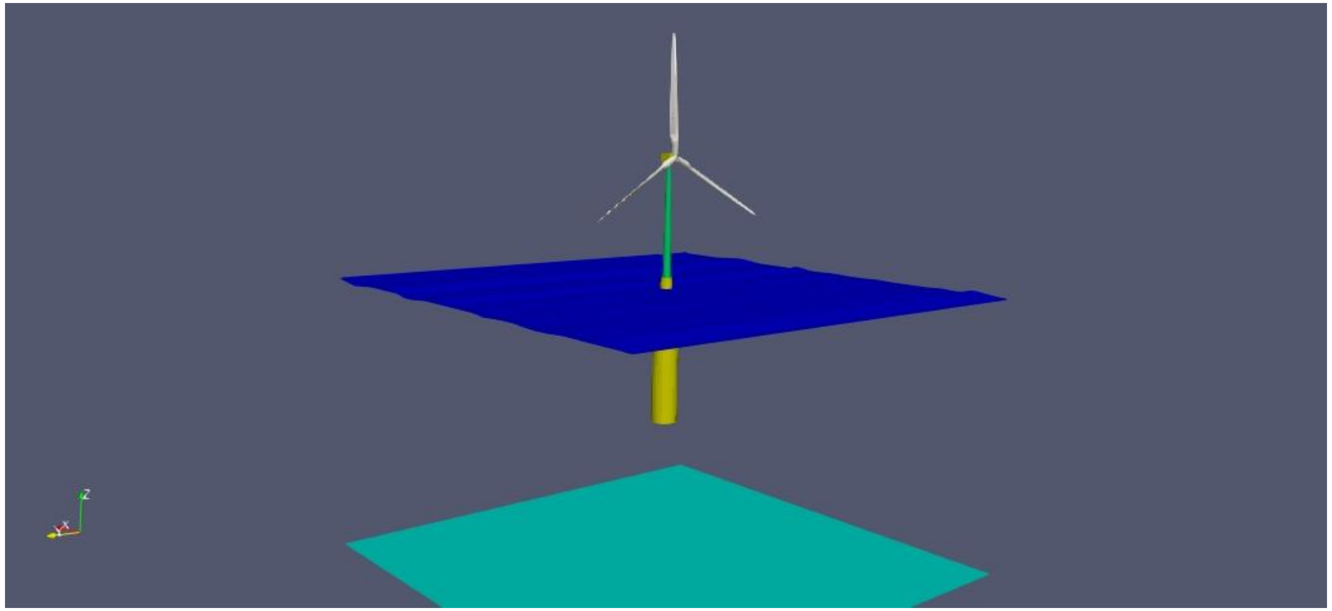
Introduction to FAST
(Fatigue, Aerodynamics, Structures and Turbulence)

Athanassios Dimas, Maria Parisopoulou, Georgia Tsoukleri

Department of Civil Engineering, University of Patras

Outline



1. FAST: origin and applications
2. FAST: methods and software structure
3. OpenFAST: installation and use
4. OpenFAST: examples and results

1. FAST: origin and applications

F A S T

F: a t i g u e — A: e r o d y n a m i c s — S: t r u c t u r e s — T: u r b u l e n c e

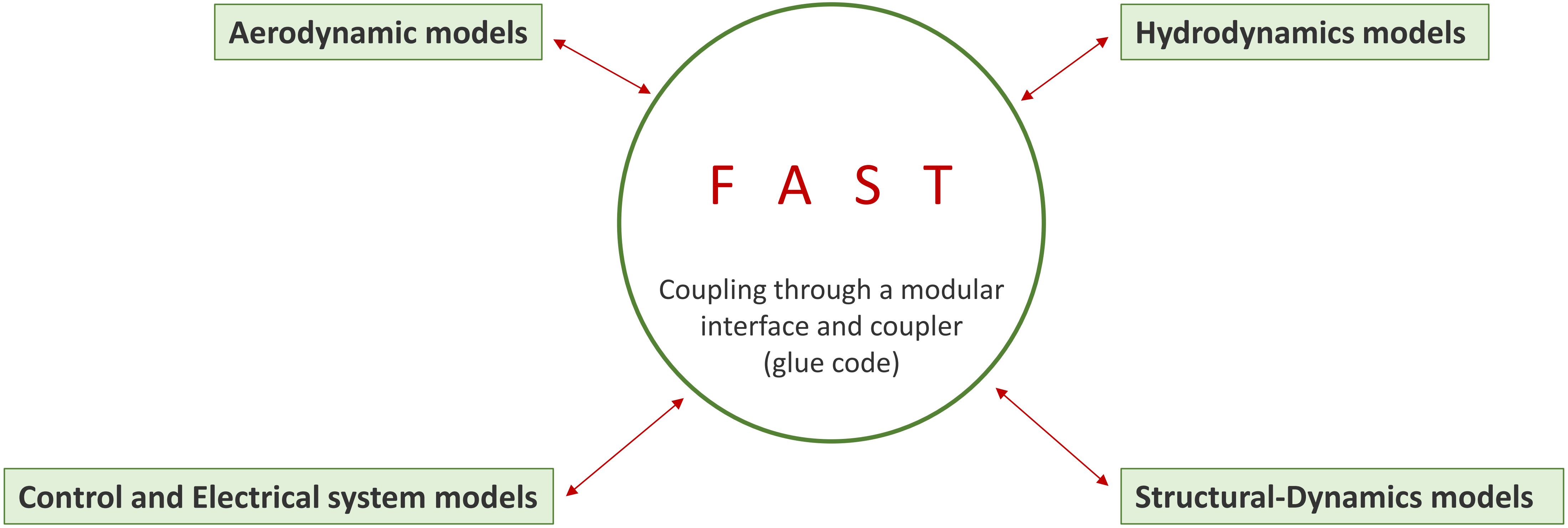
→ **NREL's** primary physics-based engineering tool for simulating the coupled dynamic response of wind turbines.

Combines:

- aerodynamics models,
- hydrodynamics models for offshore structures,
- control and electrical system (servo) dynamics models,
- structural (elastic) dynamics models

Coupled nonlinear aero-hydro-servo-elastic simulation in the time domain

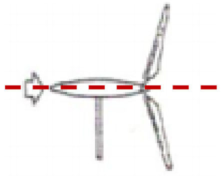
1. FAST: origin and applications



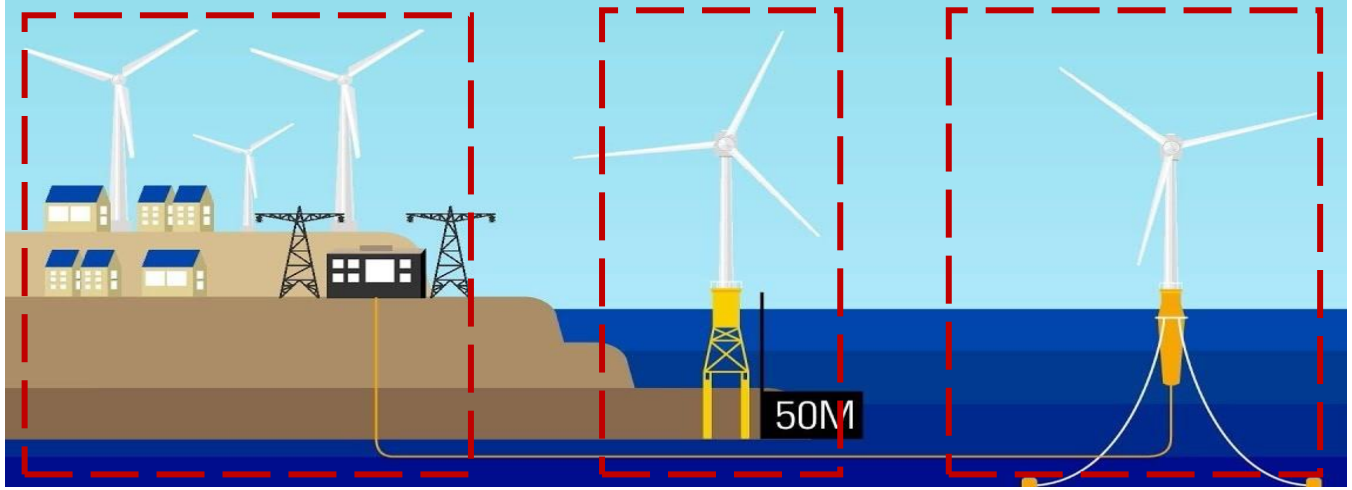
1. FAST: origin and applications

FAST tool enables the analysis of a range of wind turbine configurations, including :

Horizontal-Axis Wind Turbines can be modeled:



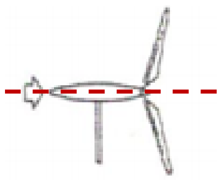
- Land
- Offshore
- Floating



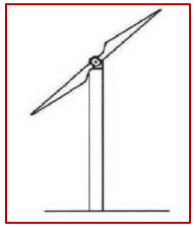
1. FAST: origin and applications

FAST tool enables the analysis of a range of wind turbine configurations, including :

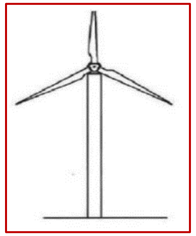
Horizontal-axis Rotor:



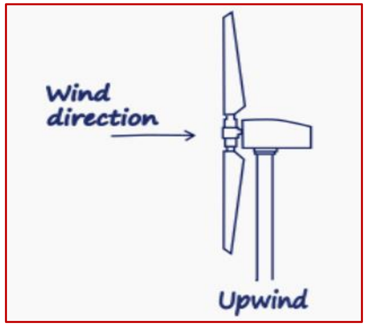
Two-Blade:



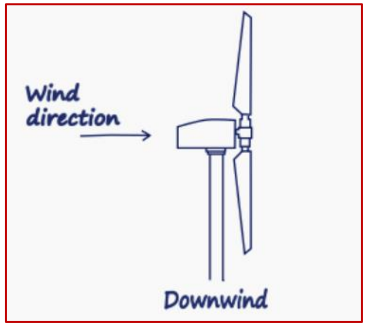
Three-Blade:



Upwind:



Downwind:

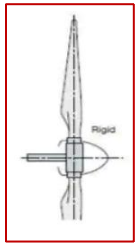


1. FAST: origin and applications

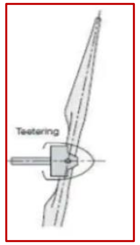
FAST tool enables the analysis of a range of wind turbine configurations, including :

Hub:

- Rigid:

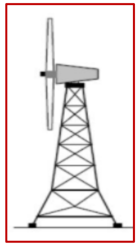


- Teetering:

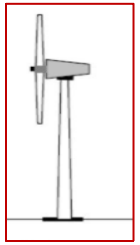


Tower:

- Lattice:



- Tubular:



Regulation:

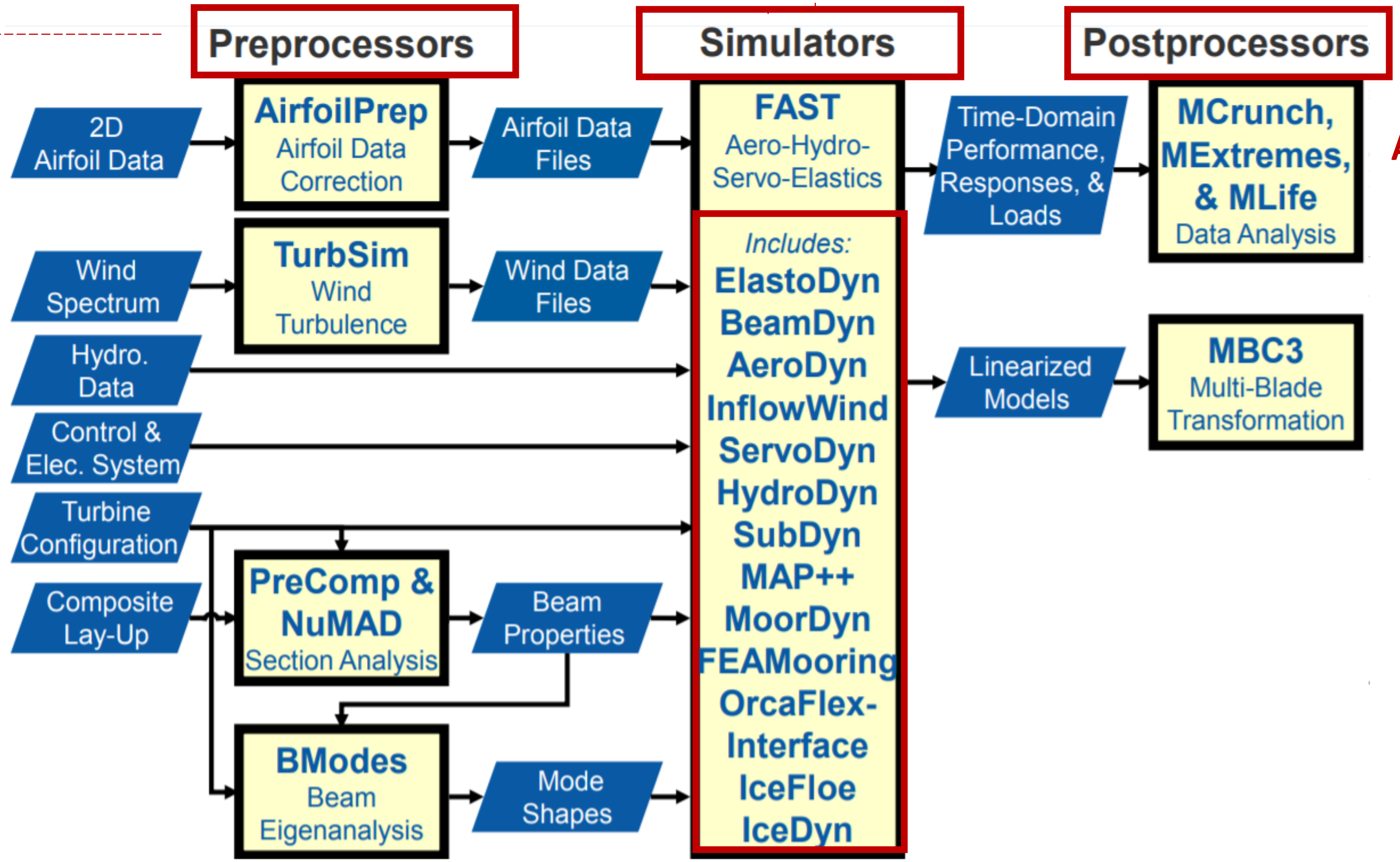
- Pitch
- Stall

2. FAST: methods and software structure

Perform the analysis

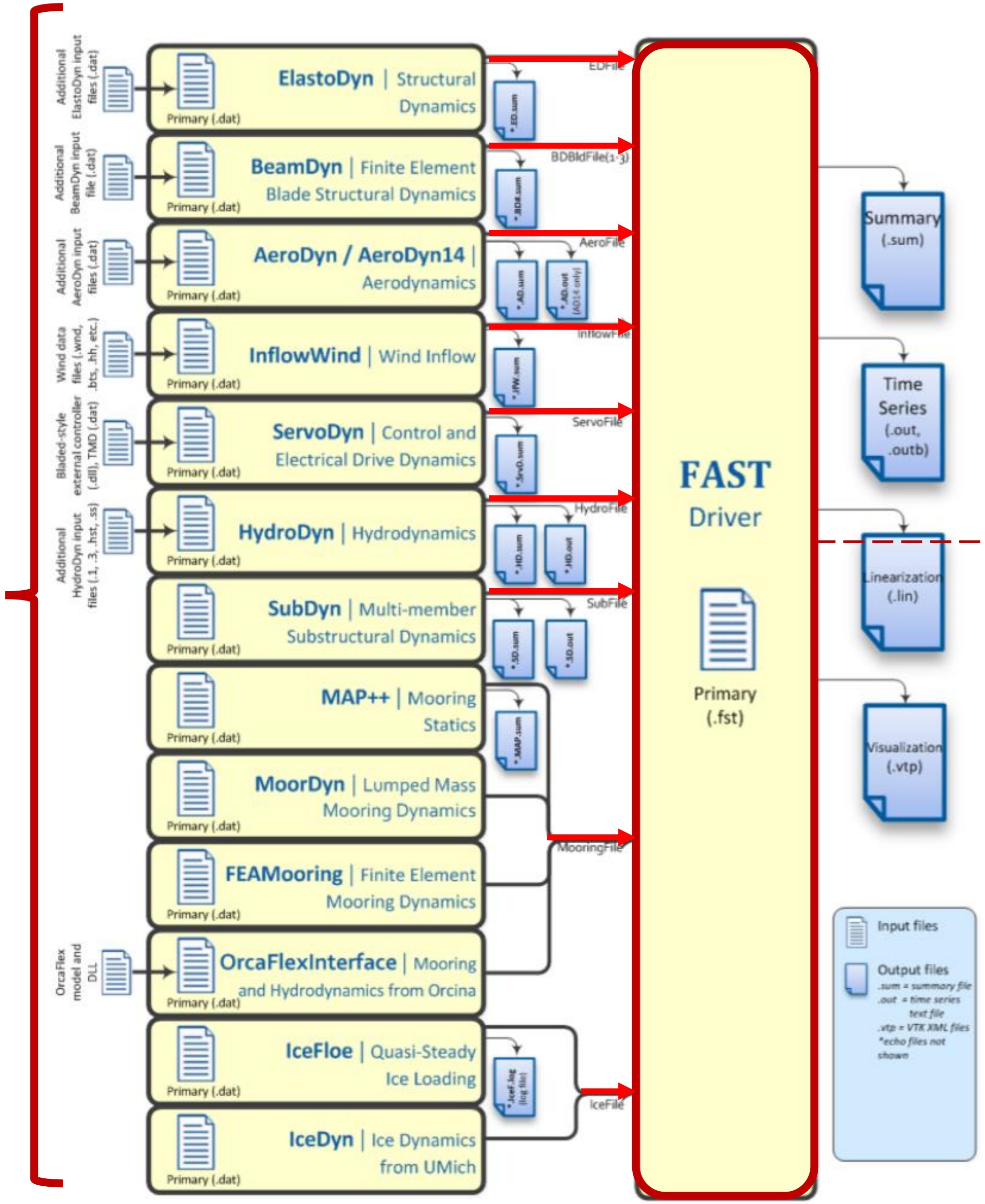
Help build models

Analyze the results



2. FAST: methods and software structure

Modules of FAST



Primary Input File (".fst")

- Describes the wind turbine's operating parameters
- Defines the paths of the operating modules

2. FAST: methods and software structure

TurbSim →

- Stochastic, full-field, turbulent-wind simulator (Preprocessor).

Statistical Model →

Simulates:

Time series of three-component windspeed vectors (u, v, w) at points in a 2D vertical rectangular grid that is fixed in space

→

Output:

Wind Velocity Vectors (u, v, w)

→ **Input to AeroDyn**

2. FAST: methods and software structure

AeroDyn →

- Aerodynamics module for use by designers of horizontal-axis wind turbines.
- Can also be driven as a standalone code, uncoupled from FAST.

TurbSim's Output:
Wind Velocity Vectors →

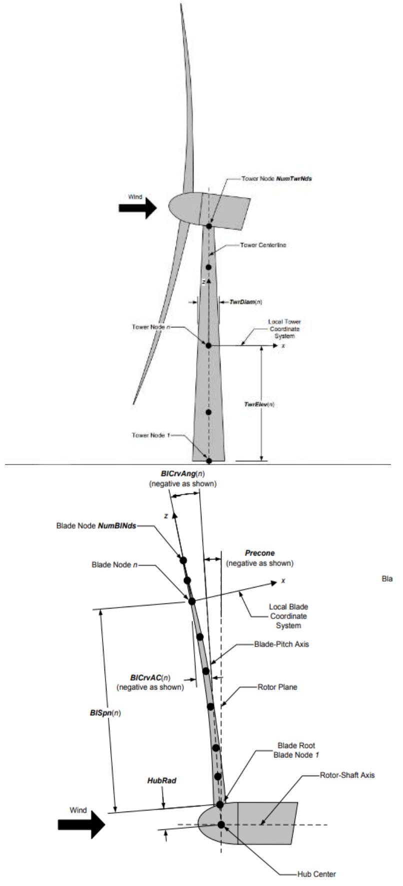
Input Parameters:

Blade discretization
Inflow model
Operating Condition
Wind data
Wind reference hub height

→

Output:

Aerodynamic and kinematic quantities at up to 9 nodes along the tower and up to 9 nodes along each blade



2. FAST: methods and software structure

HydroDyn →

- Time-domain hydrodynamics module.
- Can also be driven as a standalone code, uncoupled from FAST.
- Approaches for calculating the hydrodynamic loads on a structure: a potential-flow theory solution, a strip-theory solution, or a combination of the two.
- Waves can be regular or irregular, long-crested or short-crested and are treated using first-order or first- plus second-order wave theory.

Input Parameters:
Environmental conditions
Incident wave kinematics and current
Substructure geometry
Hydrodynamic coefficients
Marine growth
Potential-flow solution options
Flooding/Ballasting

→

Output:
Hydrodynamic loads at nodes of the structure

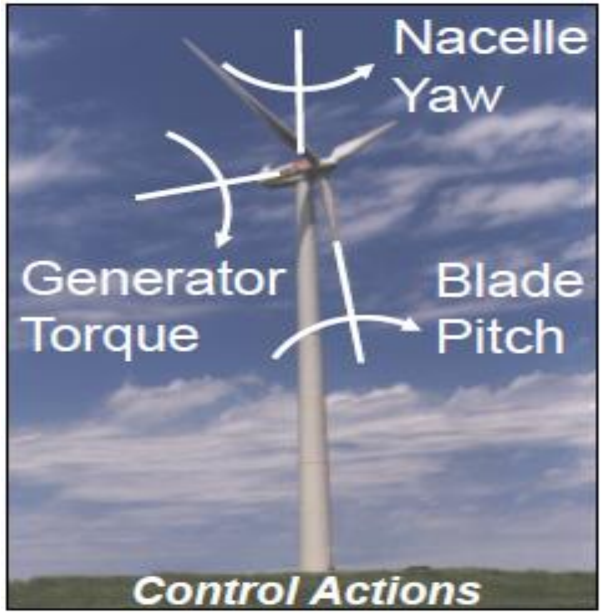
2. FAST: methods and software structure

ServoDyn →

- Control and electrical system (Servo) dynamics (Dyn) module.

Control Actions:

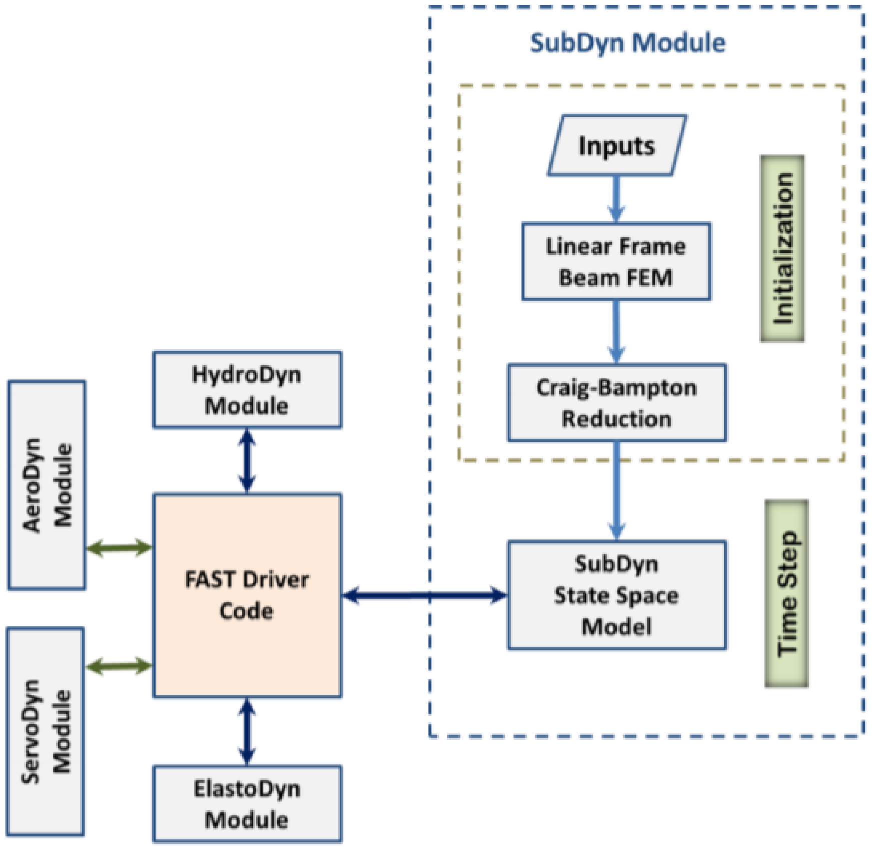
Blade-Pitch control
Generator-Torque control
Nacelle-Yaw control
Nacelle-based tuned-mass dampers
Tower-based tuned-mass dampers
Blade-tip brake



2. FAST: methods and software structure

SubDyn →

- Time-domain structural-dynamics module for multi-member fixed-bottom substructures.
- Fixed-bottom substructure types :**monopiles, tripods, jackets, and other lattice-type substructures**



Input Parameters:

Substructure geometry
Material properties
Stiffness/damping coefficients
Finite element resolution
Restrains

→

Output:

Loads and kinematic quantities at nodes of the structure

2. FAST: methods and software structure

ElastoDyn →

- Time-domain structural-dynamics module for slender structures.

Input:

Aerodynamic loads
Hydrodynamic loads
Controller commands
Substructure reactions

→

Input Parameters:

Geometry
Mass/inertia
Stiffness coefficients
Damping coefficients
Gravity

→

Output:

Displacements
Velocities
Accelerations
Reaction loads

☆ **BeamDyn** →

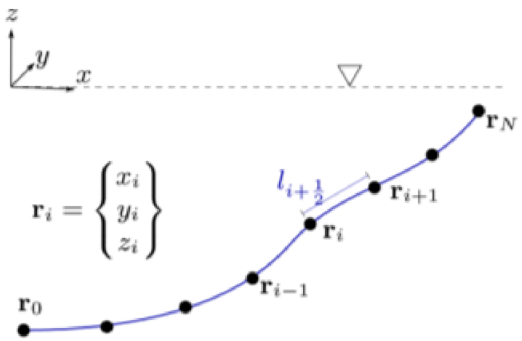
- Replaces the more simplified blade structural model of ElastoDyn (still available)
- Applicable to straight isotropic blades dominated by bending

2. FAST: methods and software structure

MAP++/MoorDyn/FEAMooring/OrcaflexInterface → Mooring file

MoorDyn →

- **Uses** a lumped-mass approach to discretize the cable dynamics over the length of the mooring line. A cable is broken up into N evenly-sized line segments connecting N+1 node points.



- **It accounts for** internal axial stiffness and damping forces, weight and buoyancy forces, hydrodynamic forces from Morison's equation, and vertical spring-damper forces from contact with the seabed.

2. FAST: methods and software structure

IceDyn/Icefloe → Ice file

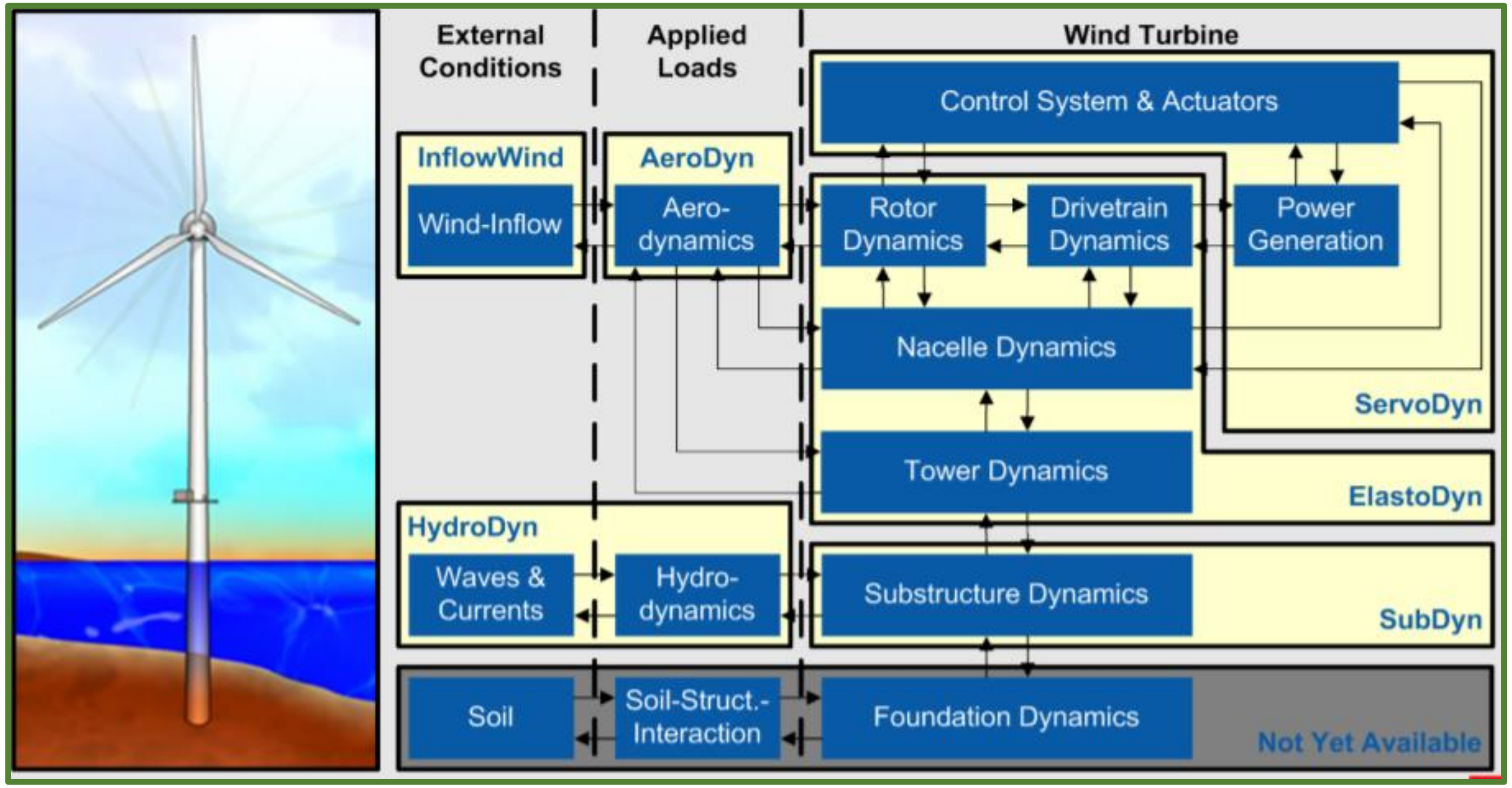
IceDyn →

- Calculates time-domain loads induced by surface ice on offshore substructures.
- Includes six ice mechanics models that incorporate ice floe forcing, deformation and failure and structure geometry:

1. Quasi-static ice loading on vertical structure
2. Dynamic ice loading on vertical structure
3. Random ice loading on vertical structure
4. Non-simultaneous ice loading on vertical structure
5. Ice loading on sloping structure
6. Large ice floe impact.

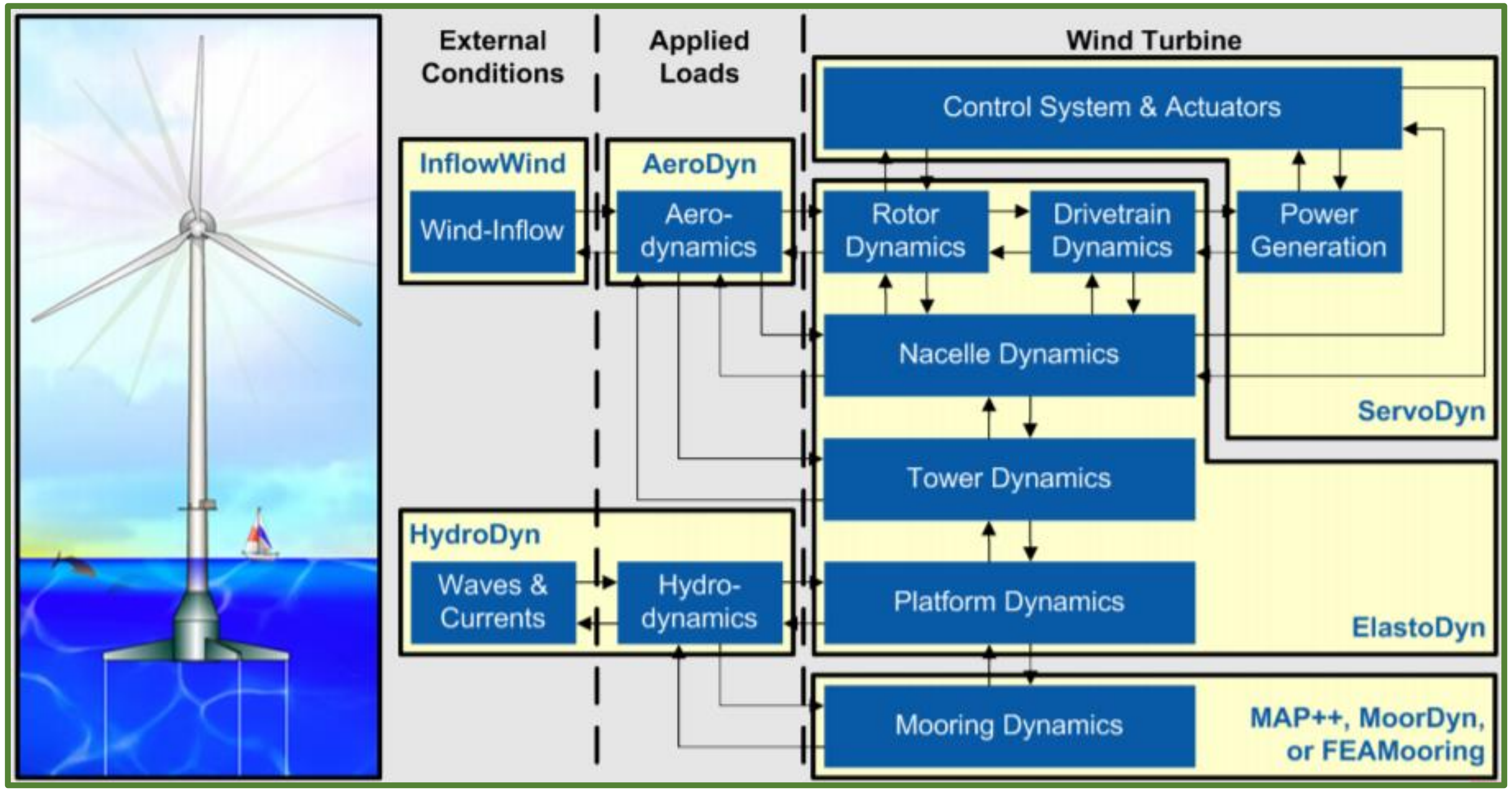
2. FAST: methods and software structure

FAST Module Control Volumes – Bed-fixed OWT

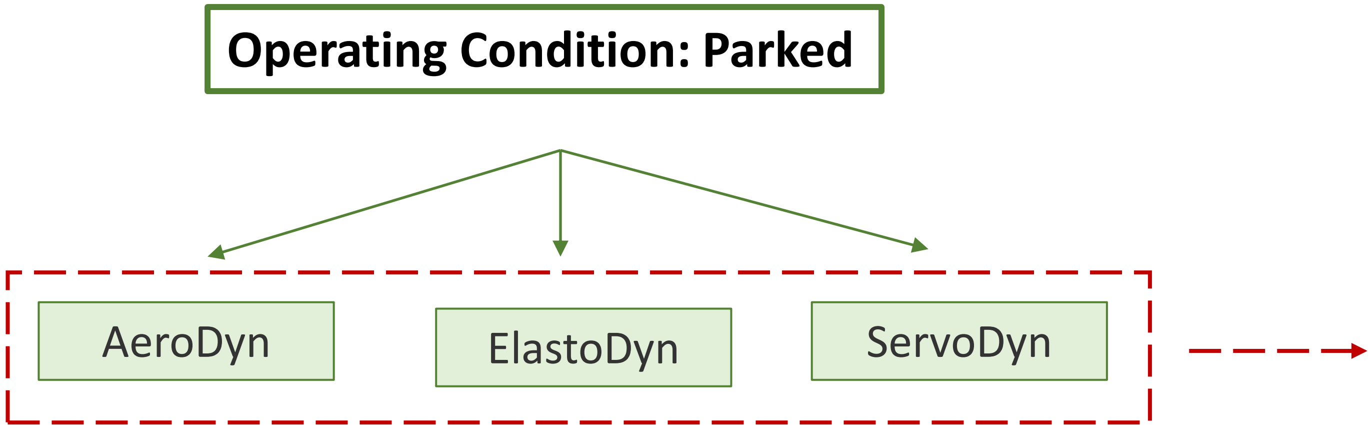


2. FAST: methods and software structure

FAST Module Control Volumes – Floating OWT



2. FAST: methods and software structure



AeroDyn	StallMod	Steady
	IndModel	None
ElastoDyn	RotSpeed	0
	BlPitch(1)	90^o
	BlPitch(2)	90^o
	BlPitch(3)	90^o
ServoDyn	PCMode	0
	GenTiStr	False
	GenTiStp	False

2. FAST: methods and software structure

Input Files Text Format

```
TurbSim Input File. Valid for TurbSim v1.50; 17-May-2010; Example file that can be used with simulations for the NREL 5MW Baseline Turbine; note that UsableTime has been decreased in this file so that
the file distributed with the FAST CertTest isn't as large

---------Runtime Options-----------------------------------
13428          RandSeed1       - First random seed  (-2147483648 to 2147483647)
RanLux         RandSeed2       - Second random seed (-2147483648 to 2147483647) for intrinsic pRNG, or an alternative pRNG: "RanLux" or "RNSNLW"
False          WrBHHTP         - Output hub-height turbulence parameters in binary form?  (Generates RootName.bin)
False          WrFHHTP         - Output hub-height turbulence parameters in formatted form?  (Generates RootName.dat)
False          WrADHH          - Output hub-height time-series data in AeroDyn form?  (Generates RootName.hh)
True           WrADFF          - Output full-field time-series data in TurbSim/AeroDyn form? (Generates RootName.bts)
False          WrBLFF          - Output full-field time-series data in BLADED/AeroDyn form?  (Generates RootName.wnd)
True           WrADTWR         - Output tower time-series data? (Generates RootName.twr)
False          WrFMTFF         - Output full-field time-series data in formatted (readable) form?  (Generates RootName.u, RootName.v, RootName.w)
False          WrACT           - Output coherent turbulence time steps in AeroDyn form? (Generates RootName.cts)
True           Clockwise       - Clockwise rotation looking downwind? (used only for full-field binary files - not necessary for AeroDyn)
0              ScaleIEC        - Scale IEC turbulence models to exact target standard deviation? [0=no additional scaling; 1=use hub scale uniformly; 2=use individual scales]

--------Turbine/Model Specifications-----------------------
 31            NumGrid_Z       - Vertical grid-point matrix dimension
 31            NumGrid_Y       - Horizontal grid-point matrix dimension
  0.05         TimeStep        - Time step [seconds]
630.0          AnalysisTime    - Length of analysis time series [seconds]
600.0          UsableTime      - Usable length of output time series [seconds] (program will add GridWidth/MeanHHWS seconds) [bjj: was 630]
 90.0          HubHt           - Hub height [m] (should be > 0.5*GridHeight)
145.0          GridHeight      - Grid height [m]
145.0          GridWidth       - Grid width [m] (should be >= 2*(RotorRadius+ShaftLength))
  0            VFlowAng        - Vertical mean flow (uptilt) angle [degrees]
  0            HFlowAng        - Horizontal mean flow (skew) angle [degrees]

--------Meteorological Boundary Conditions-------------------
IECKAI         TurbModel       - Turbulence model ("IECKAI"=Kaimal, "IECVKM"=von Karman, "GP_LLJ", "NWTCUP", "SMOOTH", "WF_UPW", "WF_07D", "WF_14D", or "NONE")
"1-ed3"        IECstandard     - Number of IEC 61400-x standard (x=1,2, or 3 with optional 61400-1 edition number (i.e. "1-Ed2") )
"B"            IECturbc        - IEC turbulence characteristic ("A", "B", "C" or the turbulence intensity in percent) ("KHTEST" option with NWTCUP, not used for other models)
NTM            IEC_WindType    - IEC turbulence type ("NTM"=normal, "xETM"=extreme turbulence, "xEWM1"=extreme 1-year wind, "xEWM50"=extreme 50-year wind, where x=wind turbine class 1, 2, or 3)
default        ETMc            - IEC Extreme turbulence model "c" parameter [m/s]
PL             WindProfileType - Wind profile type ("JET"=Low-level jet,"LOG"=Logarithmic,"PL"=Power law, or "default", or "USR"=User-defined)
 90.           RefHt           - Height of the reference wind speed [m]
 0.27          URef            - Mean (total) wind speed at the reference height [m/s]
default        ZJetMax         - Jet height [m] (used only for JET wind profile, valid 70-490 m)
default        PLExp           - Power law exponent [-] (or "default")
default        Z0              - Surface roughness length [m] (or "default")

--------Non-IEC Meteorological Boundary Conditions------------
default        Latitude        - Site latitude [degrees] (or "default")
0.05           RICH_NO         - Gradient Richardson number
default        UStar           - Friction or shear velocity [m/s] (or "default")
default        ZI              - Mixing layer depth [m] (or "default")
default        PC_UW           - Hub mean u'w' Reynolds stress [(m/s)^2] (or "default")
default        PC_UV           - Hub mean u'v' Reynolds stress [(m/s)^2] (or "default")
default        PC_VW           - Hub mean v'w' Reynolds stress [(m/s)^2] (or "default")
default        IncDec1         - u-component coherence parameters (e.g. "10.0  0.3e-3" in quotes) (or "default")
default        IncDec2         - v-component coherence parameters (e.g. "10.0  0.3e-3" in quotes) (or "default")
default        IncDec3         - w-component coherence parameters (e.g. "10.0  0.3e-3" in quotes) (or "default")
default        CohExp          - Coherence exponent (or "default")

--------Coherent Turbulence Scaling Parameters-------------------
"M:\coh_events\eventdata"  CTEventPath     - Name of the path where event data files are located
"Random"       CTEventFile     - Type of event files ("random", "les" or "dns")
true           Randomize       - Randomize disturbance scale and location? (true/false)
 1.0           DistScl         - Disturbance scale (ratio of dataset height to rotor disk).
 0.5           CTLy            - Fractional location of tower centerline from right (looking downwind) to left side of the dataset.
 0.5           CTLz            - Fractional location of hub height from the bottom of the dataset.
10.0           CTStartTime     - Minimum start time for coherent structures in RootName.cts [seconds]

==================================================
NOTE: Do not add or remove any lines in this file!
==================================================
```

[e.g. Input file from TurbSim Module]

3 Sections:

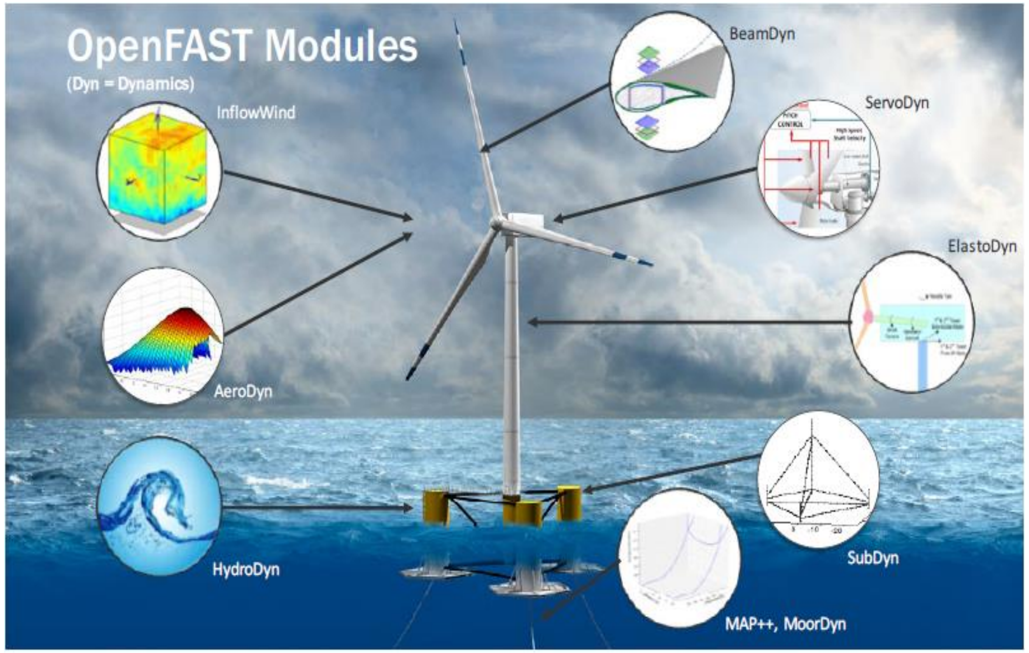
- Values
- Variables
- Descriptions and physical units

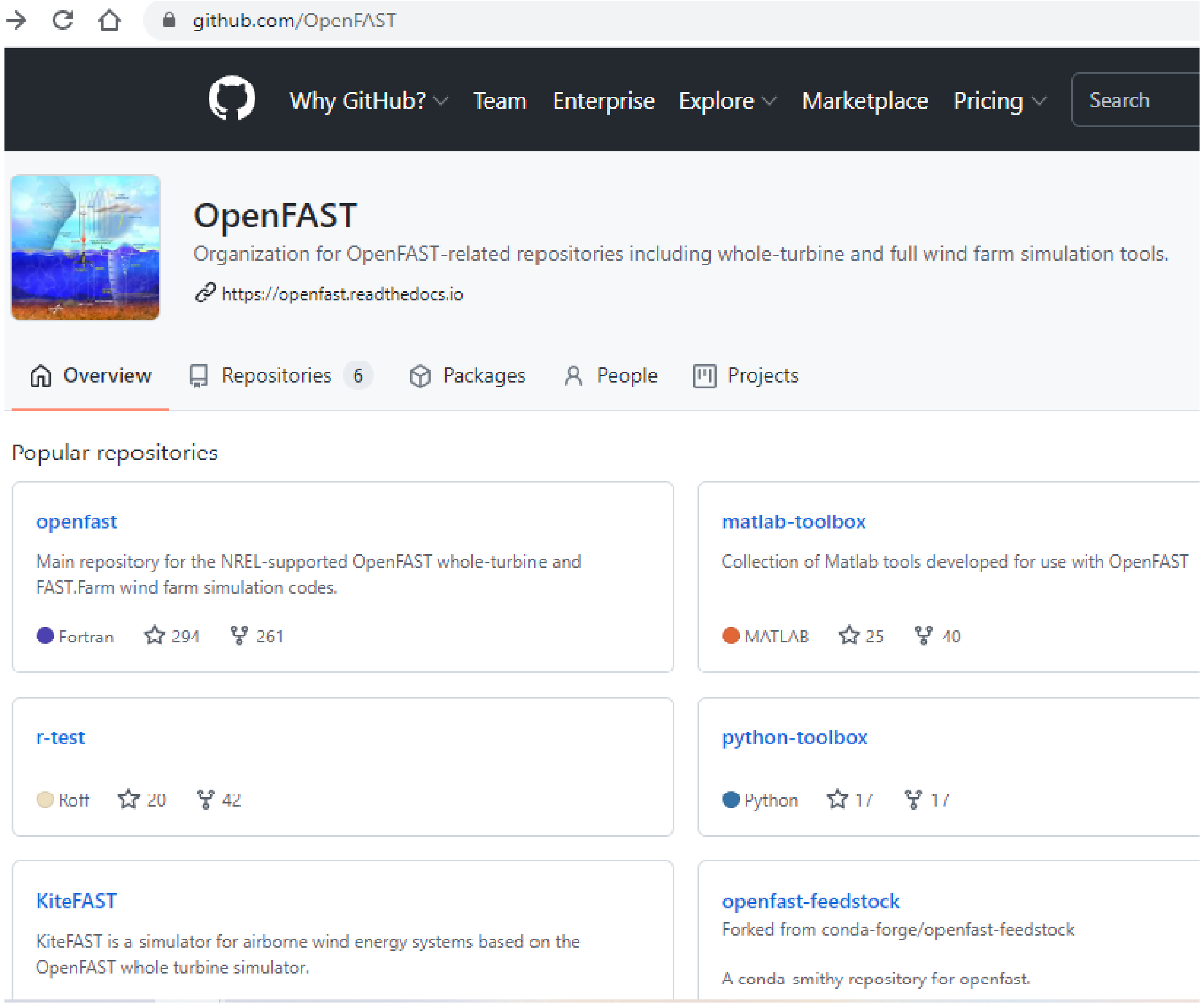
A sample line from the input file for input parameter Tmax:

20.0	Tmax	- Total run time (s)

3. OpenFAST

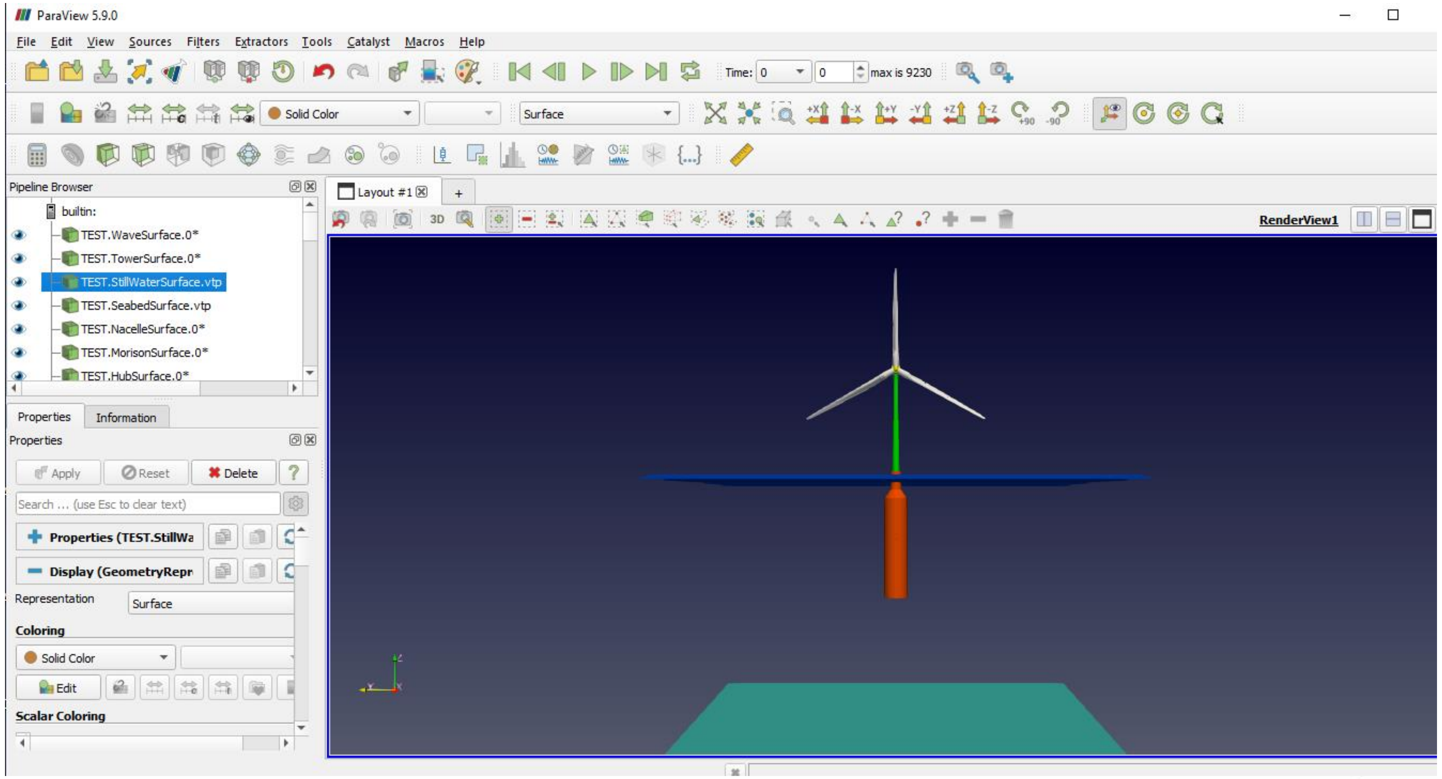
- Starting point: FAST v8
- Open-source and publicly available tool
- GitHub repository of OpenFAST.
- Land or offshore wind turbines
- Bed-fixed or floating substructures.
- Aero-Hydro-Servo-Elastic Simulation

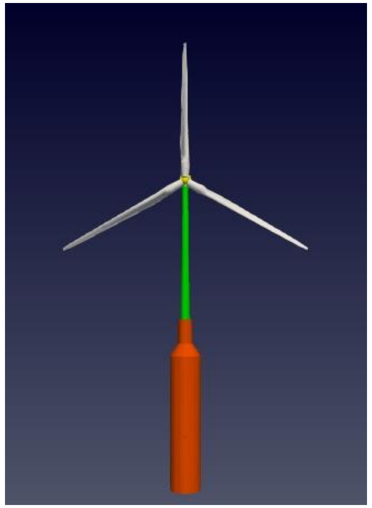




3. OpenFAST

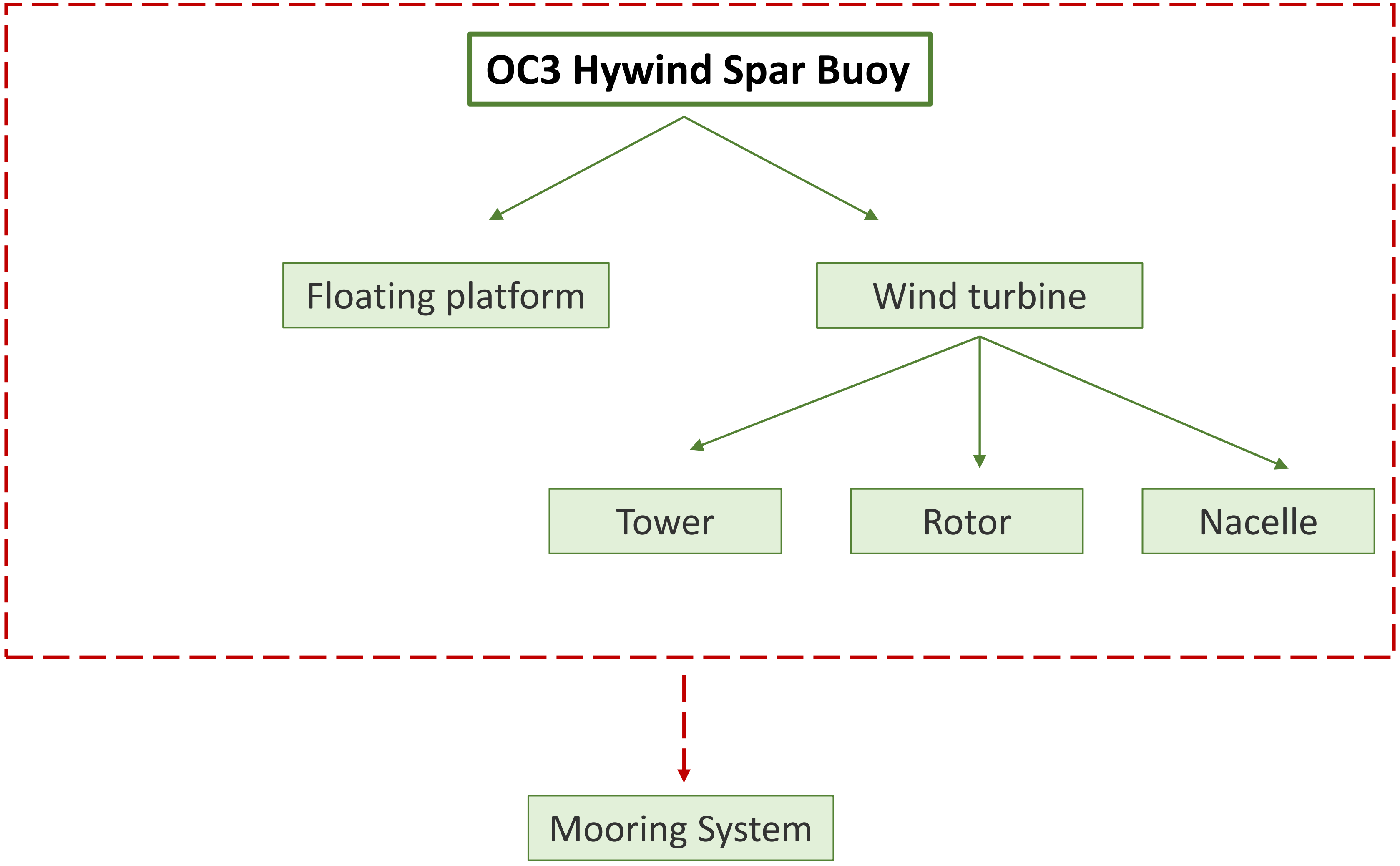
Visualization capability → Surface Stick-figure geometry → Generation of Visualization Toolkit (VTK) output files → ParaView

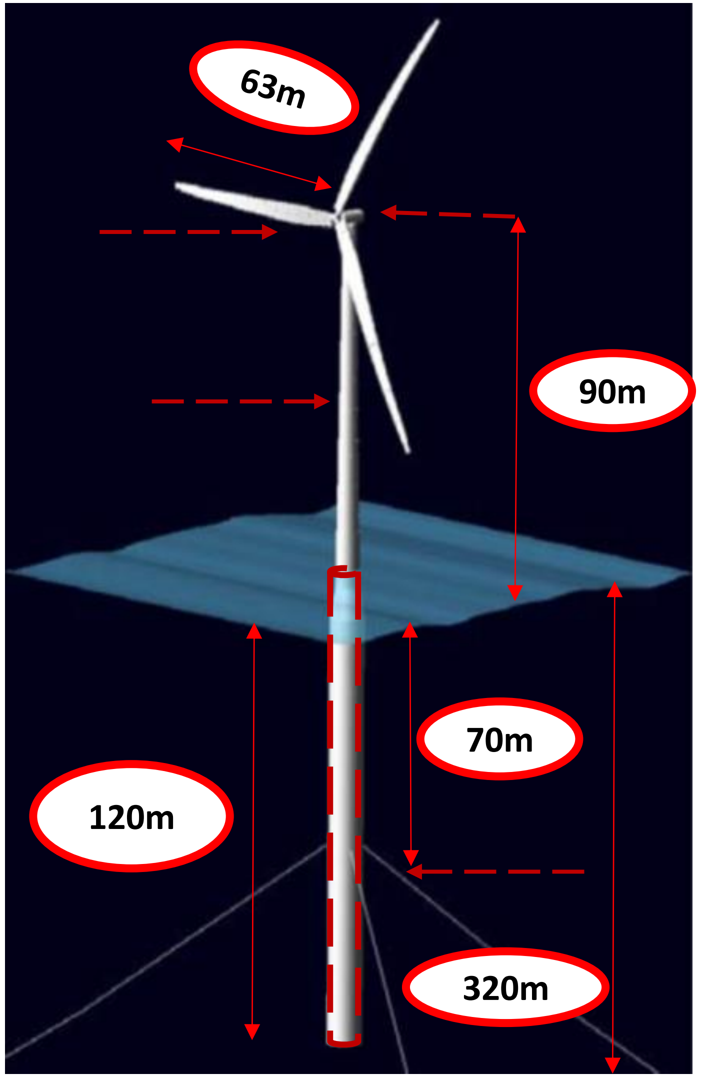




Surfaces

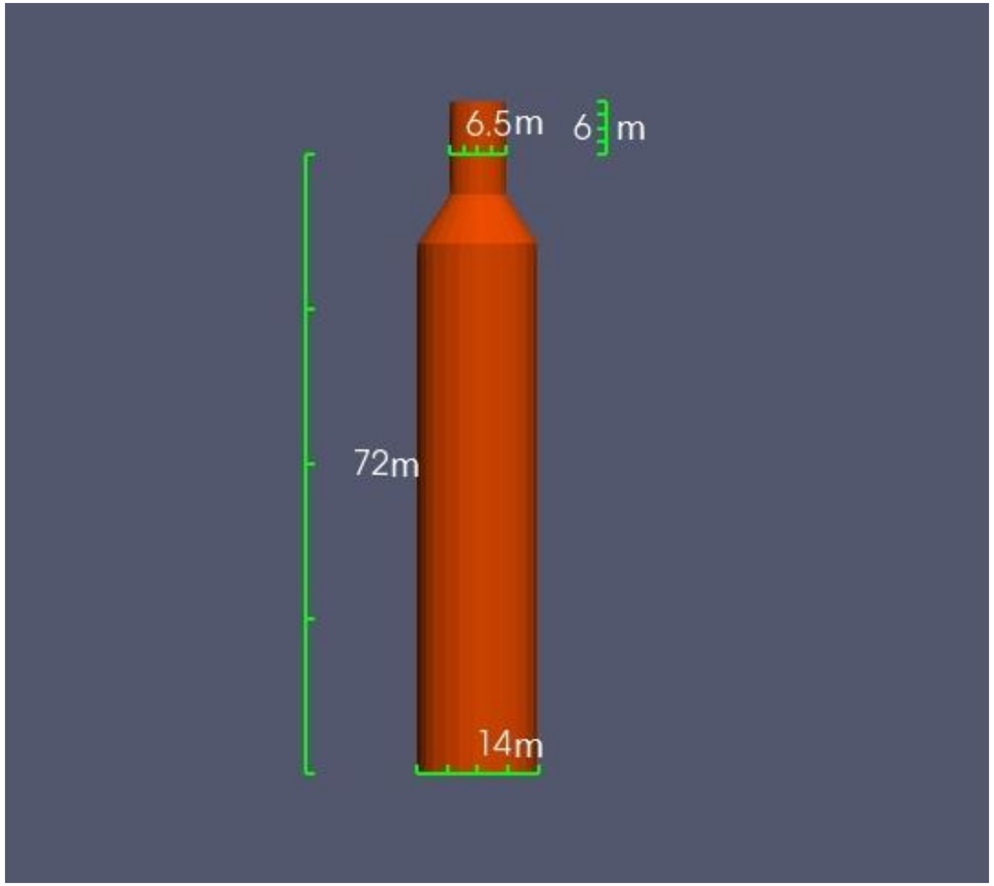
4. Simulation using OpenFAST

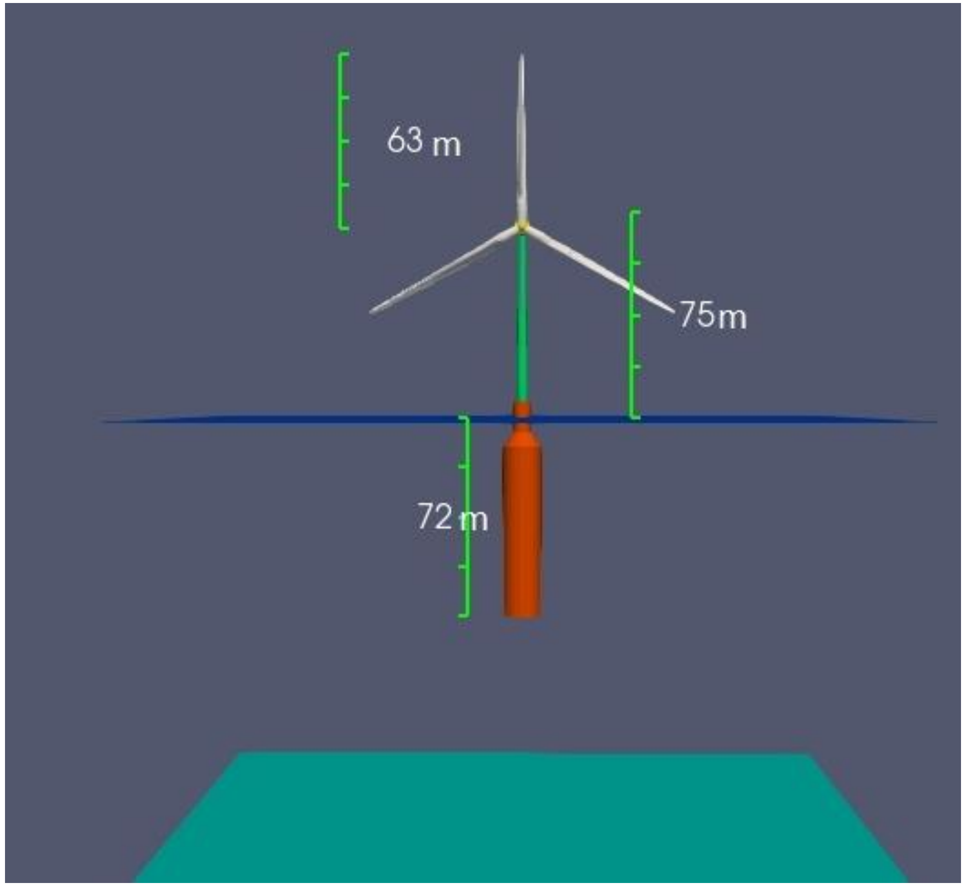




4. Simulation using OpenFAST

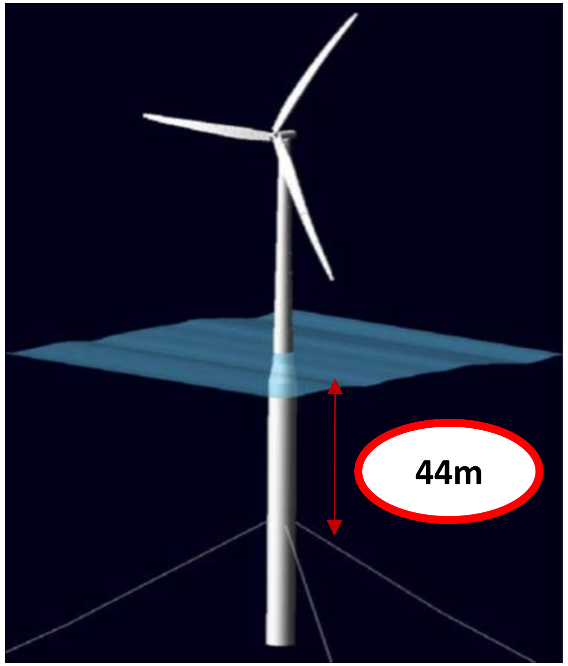
Geometry of example wind turbine → Visualization of the floating system using ParaView

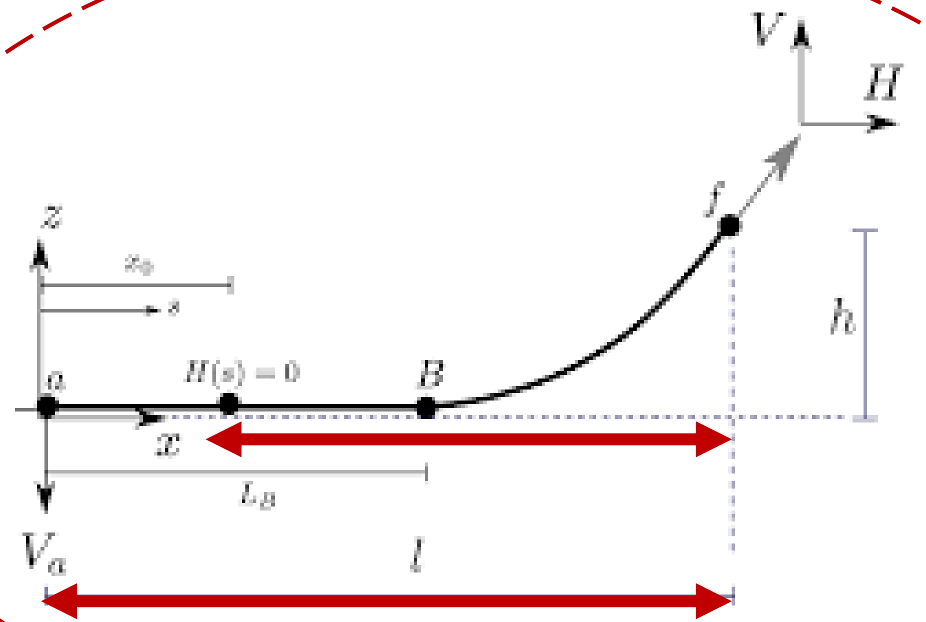




4. Simulation using OpenFAST

2 different water depths → 150m / 200m } Mooring system





4. Simulation using OpenFAST

Environmental conditions

Operational → JONSWAP Spectrum

U (z=75m)	U_{10} (m/s)	H_S (m)	T_S (s)	Beaufort
20	14,98	2,5	5,03	7
22	16,497	2,79	5,22	7
24	17,997	3,12	5,43	8
26	19,497	3,42	5,59	8
28	20,996	3,75	5,77	9
30	22,496	4,08	5,94	9

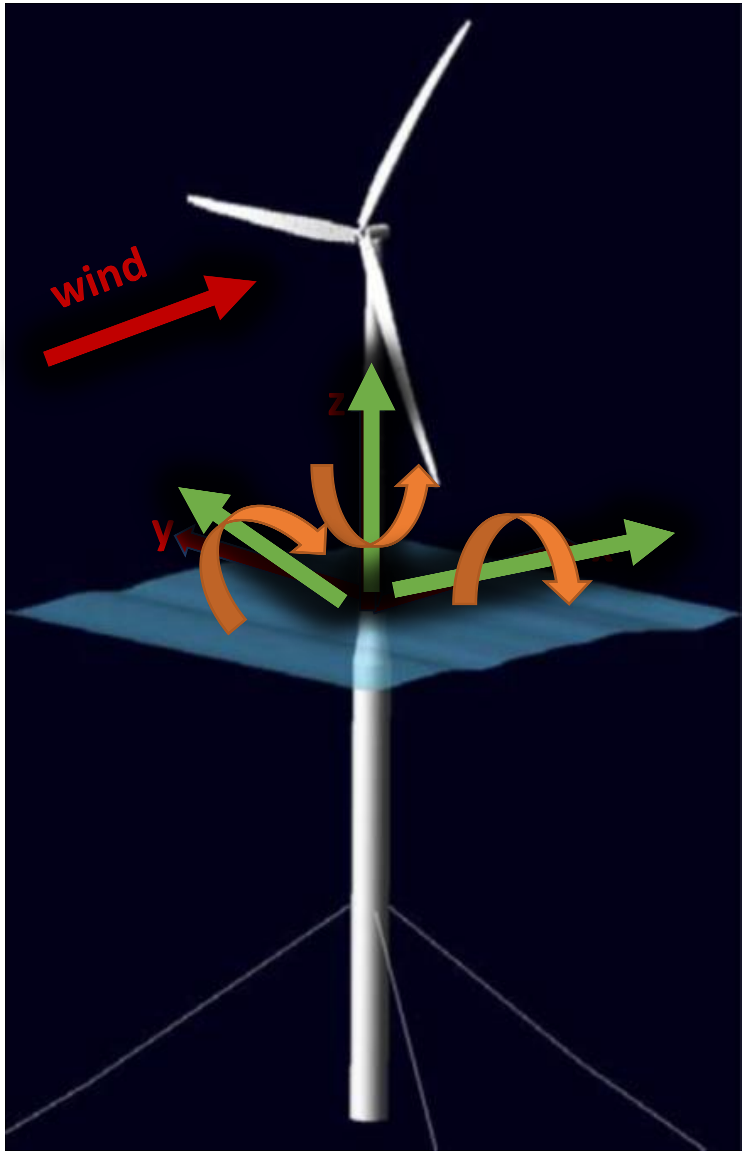
Parked → Formula of Goda

H_S (m)	T_S (s)
6	10,204

4. Simulation using OpenFAST

Coordinate system → Mean sea level (MSL) / Center of the wind turbine

Floating platform → Rigid Body → 6 DOFS → 3 Translational / 3 Rotational



Translational Motions

- Surge (X)
- Heave (Z)
- Sway (Y)

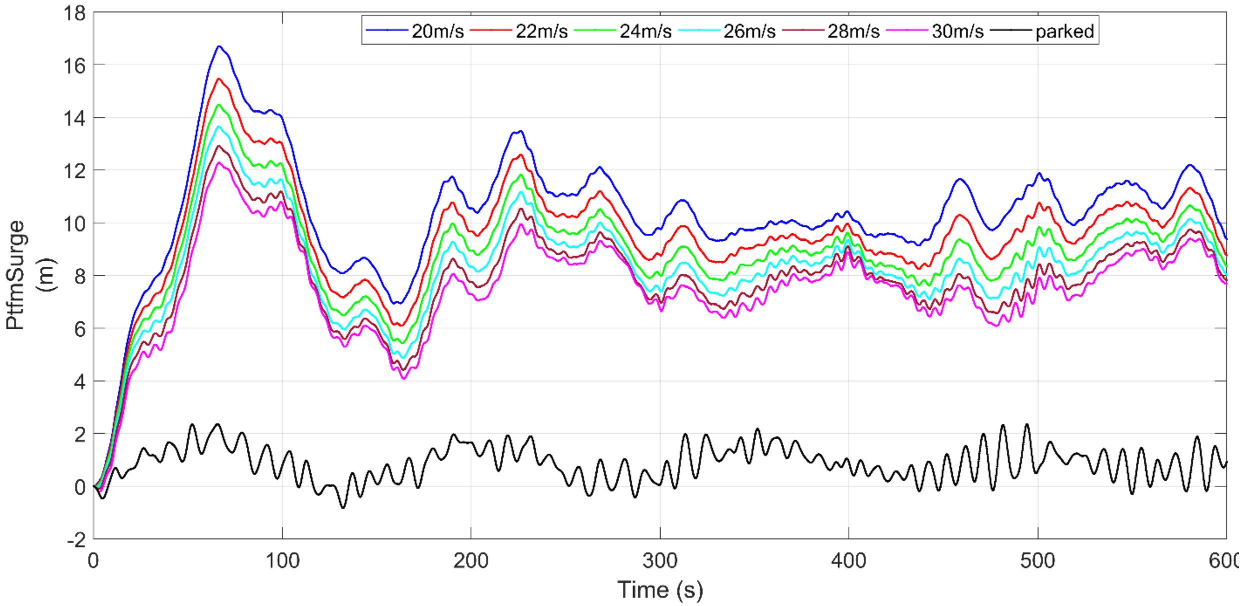
Rotational Motions

- Roll (X)
- Yaw (Z)
- Pitch (Y)

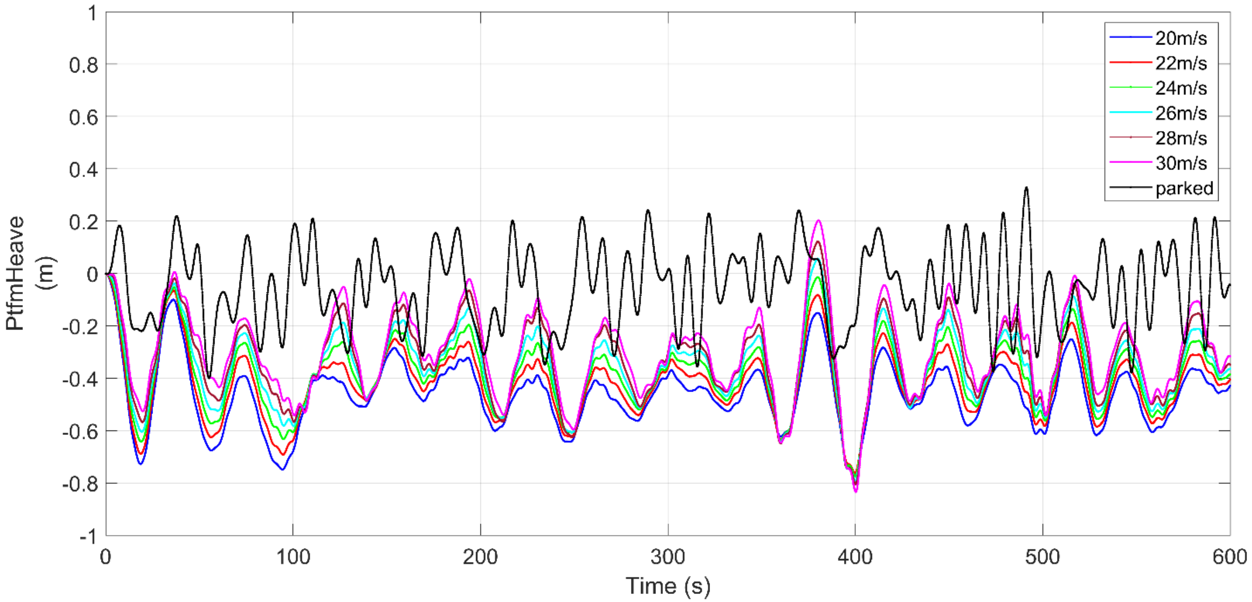
4. Simulation using OpenFAST

Simulation Results (Water depth: 150m)

Time series of platform Surge motion



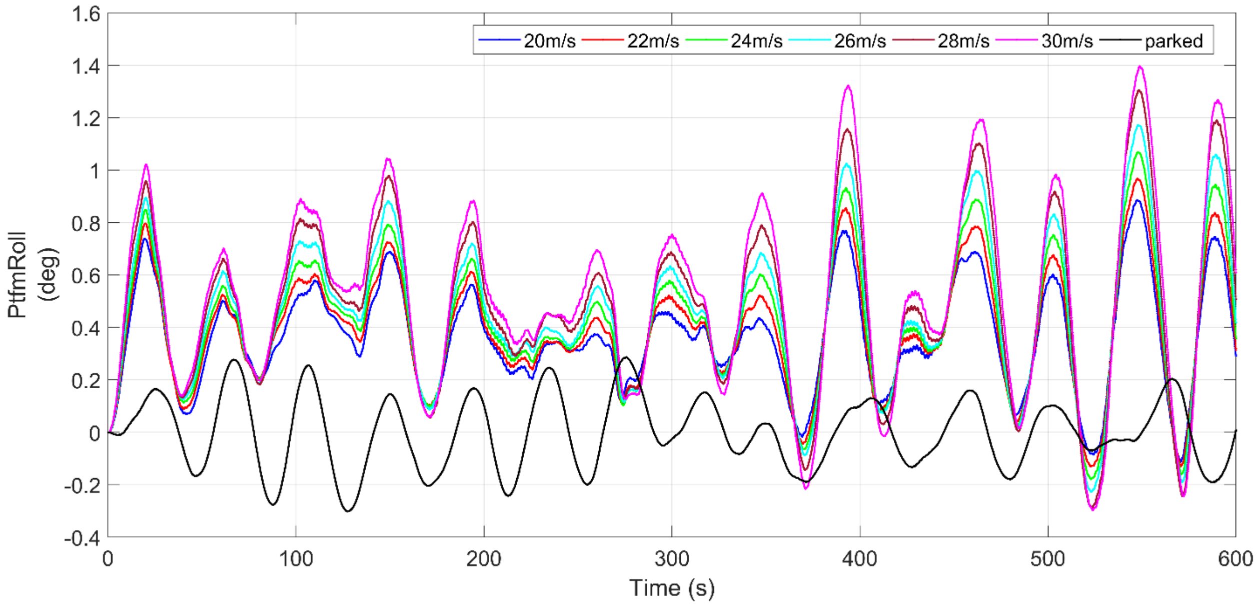
Time series of platform Heave motion



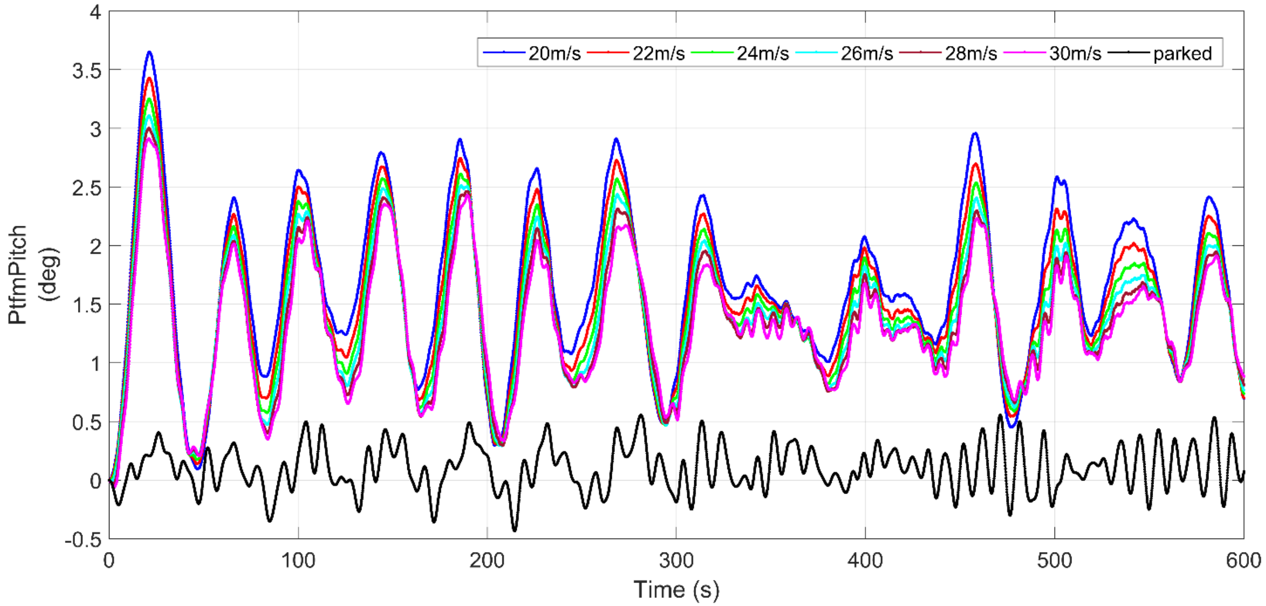
4. Simulation using OpenFAST

Simulation Results (Water depth: 150m)

Time series of platform Roll motion



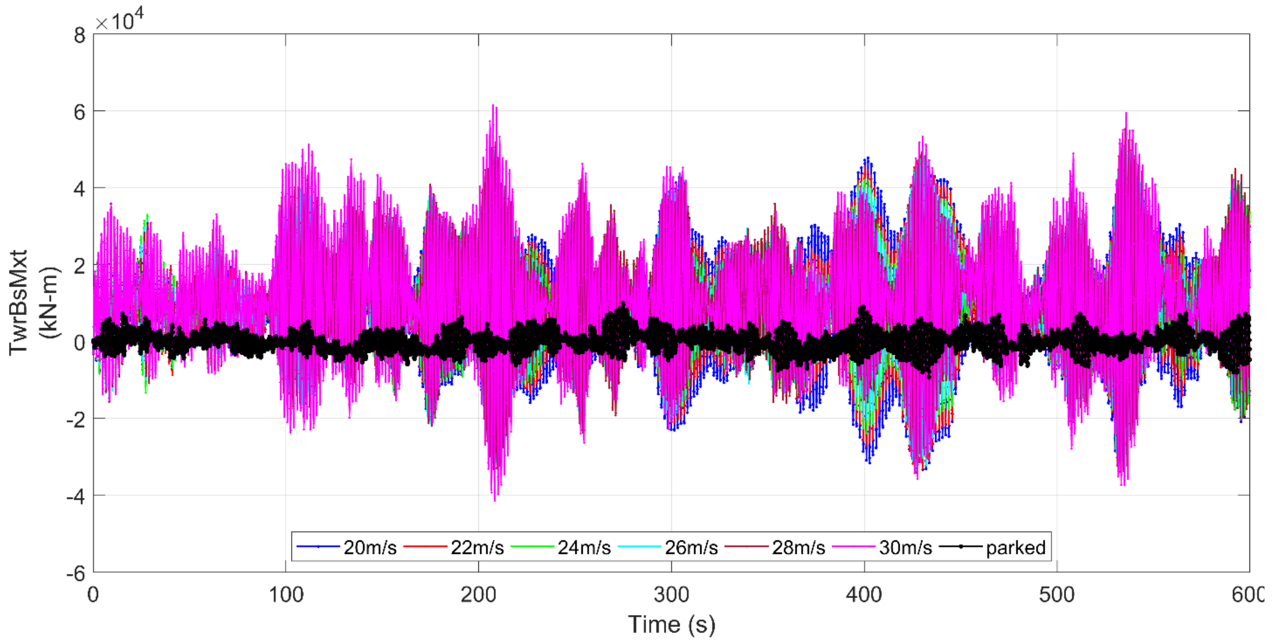
Time series of platform Pitch motion



4. Simulation using OpenFAST

Simulation Results (Water depth: 150m)

Time series of Tower Base Bending Moment Mx



Time series of Tower Base Bending Moment My