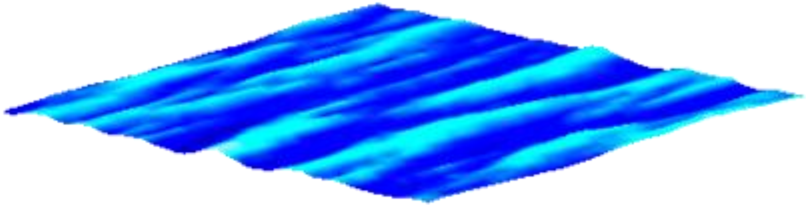
Outputs:
- Wind @ input positions



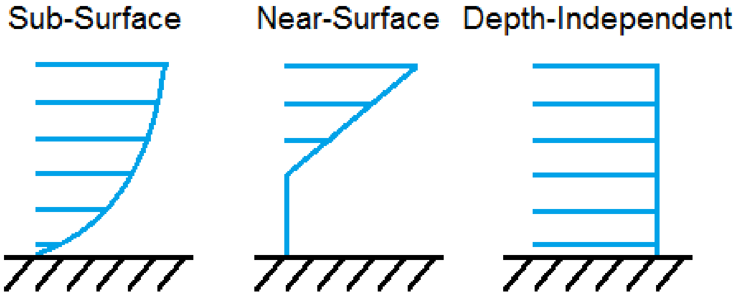
Full field *Uniform*

SeaState

- Precomputes wave velocities and accelerations
- Regular, irregular, or white noise waves
  - Pierson-Moskowitz, JONSWAP, white-noise, or user-defined
- Wave direction & directional spreading
- Currents
  - Steady, pre-defined
  - User-defined
  - Defined via InflowWind



Multi-directional sea state



Pre-defined steady currents

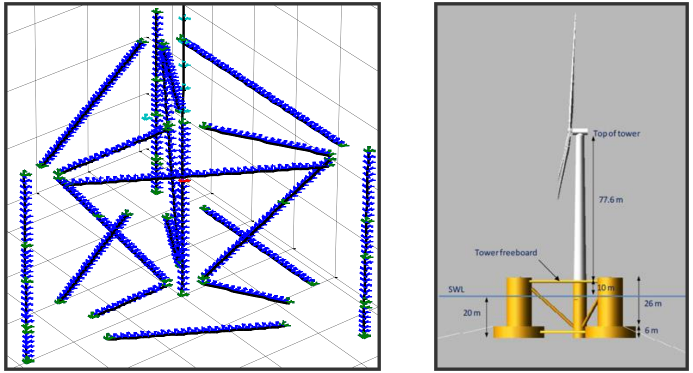
HydroDyn

- Strip theory (Morison)
  - For “slender” members
  - Inertia, added mass, viscous, and buoyancy loads
  - Multiple interconnected members
- Potential flow (WAMIT)
  - For “large” platforms
  - Radiation, diffraction, and buoyancy loads
- Hybrid combination of these two

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

HydroDyn →

Outputs:
- Hydro. loads



Strip-Theory Nodes for the OC4-DeepCwind Semisubmersible

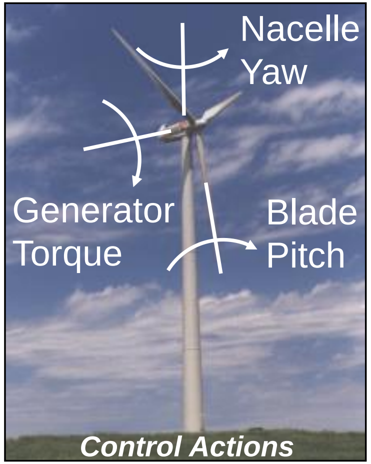
ServoDyn

- Control & electrical-drive functions
- Actuators
  – Blade pitch
  – Generator torque
  – HSS brake
  – Nacelle yaw
  – Structural controls (TMDs, TLCDs)
- Implementations
  – Simple built-in
  – User Fortran subroutines
  – Bladed-style dynamic link library (DLL)
  – MATLAB/Simulink interface
  – LabVIEW interface

Inputs:
- Structural motions
- Reaction loads
- Wind measurements

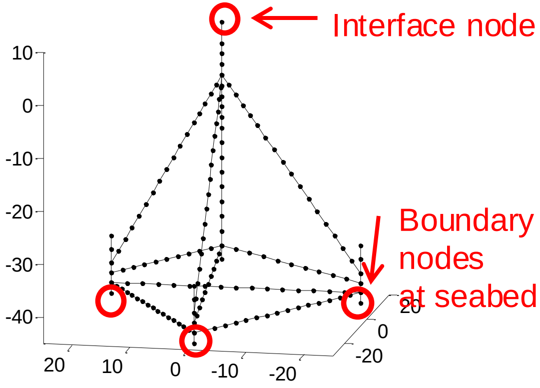
→ **ServoDyn** →

Outputs:
- Controller commands
- TMD reactions



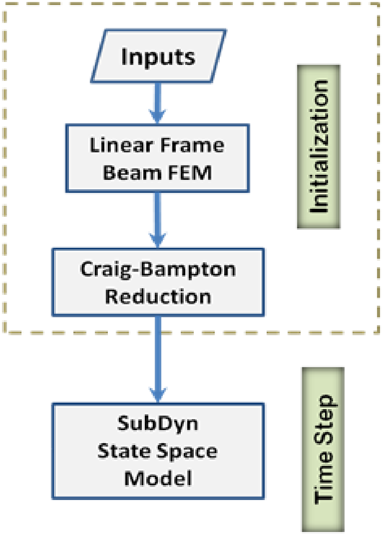
SubDyn

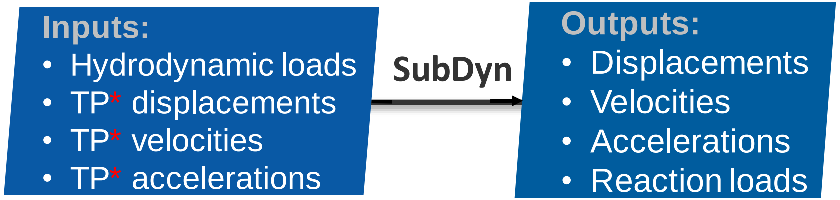
- Linear frame finite-element beam model
- Craig-Bampton dynamic system reduction



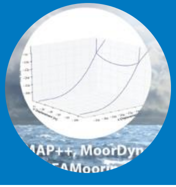
Finite-Element Discretization of the OC3-Tripod

SubDyn Flow Chart





**TP = Transition piece*



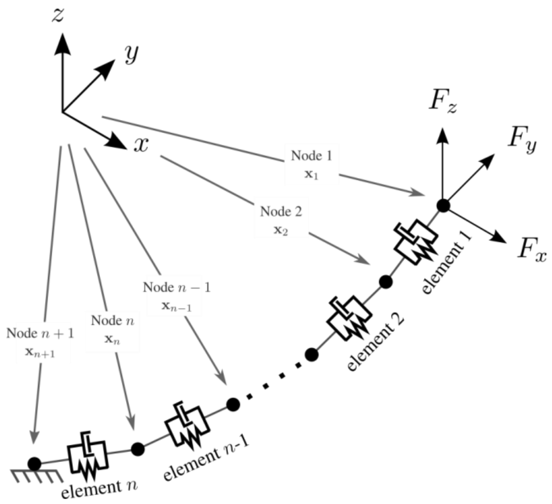
MoorDyn

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

Inputs:
- Platform disp.

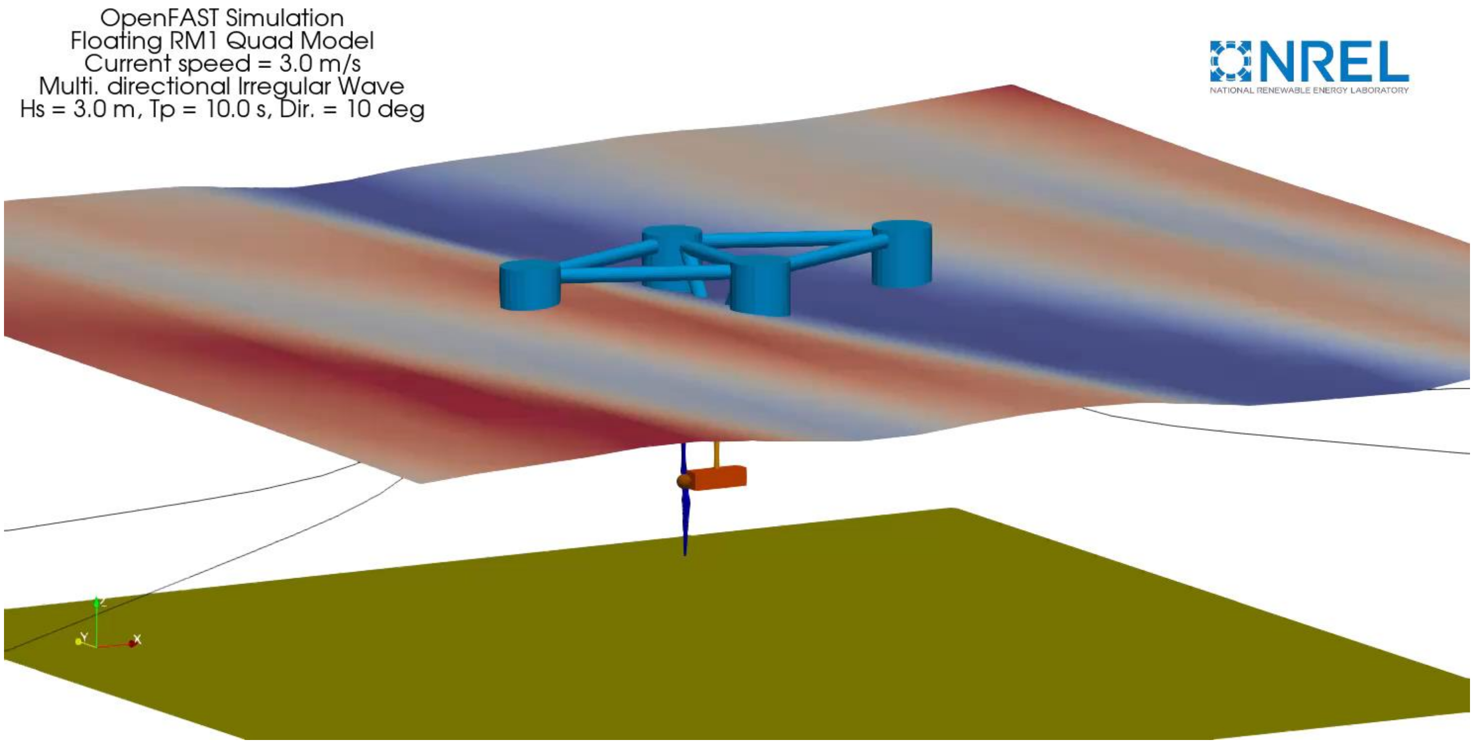
MoorDyn →

Outputs:
- Line tensions
- Line disp.



Lumped-Mass Mooring Dynamics

Example Simulation Output



CT-Opt Overview

1. CT-Opt Introduction
2. RAFT Level-1 Overview
3. DFSM Level-3 Overview
4. OpenFAST Overview for HKT Turbines
5. CT-Opt Development Progress

CT-Opt

CT-Opt Architecture

- Level 1: **RAFT** (Response Amplitude of Floating Turbines)
- Level 2: **Linearized OpenFAST**
- Level 3: **DFSM** (Derivative Function Surrogate Model)
- Level 4: **OpenFAST**

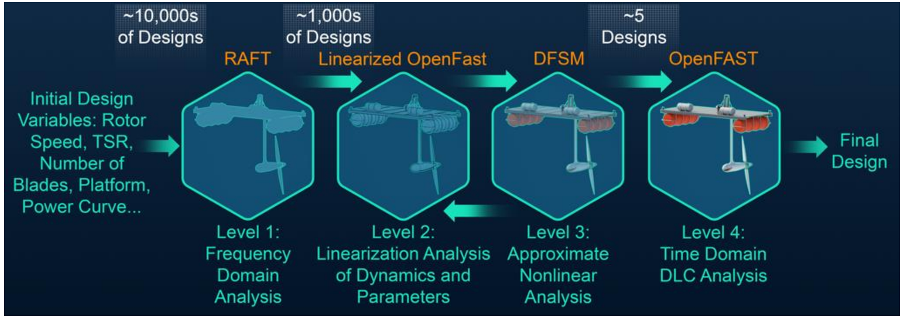


Illustration by Besiki Kazaishvili, NREL

Integrated/Control Co-Design

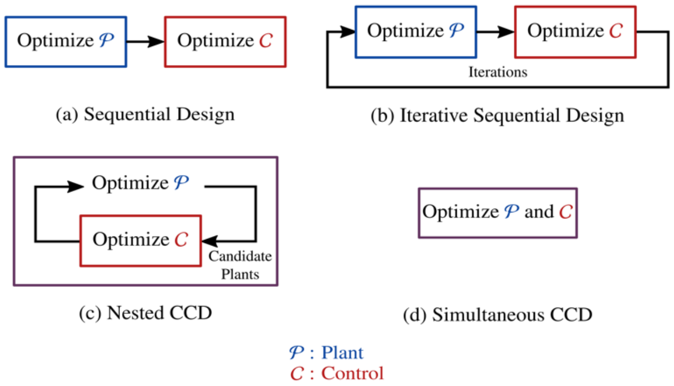
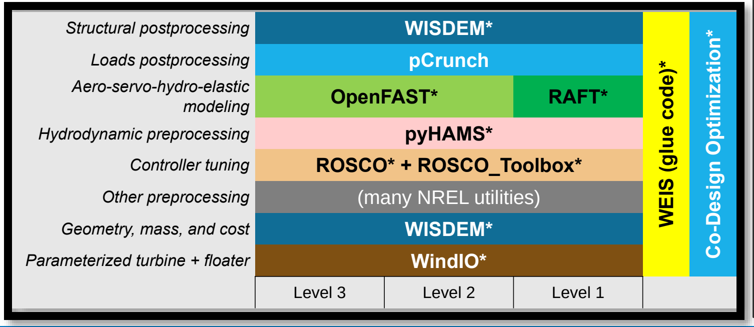
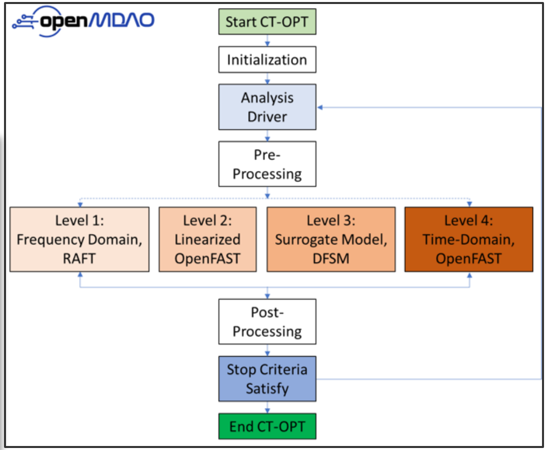


Illustration from Daniel Herber, Colorado State University

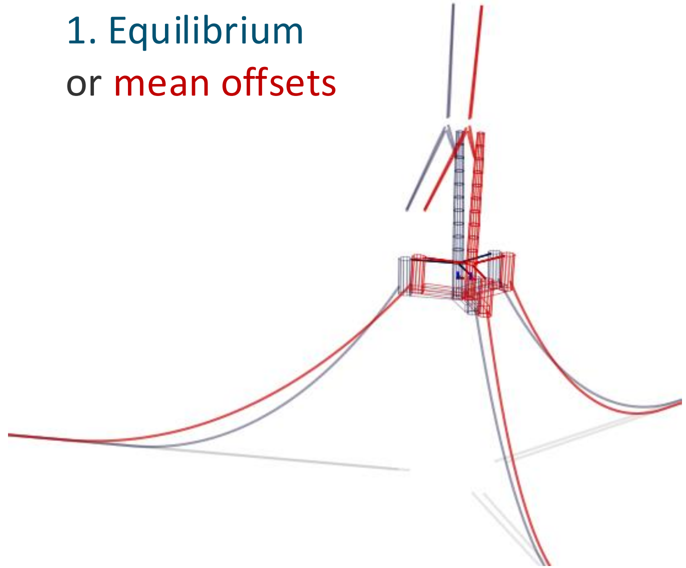


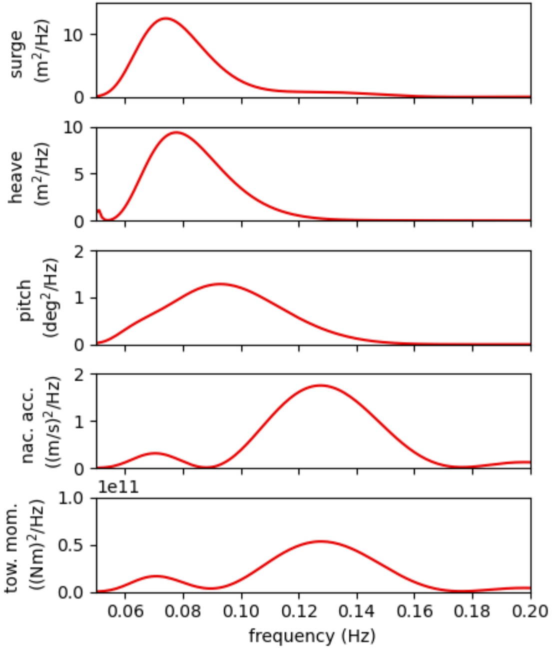


RAFT (Response Amplitudes of Floating Turbines)

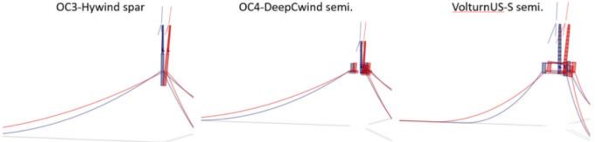
RAFT is an efficient Python-based model for floating turbine systems that solves two main things:

1. Equilibrium
or mean offsets

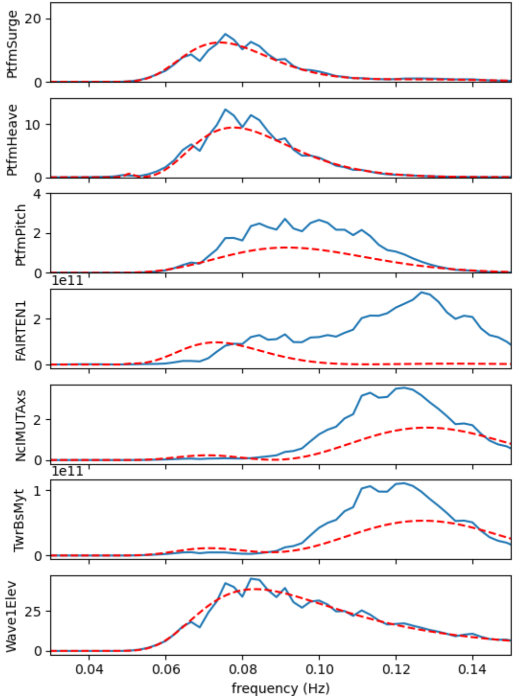




2. Steady-state frequency-domain response amplitudes or spectra



VolturnUS-S power spectral density comparison with OpenFAST

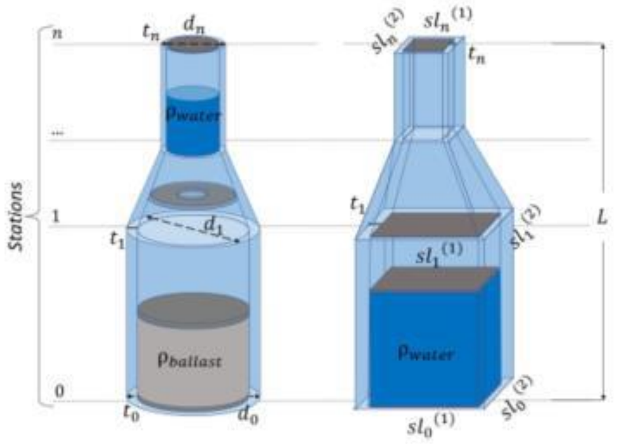


RAFT (Response Amplitudes of Floating Turbines)

- **Text-based**: RAFT's YAML input file format captures the complete design description and load case information.

Or

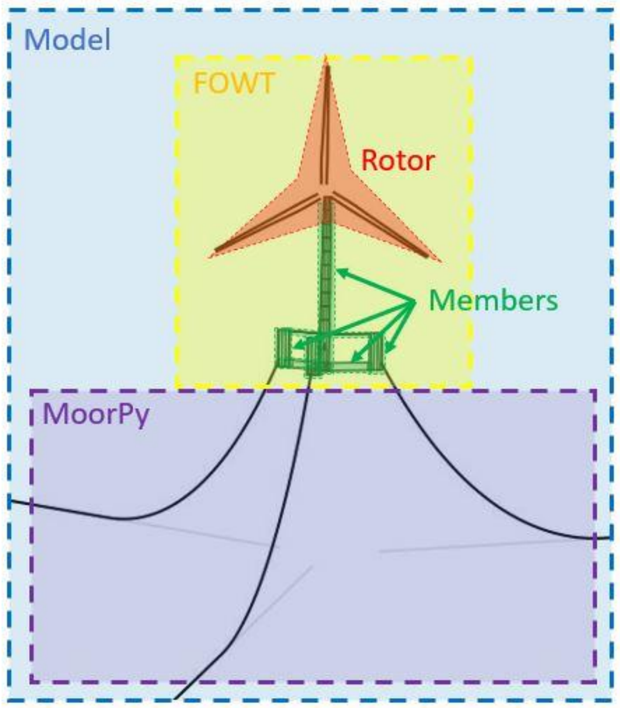
- **Programmatic**: Design and load case information can be specified through the Python API or OpenMDAOwrapper

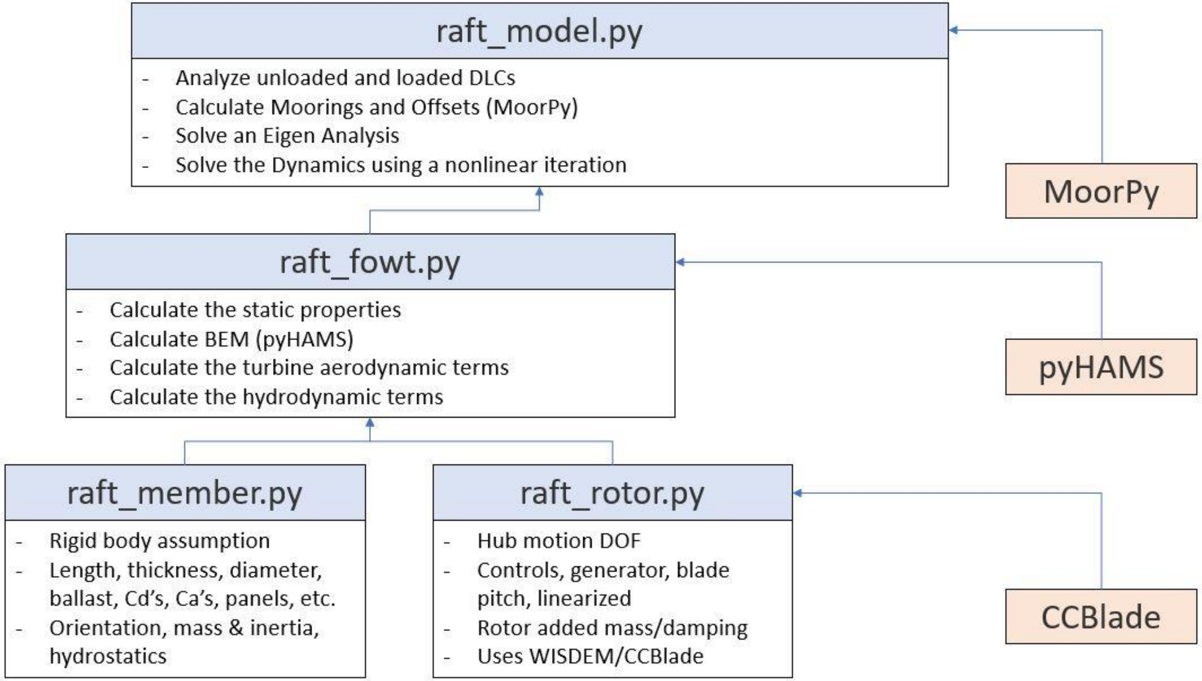



```yaml
type: input file for RAFT
name: 5MW with OC4-DeepCWind semi-sub

turbine:

    mRNA          :      350000          #  [kg]       RNA mass
    IxRNA         :    35444067          #  [kg-m2]    RNA moment of inertia about local x axis (assum
    IrRNA         :    26159984.0        #  [kg-m2]    RNA moment of inertia about local y or z axes |
    xCG_RNA       :           0          #  [m]        x location of RNA center of mass [m] (Actual is
    hHub          :        90.0          #  [m]        hub height above water line [m]
    Fthrust       :       800.0E3        #  [N]        temporary thrust force to use

    tower:  # (could remove some entries that don't apply for the tower)
        name      :  tower                          # [-]    an identifier (no longer has to be number)
        type      :  1                              # [-]
        rA        :  [ 0, 0,   10]                  # [m]    end A coordinates
        rB        :  [ 0, 0, 87.6]                  # [m]    and B coordinates
        shape     :  circ                           # [-]    circular or rectangular
        gamma     :  0.0                            # [deg]   twist angle about the member's z-axis
        # --- outer shell including hydro---
        stations  :  [ 10, 17.76, 25.52, 33.28, 41.04, 48.8, 56.56, 64.32, 72.08, 79.84, 87.6 ]
        d         :  [ 6.5, 6.237, 5.974, 5.711, 5.448, 5.185, 4.922, 4.659, 4.396, 4.133, 3.870 ]
        t         :  [ 0.027, 0.0262, 0.0254, 0.0246, 0.0238, 0.023, 0.0222, 0.0214, 0.0206, 0.0198
        rho_shell :  8500                           # [kg/m3]   material density

        # --- ballast ---
        l_fill    :  0                              # [m]
        rho_fill  :  0                              # [kg/m3]D
platform:

    min_freq_BEM : 0.03    #  [Hz]  lowest frequency and frequency interval to use in BEM analysis
    dz_BEM       : 3.0     #  [m]   axial discretization panel length target for BEM analysis
    da_BEM       : 2.0     #  [m]   azimuthal discretization panel length target for BEM analysis
    potModMaster : 1

    members:   # list all members here

      - name      :  main_column                    # [-]    an identifier (no longer has to be number)
        type      :  2                              # [-]    (1=turbine, >1=substructure, for now)
        rA        :  [ 0, 0,  -20]                  # [m]    end A coordinates
        rB        :  [ 0, 0,   10]                  # [m]    and B coordinates
        shape     :  circ                           # [-]    circular or rectangular
        gamma     :  0.0                            # [deg]  twist angle about the member's z-axis
```

RAFT Structure

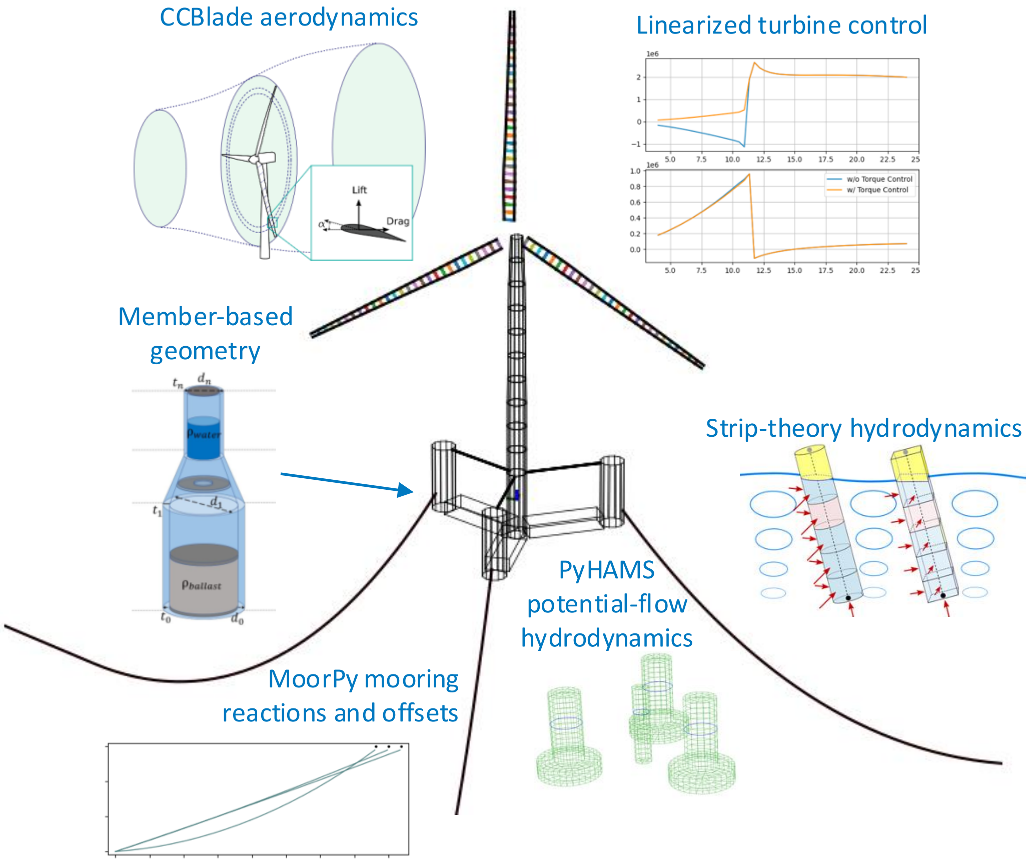
RAFT represents a floating turbine system as a collection of different object types.

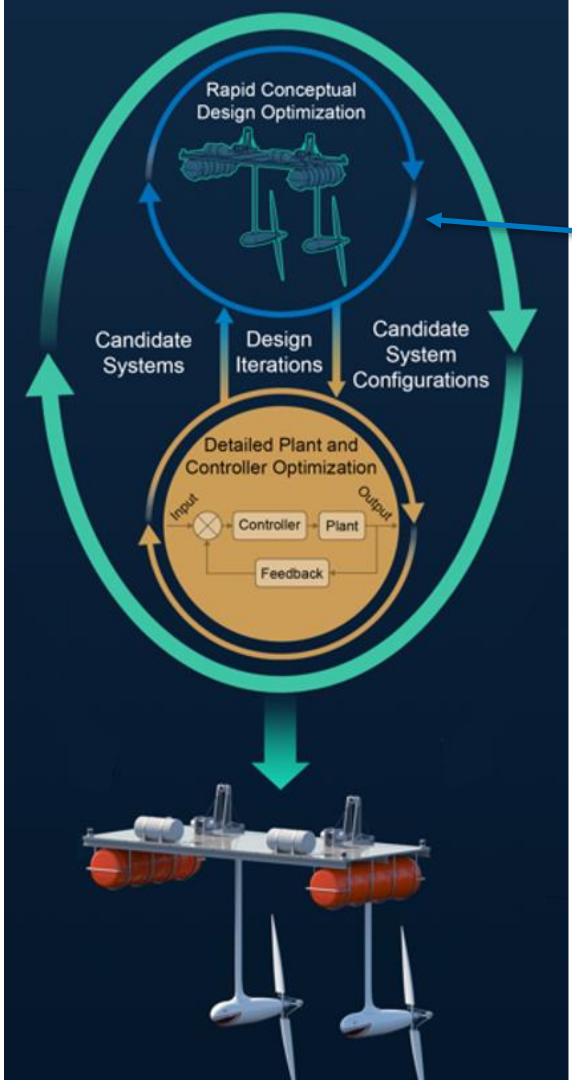




RAFT Model Components

- Blade-element-momentum rotor fluid dynamics
  - CCBlade solves rotor linearized aerodynamic coefficients across wind speed range
- Linearized turbine pitch and torque control
  - Frequency-dependent response contributes added mass, damping, and excitation
- Substructure composed of distinct members
  - Cylindrical or rectangular cross sections
- Versatile hydrodynamics modeling
  - Linearized strip-theory model
  - Potential-flow coefficients from pyHAMS
- Mooring system and mean offsets
  - MoorPy solves nonlinear system mean offsets and linearized mooring reactions
- Rigid floating system response solution





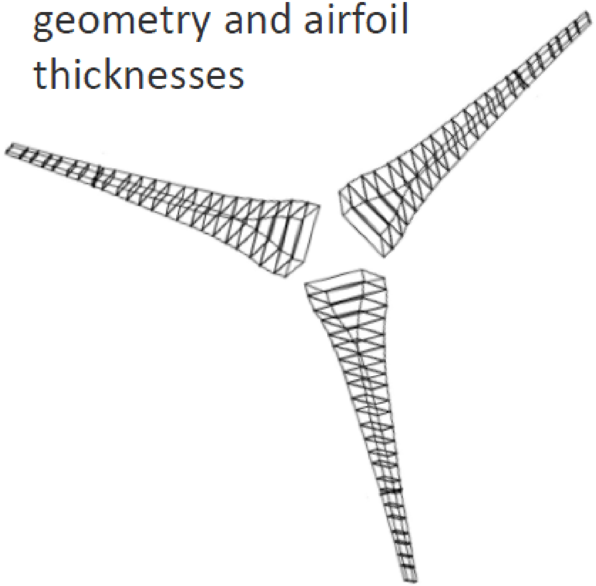
Adding MHK Capabilities in RAFT

- RAFT is the Level 1 model in CT-Opt to provide efficient design exploration of MHK turbine topologies
- New modeling features to support these applications:

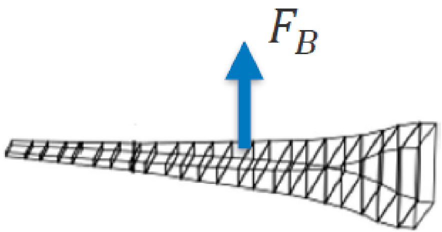
Rotor added mass effects
Fluid inertia excitation on rotor
Buoyancy forces on rotor
Blockage effects multirotor/seabed/surface
Cavitation check
Multiple rotors and arbitrary attachment
Rotor gyroscopic reactions
Quasi-dynamic mooring line modeling
Mean current profile with depth

New Capabilities: Rotor Buoyancy and Added Mass

RAFT constructs a simplified rotor representation with rectangular sections based on the rotor geometry and airfoil thicknesses



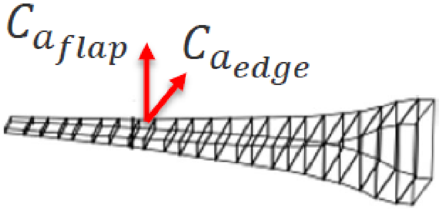
Rotor buoyancy



Buoyancy forces are calculated based on the volume of each section

$$F_B = \rho g V$$

Rotor added mass



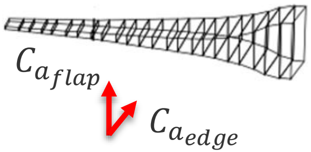
Each section has flapwise and edgewise added mass coefficients to produce the rotor added mass matrix

New Capabilities: Rotor inertial excitation and blockage effects

- Rotor inertial excitation forces (due to accelerations of the inflow current) is now modeled based on rotor added mass coefficients

- Blockage effects on the rotor performance are now included through user-specified inflow speed scaling coefficients
  - For specific cases these can be tuned to represent increased inflow speed due to proximity to the seabed, the sea surface, or other rotors

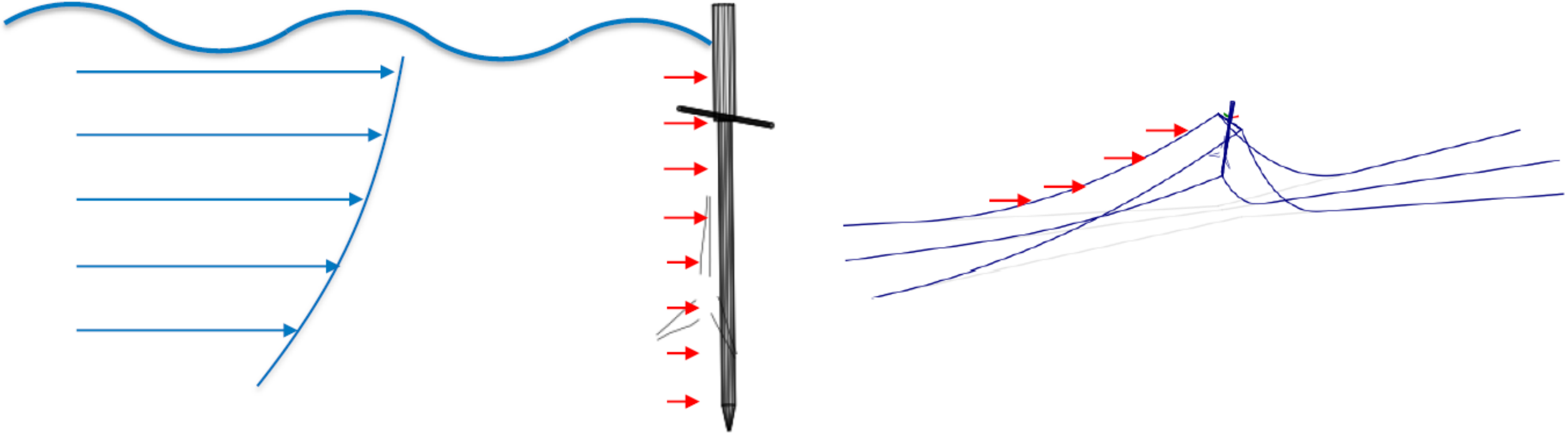
- *Verification of new features will depend on the creation of a proper reference design and subsequent comparison with OpenFAST results*



Each rectangular member is an interpolated airfoil with an edgewise and flapwise added mass coefficient. The summed coefficients are multiplied by the frequency-dependent inflow acceleration.

New Capabilities: Current Profile and Drag Loads

Power-Law Current Profile | *Drag on Substructure* | *Drag on Mooring System*

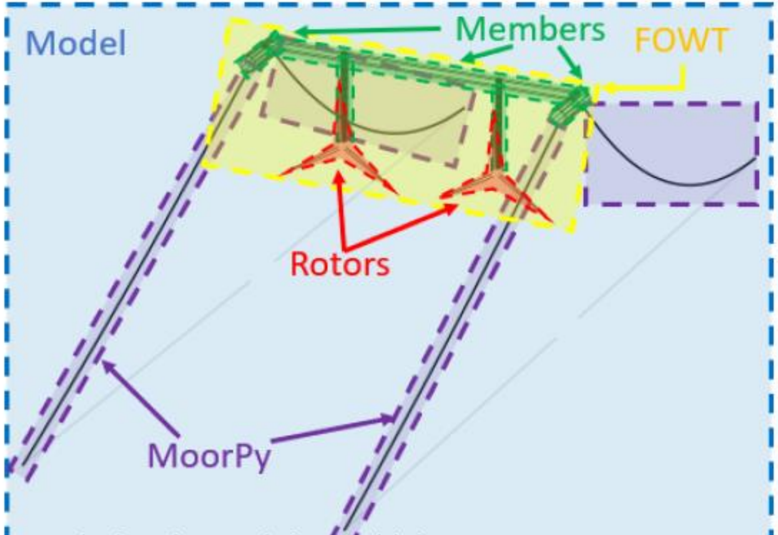


Steady current flow with a power law profile is superimposed with wave kinematics to compute drag loads on the support structure

36

New Capabilities: Multiple Rotors and Cavitation

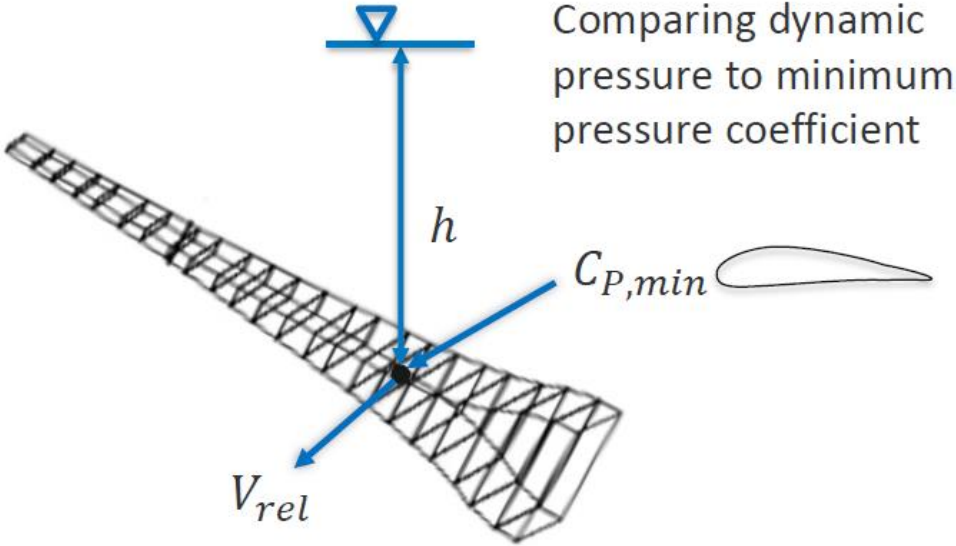
Multiple Rotors



Example of a multi-rotor platform modeled in RAFT. *Illustration by Stein Housner, NREL*

Support for multiple arbitrary rotors and attachment structures

Cavitation Check

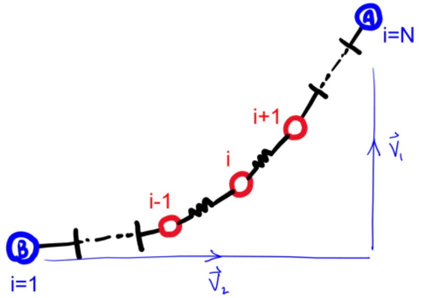


$$\sigma_{crit} = \frac{P_{atm} + \rho g h - P_{vap}}{0.5 \rho V_{rel}^2} < -C_{P,min}$$

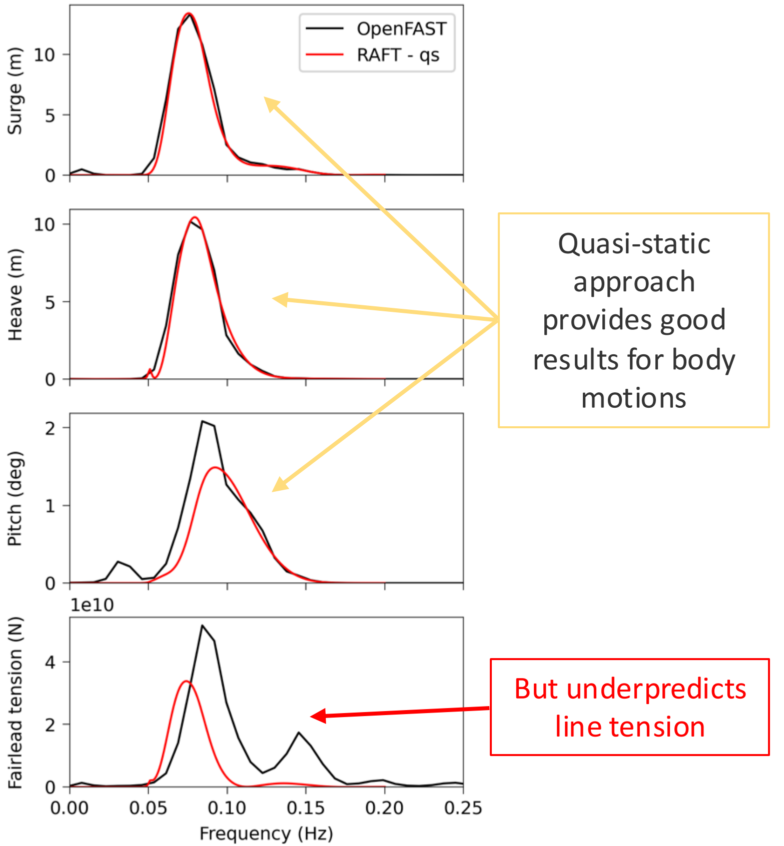
37

New Capabilities: Dynamic Mooring Line Tensions

- Implemented a lumped mass approach in MoorPy that can account for **line inertia, hydrodynamic added mass, and (linearized) hydrodynamic drag** acting to improve predictions of mooring line tensions



- The mooring line is discretized in nodes with a lumped mass connected by a spring and damper (same approach as MoorDyn)
- Requires a MoorDyn format input file



RAFT Documentation: New MHK Page

RAFT

Search docs

- Home
- Getting Started
- Model Structure
- Usage and Workflow
- MHK Turbine Applications
  - Setting up and Running RAFT
  - Additional Phenomena
  - Input File Differences
  - Example MHK Turbine Case
- Theory

MHK Turbine Applications

As part of the CT-Opt project, RAFT is being expanded to also support underwater marine hydrokinetic (MHK) turbines. Just as with floating wind turbines, RAFT supports frequency-domain modeling of the global response and linearized controlled rotor dynamics of a moored, floating, MHK turbine system. The initial capability for floating MHK systems, which is still being developed, is available in RAFT's CT-Opt branch on GitHub.

This page provides information about using the under-development MHK capabilities of RAFT. Please refer to the other pages for general usage, and then this page for specific usage changes needed for MHK applications.

Setting up and Running RAFT

Usage patterns for MHK applications are identical to those for floating wind turbine applications. Refer to the Usage and Workflow page for more information.

The main differences for MHK applications are in how the design is set up in the input dictionary or YAML file. Current speed, shear exponent, and heading must be entered in the Case input section. And the rotor location must be specified beneath the seabed.

Additional Phenomena

For MHK applications, RAFT simulates a number of additional phenomena. The features that have been added are as follows.

- Rotor added mass

Input File Differences

(This section to be updated)

There are no changes in the modeling settings.

In site characteristics, viscosity and shear exponent have been added for water to use in current loading and rotor hydrodynamic calculations:

```
site:
    water_depth : 60          # [m]       uniform water depth
    rho_water   : 1025.0      # [kg/m^3] water density
    rho_air     : 1.225       # [kg/m^3] air density
    mu_air      : 1.81e-05    #           air dynamic viscosity
    shearExp_air: 0.12        #           wind shear exponent
    mu_water    : 1.00e-03    # [kg/ms]  water dynamic viscosity
    shearExp_water : 0.12     #           current shear exponent
```

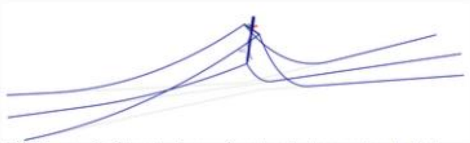
In Load Cases, the list of case parameters has been edited and expanded to consist of the following:

- wind_speed
- wind_heading
- wind_turbulence
- turbine_status

Example MHK Turbine Case

A rough example MHK turbine case has been added to the designs included in RAFT. While a proper reference design is in development, this example can be used to demonstrate the new features. See the FOCTT_example.yaml file for more information.

The figure below is generated by RAFT and shows the calcualted system equilibrium state in unloaded and loaded conditions (produced using the Model.plot method).



As with FOWTs, properties like natural frequencies and mode shapes can be calculated.

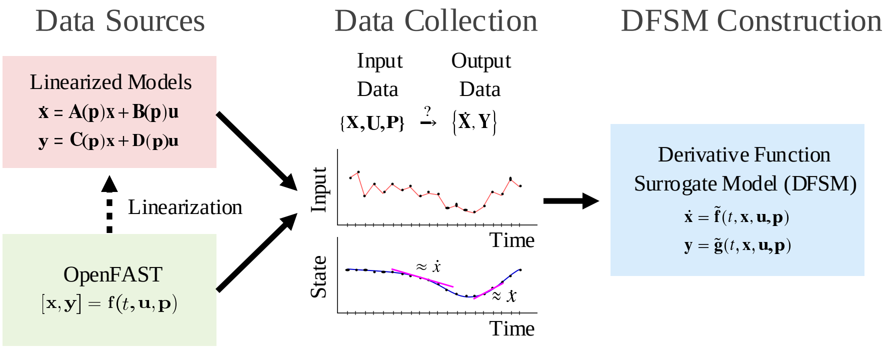
The plot below show the power spectral densities of select responses calculated from a basic load case (produced using the Model.plotResponse method).

https://openraft.readthedocs.io/en/ctopt/ctopt.html

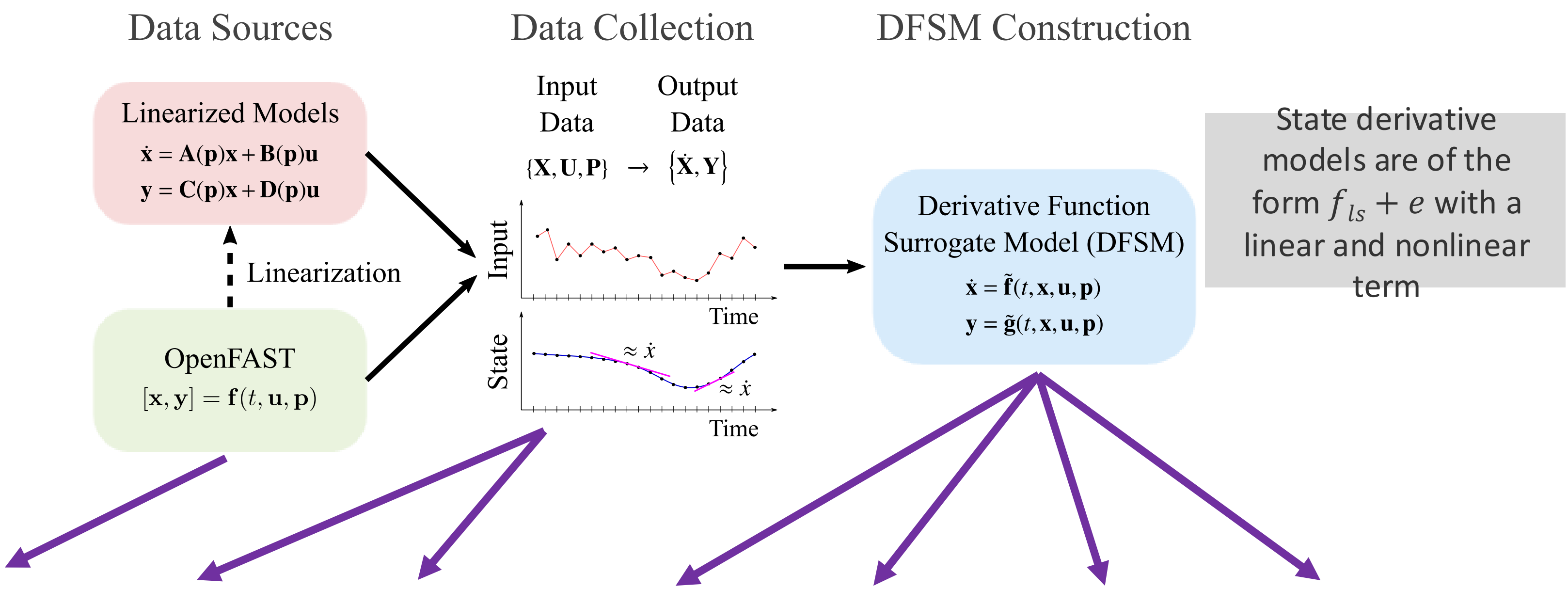
39

Derivative Function Surrogate Modeling (DFSM)

- Provide more effective dynamic models for use in **control co-design studies**, especially when the ground truth model is particularly expensive
- Accomplish by approximating state derivatives using information from OpenFAST simulation data
  - Smoothed interpolating polynomial approximation of the states are used to predict the state derivatives
- Two approaches for building the DSFM:
  - Linear regression-based approach providing a linear dynamic model
  - Neural network (NN)-based approach providing a nonlinear dynamic model
- This DFSM model then can be used for CCD optimization at Levels 2 and 3 (both open-loop and closed-loop studies)



Multi-fidelity DFSM Approach



Data Sources (1)
- Run OpenFAST to obtain simulation

Data Collection (1)
- Filter data to remove high frequency noise from simulation results

Data Collection (2)
- Construct polynomial approximation of states and determine the approximate state derivatives

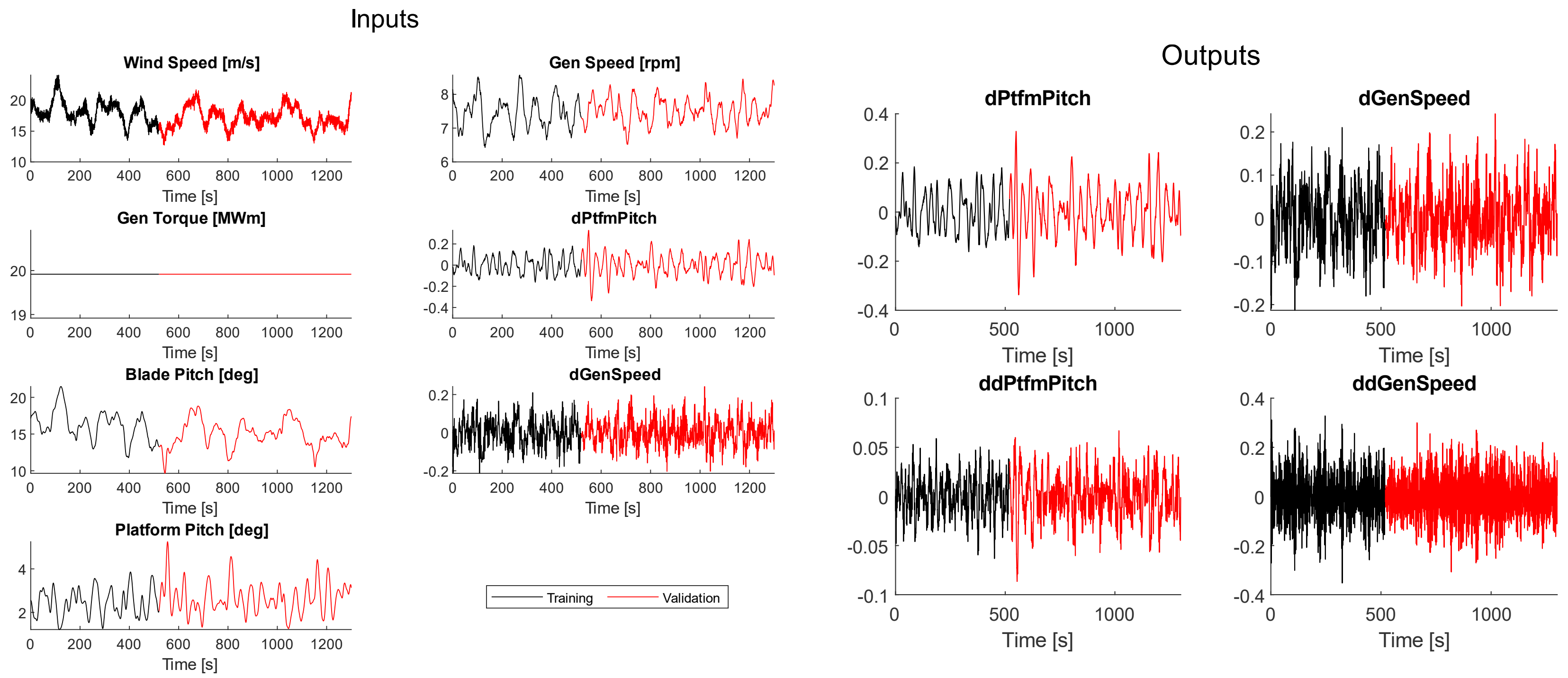
DFSM Construction (1)
- Fit a linear model between state derivatives and states and controls to obtain f_{ls}

DFSM Construction (2)
- Evaluate error between linear-fit model f_{ls} and original derivatives 'e'

DFSM Construction (3)
- Train a Gaussian Process Regression (GPR) model to predict the error 'e'

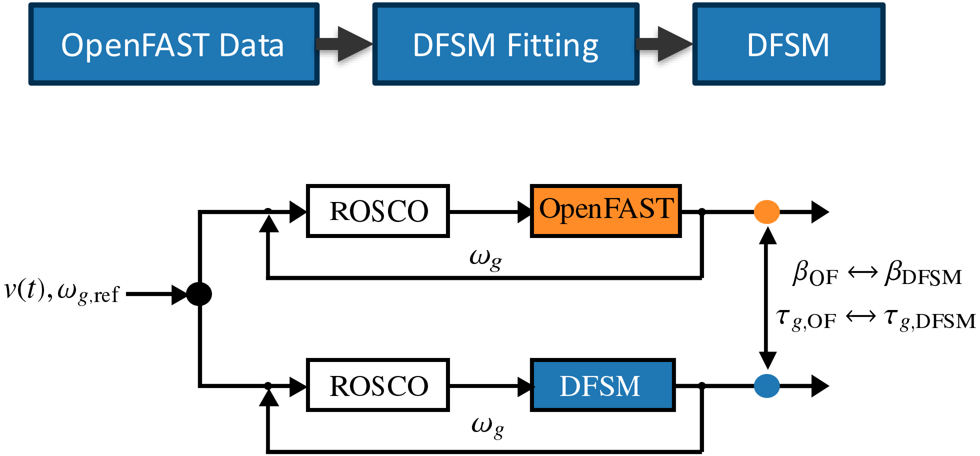
DFSM Construction(4)
- Test the multifidelity model 'f_{ls}+e'

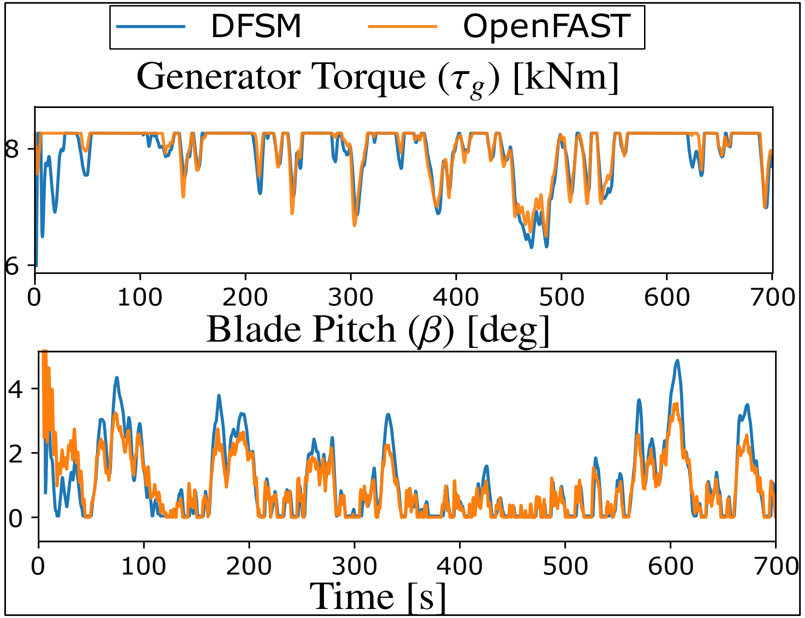
DFSM Approach: Input and Output Data from OpenFAST



Time series plot of inputs, outputs, and the training/validation splits used to train and test the network

DFSM Approach: Validation Test and Results

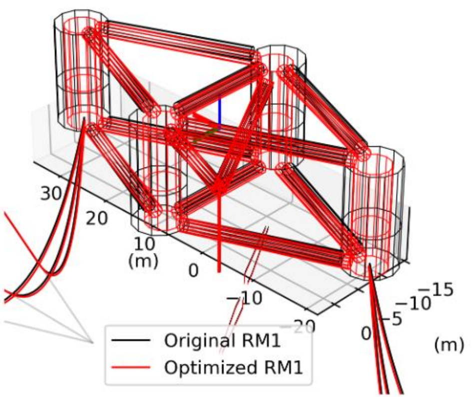




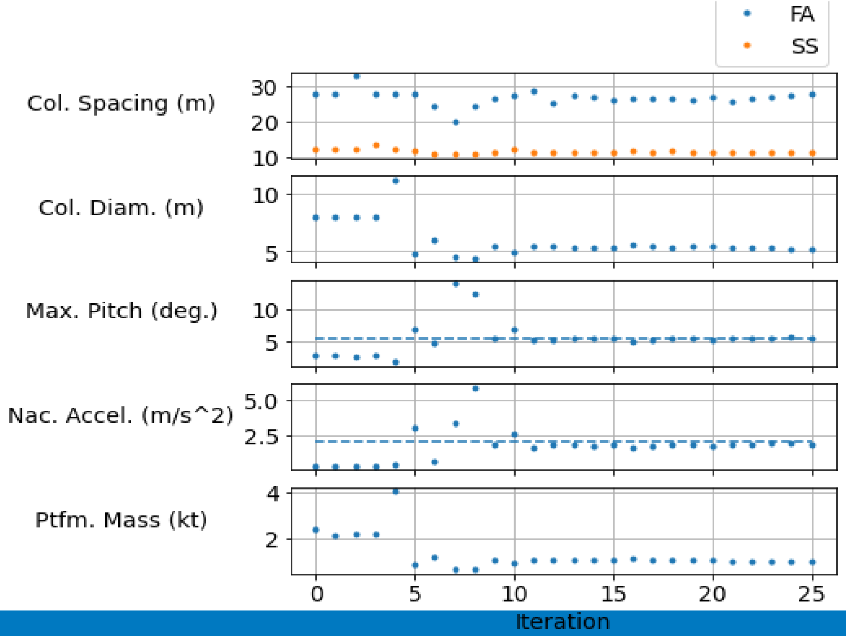
About **1000x speed-up** for one simulation
OpenFAST simulation : 17 hours
DFSM simulation: 67 sec

Results for a case primarily in the transition region

Simple Platform Optimization in CT-Opt

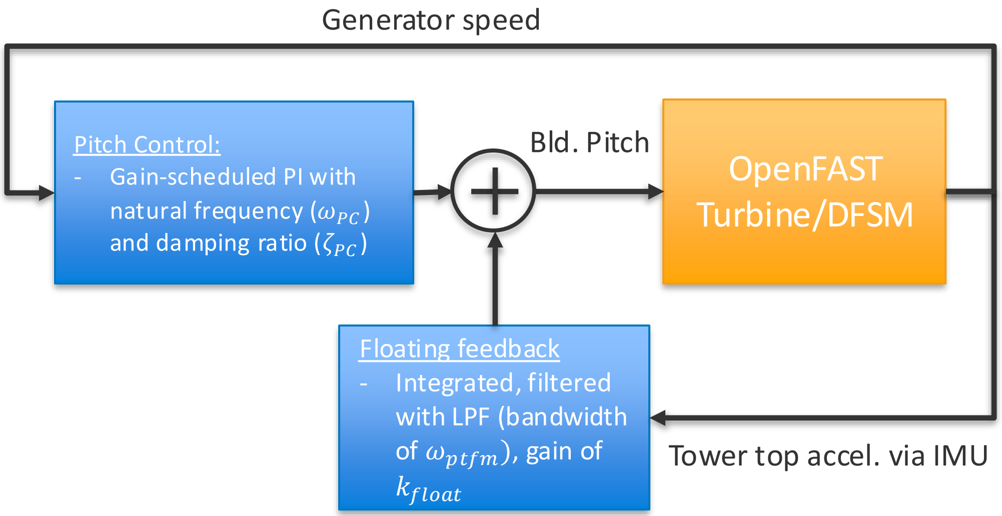


- Geometry Options
  - RM1 initial platform design (right)
- Analysis Options
  - Design Variables
    - Column spacing: Fore-aft, port-starboard
    - Column diameter (smaller)
    - Draft, freeboard (to be investigated)
  - Constraints
    - Pitch, heave period > 10 seconds (to be investigated)
    - Ballast capacity, draft/freeboard margin
    - Max. nacelle acceleration (< 2 m/s^2, active)
    - Maximum platform pitch (< 5.5 deg, active)
  - Merit Figure: Platform mass (60% reduction)
- Modeling options
  - OpenFAST used for dynamic constraints
  - RAFT used for period calculations
  - DLC 1.1 (normal operation, Cook Inlet metocean)



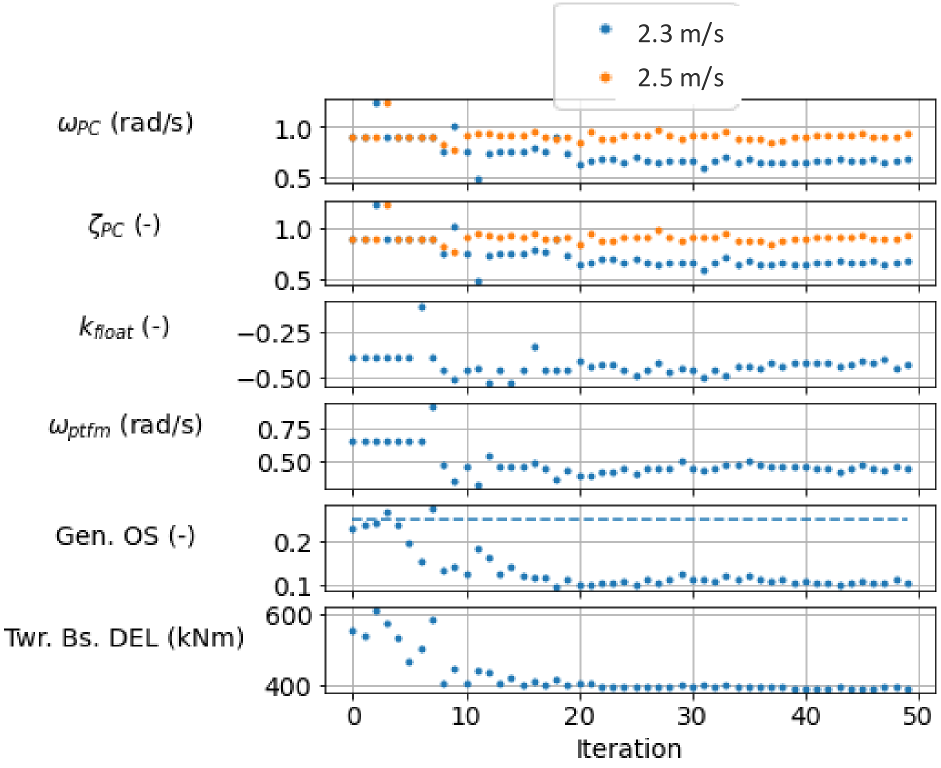
Controller Optimization in CT-Opt

- Geometry Options
  - RM1 initial platform design with initial controller
- Analysis Options
  - Design Variables
    - Pitch control bandwidth (ω_{PC}), damping (ζ_{PC}) at various wind speeds
    - Floating feedback gain (k_{float}) and filter (ω_{ptfm})
  - Constraints
    - Generator overspeed
  - Merit Figure: Tower base DELs (typically used in FOWT optimizations, first attempt at MHK)
- Modeling options
  - OpenFAST with DLC 1.1 (normal operation, Cook Inlet metocean)



Controller Optimization in CT-Opt

- Geometry Options
  - RM1 initial platform design with initial controller
- Analysis Options
  - Design Variables
    - Pitch control bandwidth (ω_{PC}), damping (ζ_{PC}) at various wind speeds
    - Floating feedback gain (k_{float}) and filter (ω_{ptfm})
  - Constraints
    - Generator overspeed
  - Merit Figure: Tower base DELs (typically used in FOWT optimizations, first attempt at MHK)
- Modeling options
  - OpenFAST with DLC 1.1 (normal operation, Cook Inlet metocean)



CT-Opt Demonstration Results

- Used CT-Opt to demonstrate several pathways towards LCOE reduction
  - Platform hull reduction: -7.4%
  - With additional mooring cost reduction: -16.3%

  - Increased rotor size: -7.6%
  - Increased generator size: -22.5%
  - Increased both: -28.9%

- Output: System engineering and OpenFAST models (along with lower fidelity models) for further analysis