NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Recent Analysis Code Development at NREL

Sandia Blade Workshop

July 20-22, 2010

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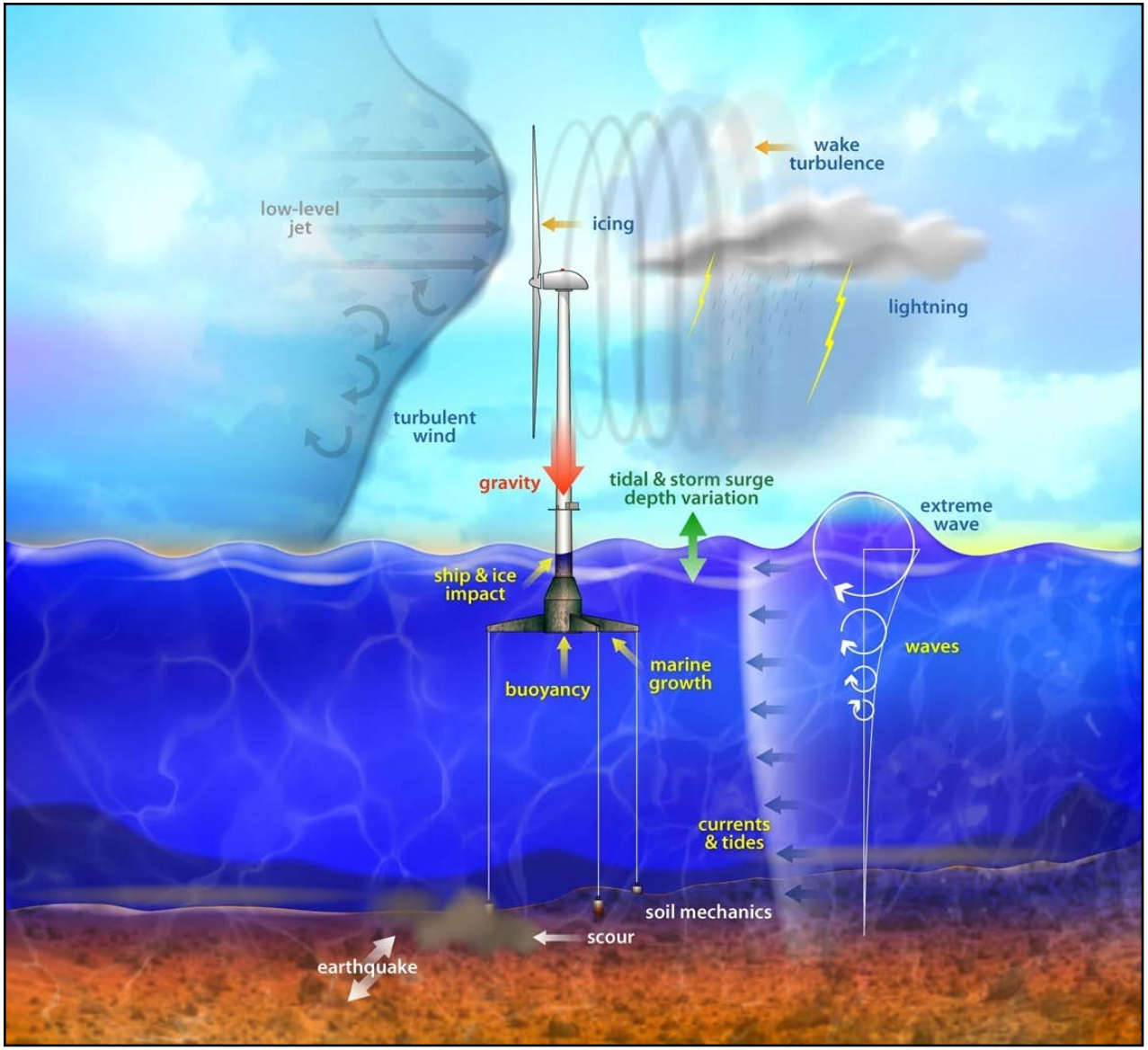
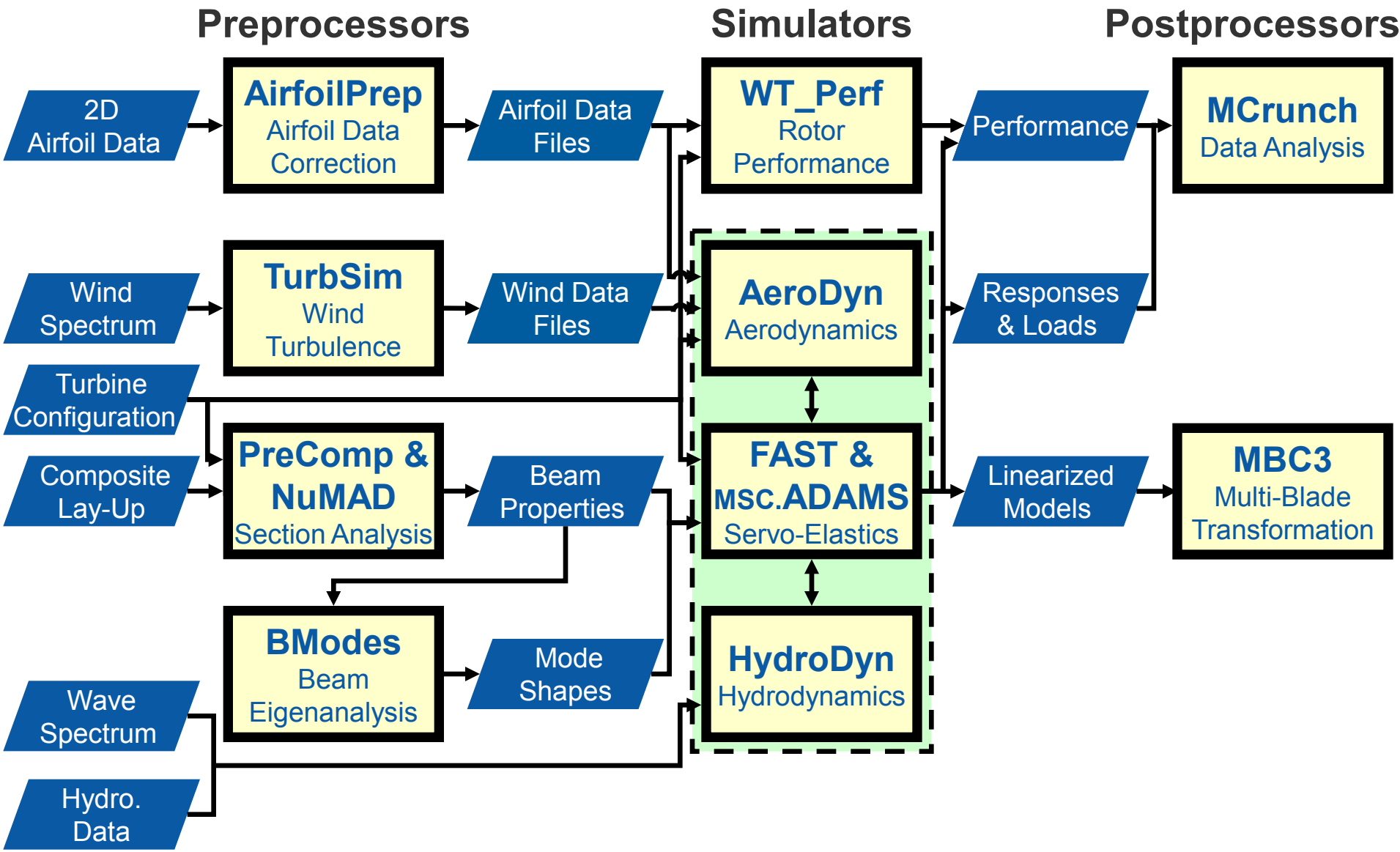
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Modeling Requirements



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

NREL Design Code Overview

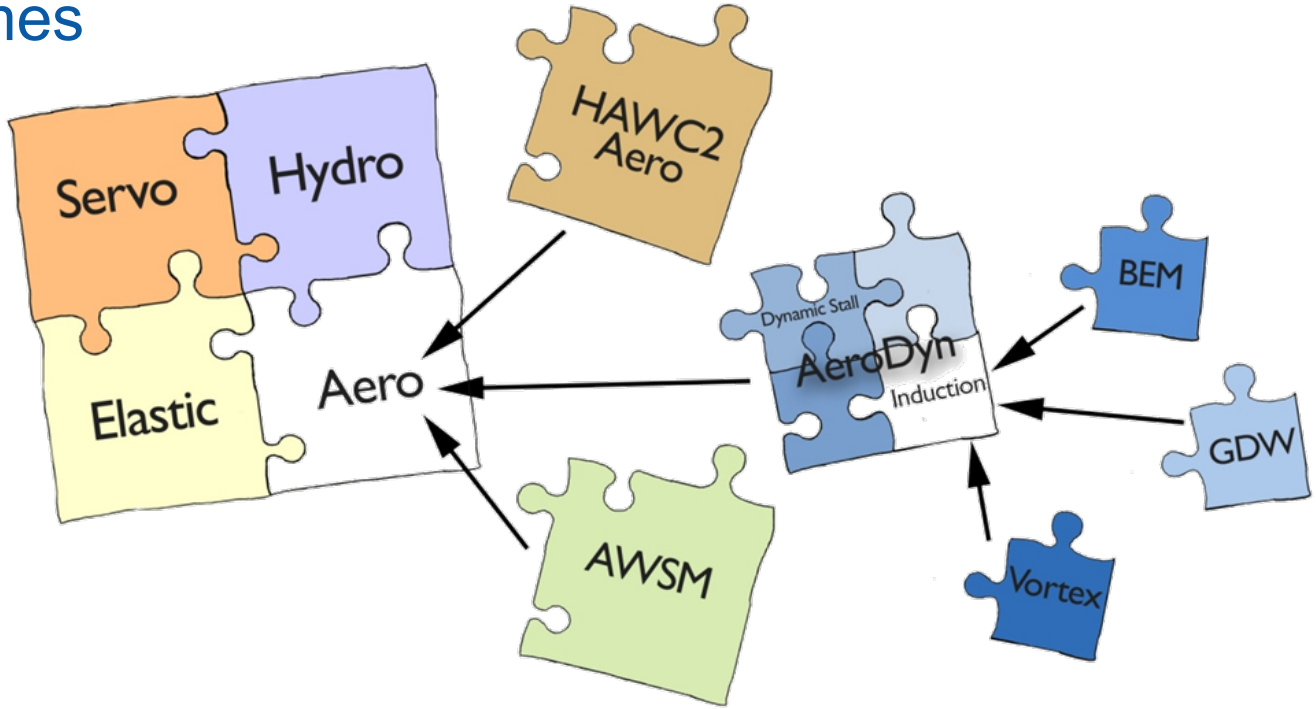


Recent & Ongoing Developments

- **WT_Perf** – Introduced more robust solution algorithm & developed a rotor performance optimization utility (**HARP_Opt**)
- **AeroDyn** – Overhauled interface to structural codes & reworking theory basis
- **FAST** – Introducing earthquake excitation, more control options, & output functionality
- **HydroDyn** – Establishing as a stand-alone module & validating in DeepCwind project
- **MCrunch** – Modularizing for improved numerical processing of fatigue & extreme analysis

Overarching Theme: Modularization & Coupled Simulation

- Motivation – Increasing system complexity requires coupled analysis
- Benefits – Enables shared code development, improves maintainability, & eases integration of science advances
- Challenges – Establishing standardized interfaces & coupling schemes



BModes

- Provides nonlinear FE models for
  - Rotating blades
  - Tower support structures—onshore or offshore (hydro-elastic FE model)
- Provides coupled modes for blades and towers.

Applications

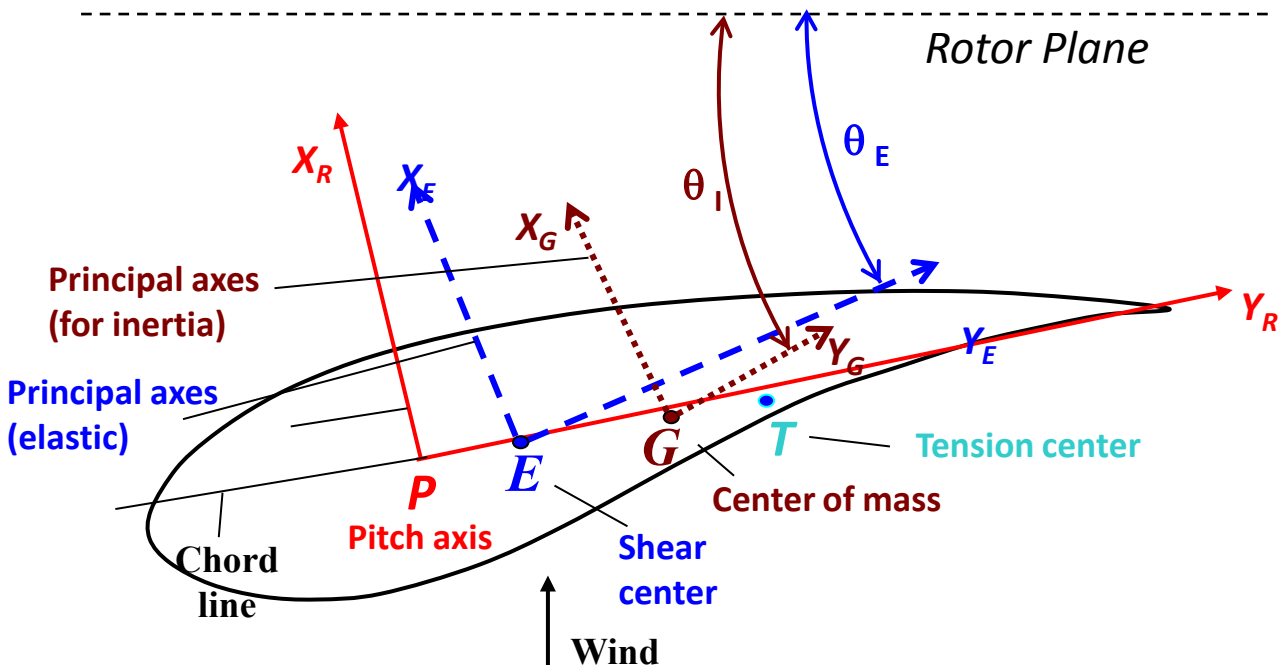
- Experimental validation or code-to-code verification of blade & tower models
- Model updating
- Modal reduction
- Physical interpretation of dynamic couplings
- Aid stability analysis
- Modal-based fatigue analysis
- Integration with CFD (NASA request)

Rotating Blade Model

- The blade FE model accounts for
  - Complex boundary conditions
  - Tip mass (6x6 inertia matrix and arbitrary c.m. offset)
  - Precone; pitch control setting
  - Rotary inertia effects
  - Distributed geometric & structural properties

Blade Section Properties

- Flap, lag, torsion, axial stiffness.
- Mass and mass moments of inertia



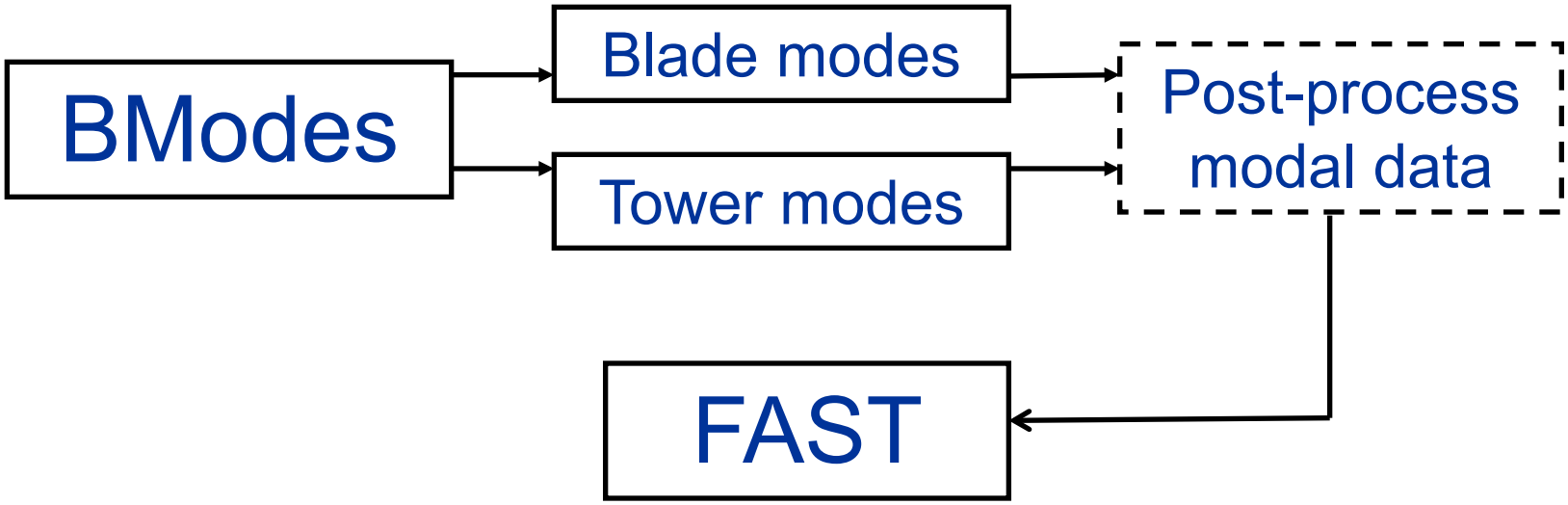
Tower Model

- Onshore tower model accounts for
  - tower-top inertia (nacelle & rotor)
  - tension-wires support (optional)
- Offshore tower may be supported by
  - monopile in elastic foundation
  - floating-platform
    (TLP, barge or spar buoy—all with mooring lines)

Coupled Modes

- Blade modal coupling → coupling of flap, lag, axial, and torsion motions
- Tower modal coupling → coupling of tower F-A, S-S, Axial, twist , and platform motions

Modal-based codes, such as FAST, use these modes to build wind turbine models:



Sample Modal Results For Blades

Rotating Uniform Blade

Comparison of Flap Frequencies

Blade Spin Rate, Ω (*rad/sec*)	First Flap Frequency (*rad/sec*)		Second Flap Frequency (*rad/sec*)		Third Flap Frequency (*rad/sec*)	
	Analytical	BModes	Analytical	BModes	Analytical	BModes
0	3.516	3.516	22.035	22.034	61.697	61.696
1	3.682	3.682	22.181	22.181	61.842	61.841
2	4.137	4.137	22.615	22.615	62.273	62.272
3	4.797	4.797	23.320	23.320	62.985	62.984
4	5.585	5.585	24.273	24.273	63.967	63.966
5	6.450	6.450	25.446	25.446	65.205	65.204
6	7.360	7.360	26.809	26.809	66.684	66.683
7	8.300	8.300	28.334	28.334	68.386	68.385
8	9.257	9.257	29.995	29.995	70.293	70.293
9	10.226	10.226	31.771	31.770	72.387	72.386
10	11.202	11.202	33.640	33.640	74.649	74.649
11	12.184	12.184	35.589	35.589	77.064	77.063
12	13.170	13.170	37.603	37.603	79.615	79.614

Rotating Uniform Blade with Tip Mass: Flap Frequencies

Blade Spin Rate *(rad/sec)*	First Flap Frequency (*rad/sec*)		Second Flap Frequency (*rad/sec*)	
	Analytical	**BModes**	**Analytical**	**BModes**
0	1.557	1.557	16.25	16.25
1	1.902	1.902	16.76	16.76
2	2.670	2.670	18.19	18.19
3	3.582	3.582	20.35	20.35
4	4.543	4.543	23.03	23.03
5	5.522	5.522	26.04	26.04
6	6.509	6.509	29.29	29.29
7	7.501	7.501	32.70	32.70
8	8.495	8.495	36.21	36.21
9	9.490	9.490	39.80	39.80
10	10.49	10.49	43.45	43.45
11	11.48	11.48	47.14	47.15
12	12.48	12.48	50.86	50.87

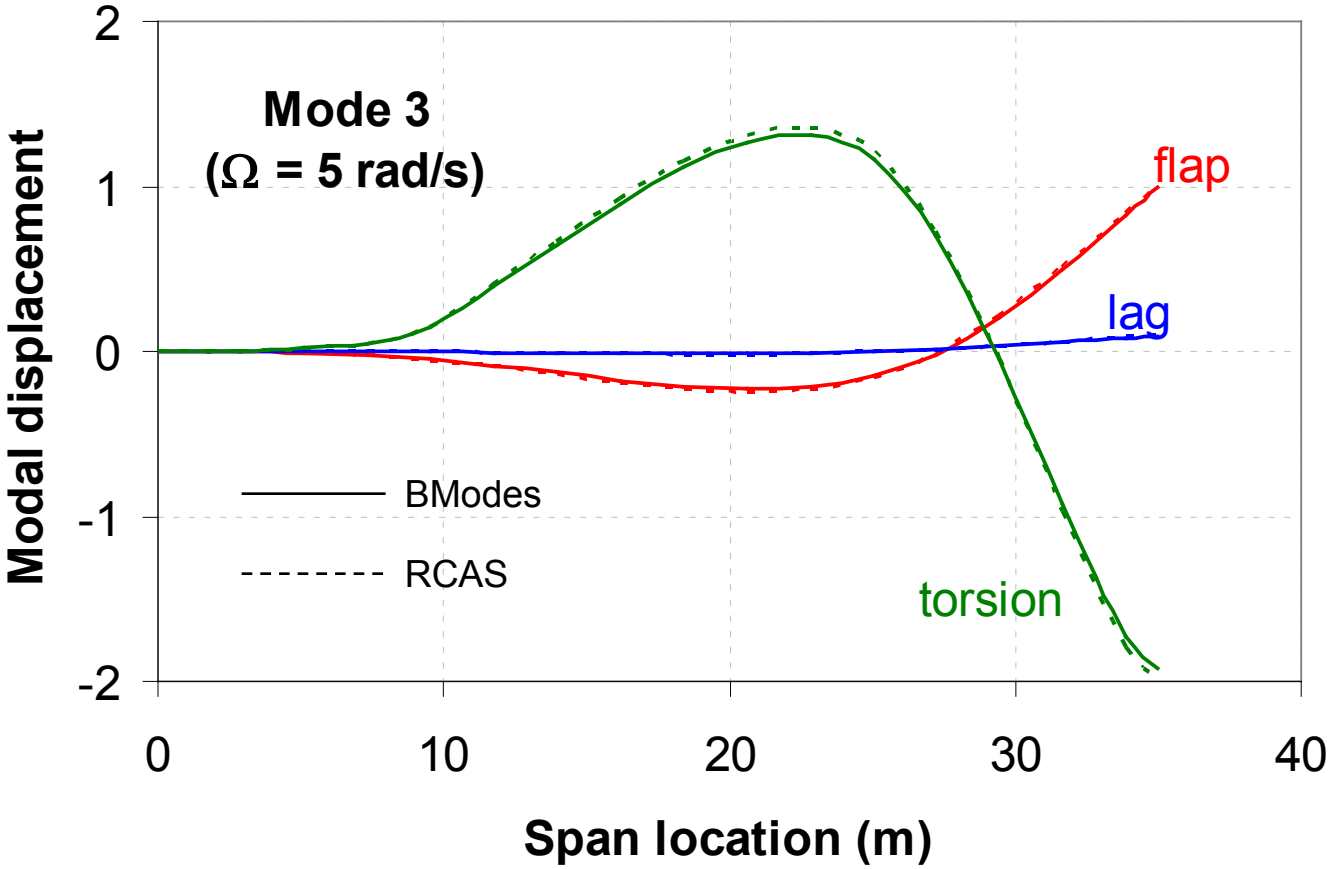
WindPact 1.5 MW Turbine Blade

Comparison of Modal Frequencies

Blade Spin Rate, Ω (*rad/sec*)	First Modal Frequency (Hz)		Second Modal Frequency (Hz)		Third Modal Frequency (Hz)	
	RCAS	BModes	RCAS	BModes	RCAS	BModes
0	1.229	1.228	1.875	1.873	3.662	3.657
2	1.300	1.298	1.889	1.887	3.736	3.732
5	1.608	1.606	1.959	1.957	4.104	4.100
10	2.146	2.144	2.384	2.381	5.159	5.154
15	2.429	2.426	3.209	3.205	6.366	6.359
20	2.732	2.730	4.055	4.051	7.237	7.229
25	3.044	3.041	4.905	4.900	7.339	7.331
35	3.669	3.665	4.546	4.541	6.612	6.605
50	4.591	4.586	9.150	9.140	12.389	12.375

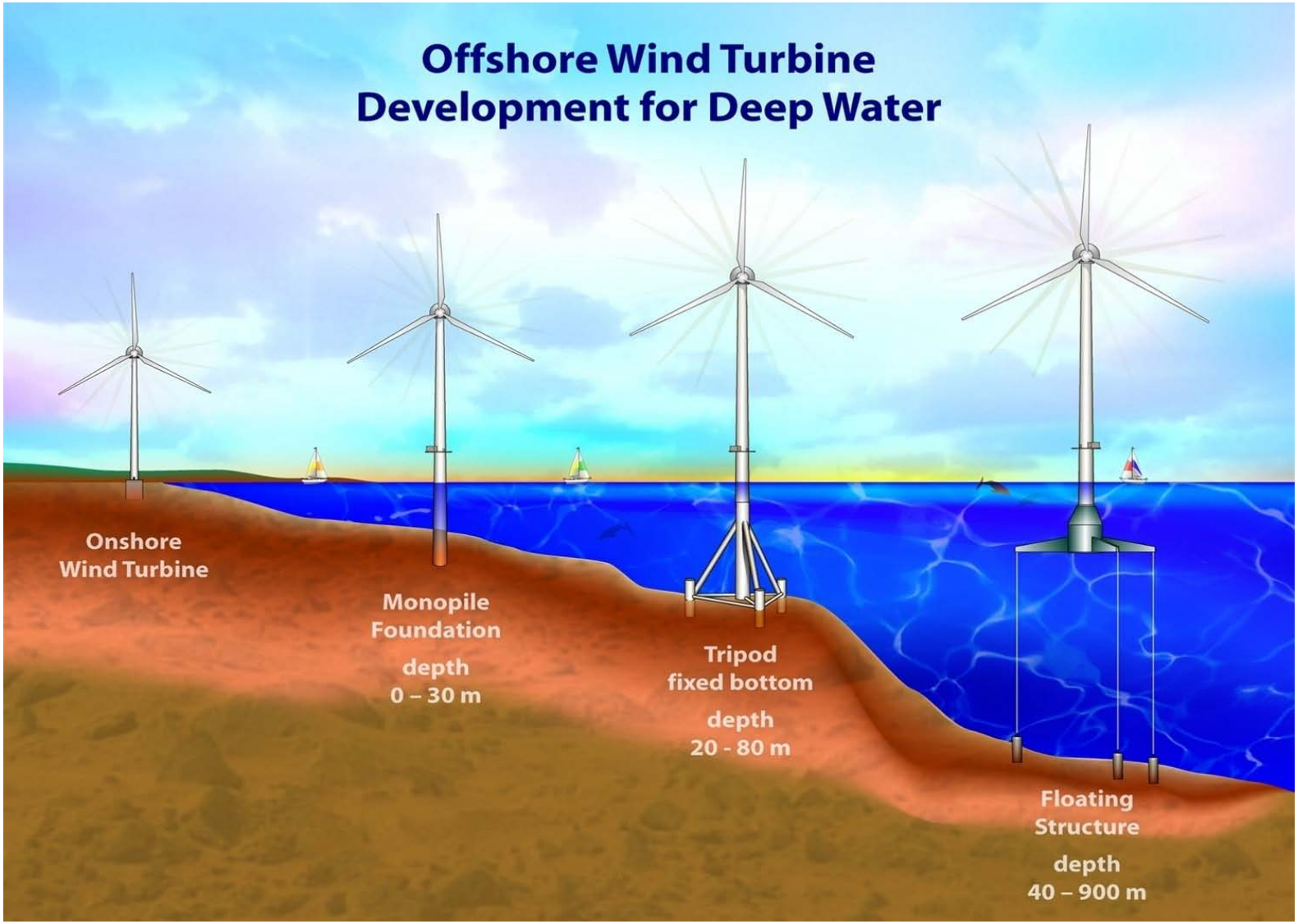
WindPact 1.5 MW Turbine Blade

Comparison of Mode Shapes

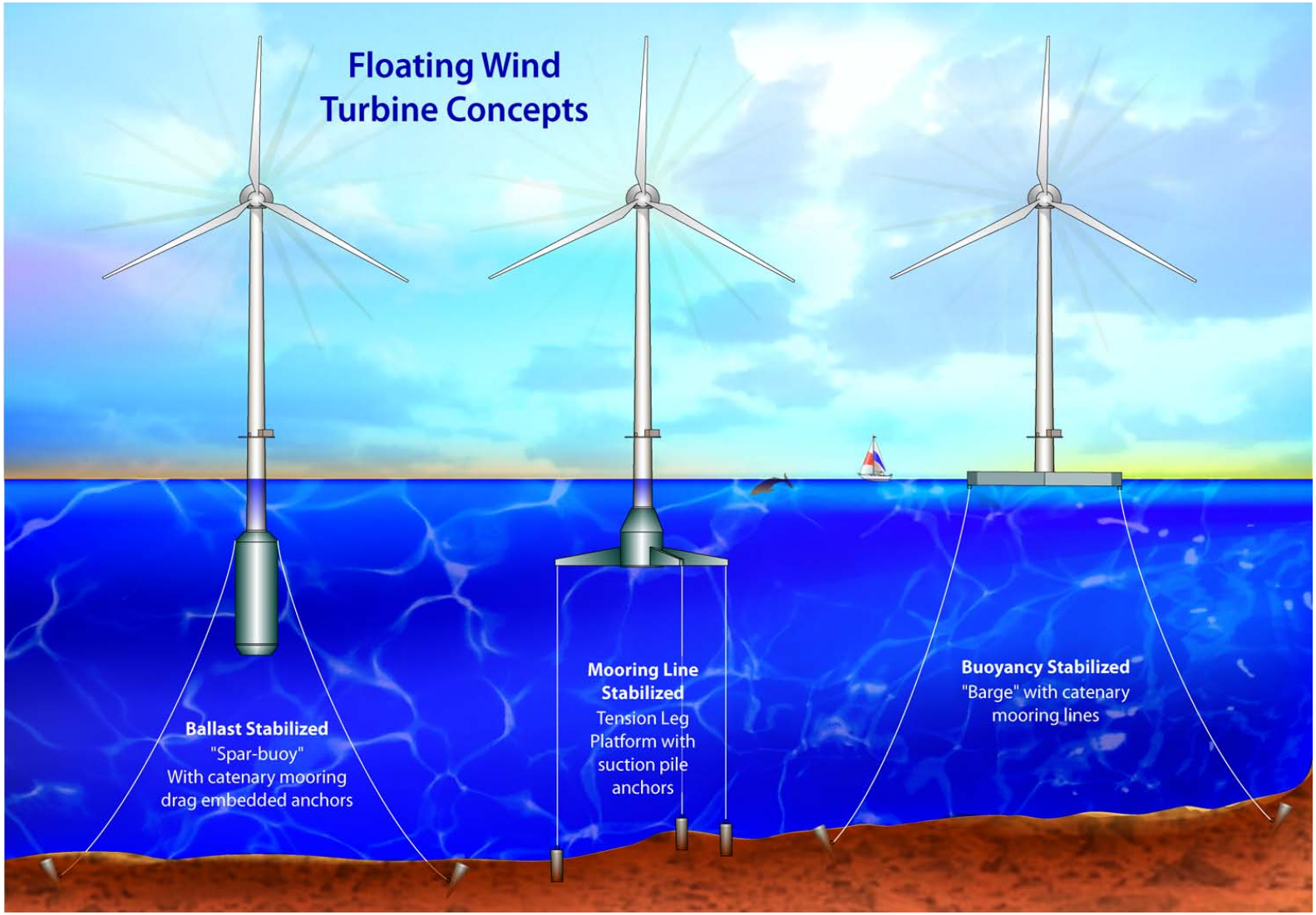


Sample Modal Results
For Tower Support Structures

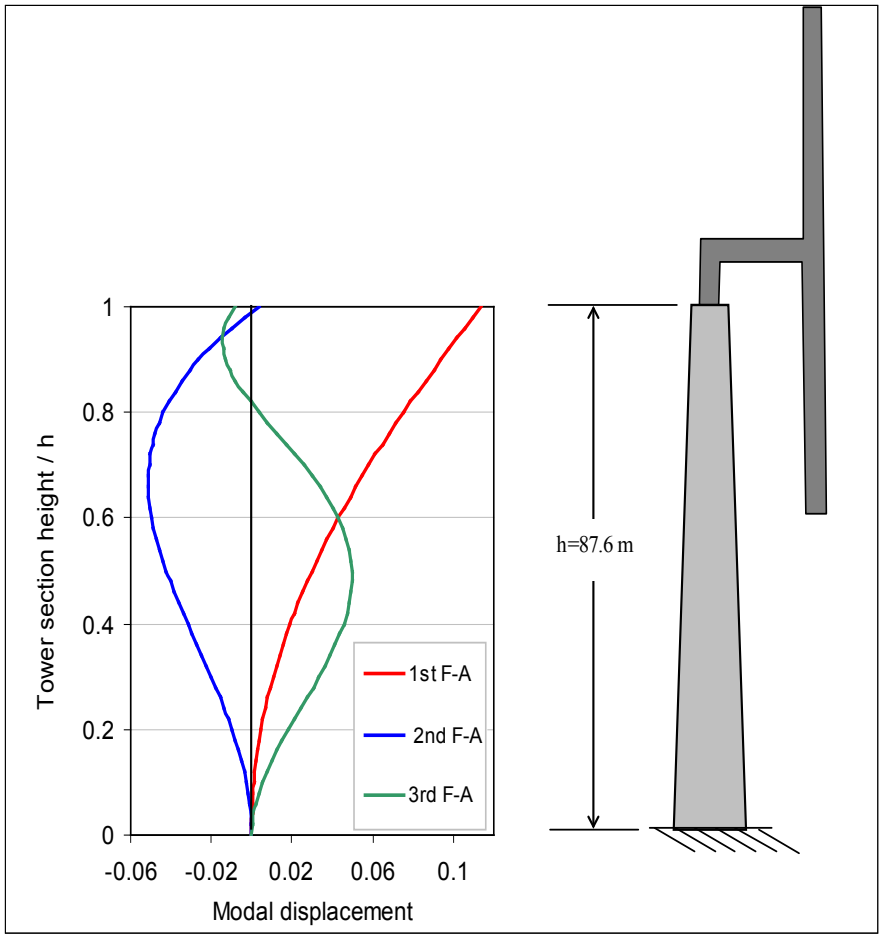
Wind Turbine Configurations

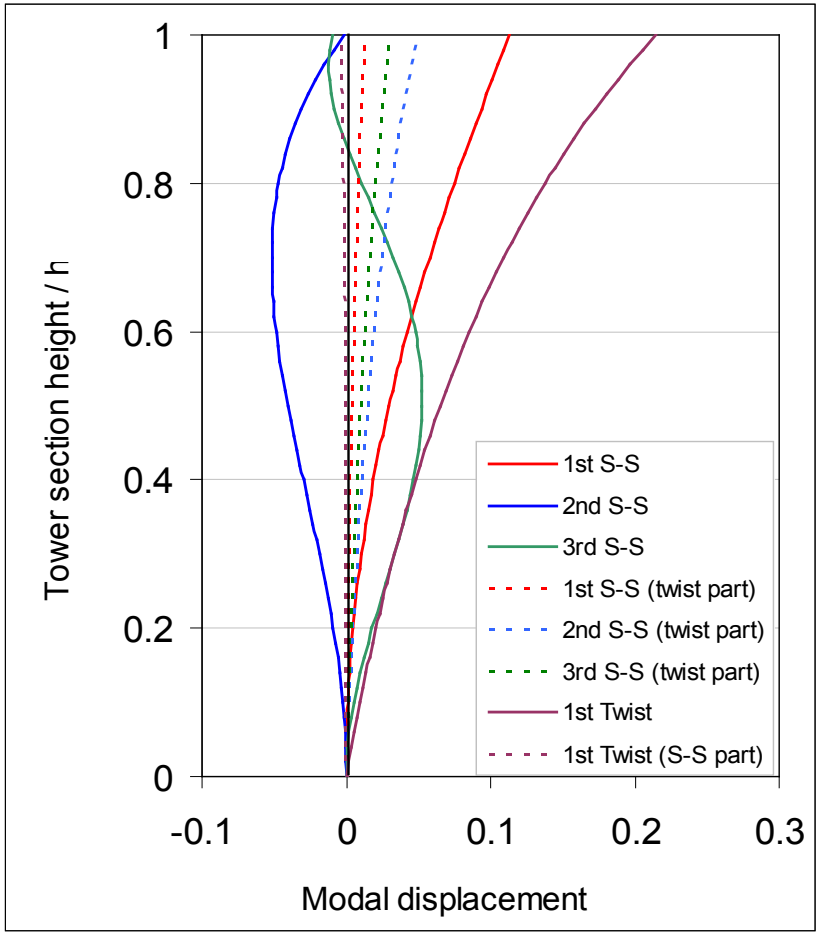


Floating Turbine Concepts



Land-Based Tower: Mode Shapes



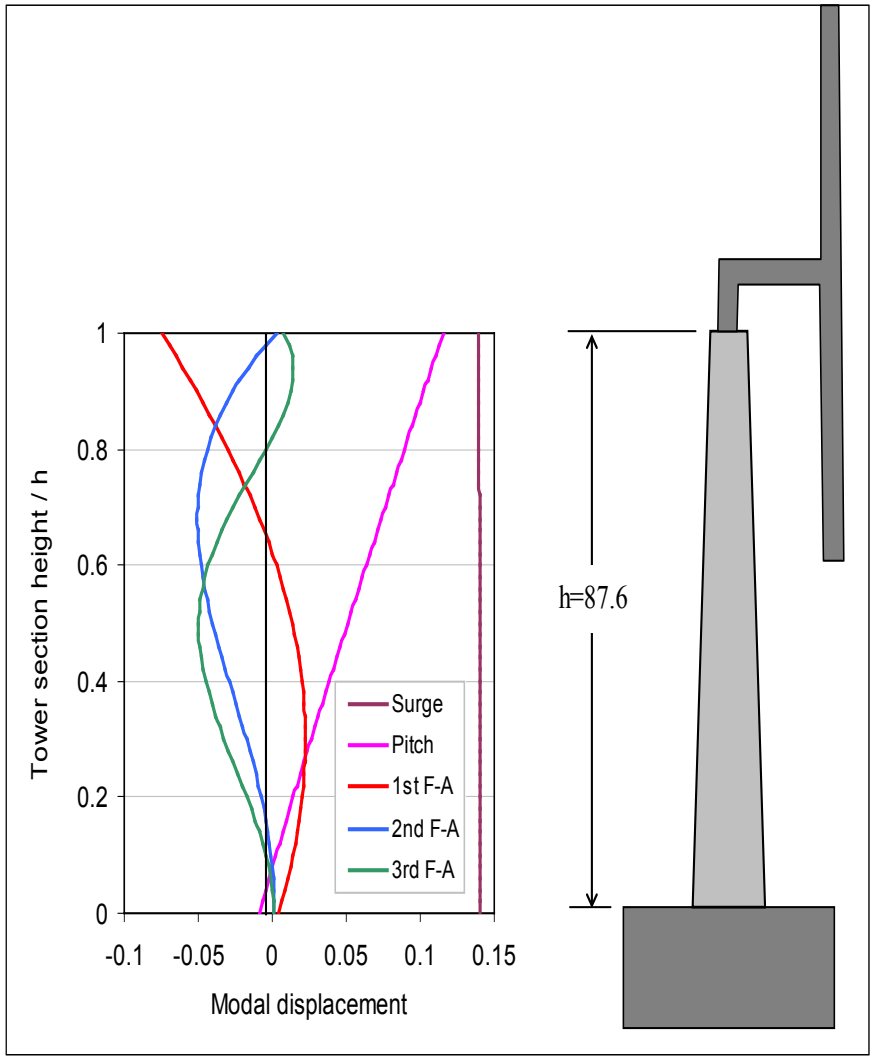


Land-Based Tower: Modal Frequencies

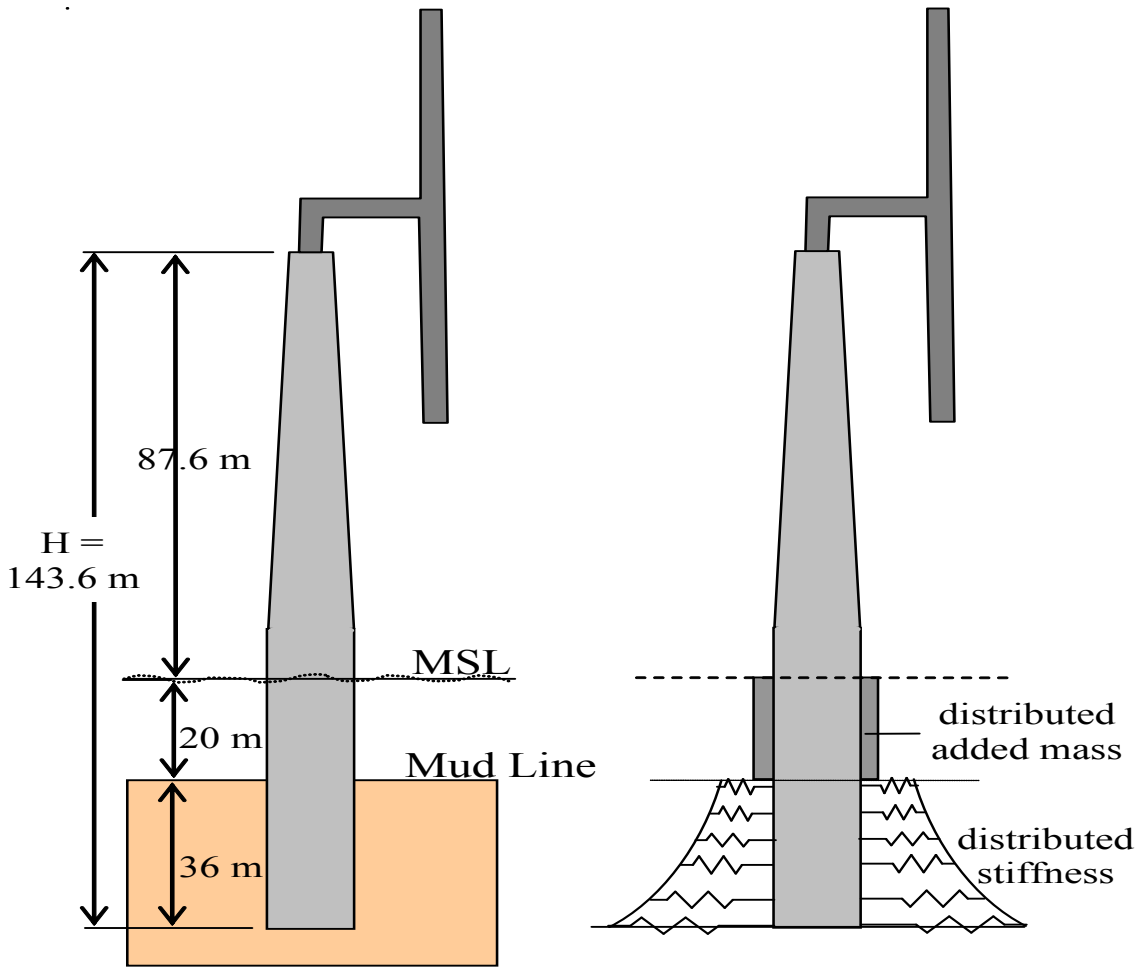
Mode Number	Mode Type	Without Head Mass			With Head Mass		
		Frequency (Hz)			Frequency (Hz)		
		BModes	ADAMS	Diff	BModes	ADAMS	Diff
1	1st SS	0.8913	0.8904	0.001	0.3291	0.3188	0.010
2	1st FA	0.8913	0.8904	0.001	0.3324	0.3218	0.011
3	2ndSS	4.3743	4.3437	0.031	1.8805	1.8820	0.002
4	2nd FA	4.3743	4.3435	0.031	2.2432	2.2391	0.004
5	3rd SS	11.3911	11.1856	0.205	4.6526	4.7244	0.072
6	3rd FA	11.3911	11.1843	0.207	4.9865	5.1833	0.197
7	1st Torsion	11.9656	11.4448	0.521	1.4703	1.4763	0.006
8	1st Axial	16.5217	16.5222	0.001	8.1311	7.9375	0.194
9	4th SS	21.8655	21.1146	0.751	11.3142	11.2678	0.046
10	4th FA	21.8655	21.1093	0.756	11.4591	11.4719	0.013
11	2nd torsion	27.7783	26.1221	1.656	17.9632	17.9535	0.010
12	5th SS	35.8273	33.8392	1.988	21.7054	21.3291	0.376
13	5th FA	35.8273	33.8236	2.004	21.7625	21.4419	0.321
14	2nd Axial	43.4596	42.1715	1.288	30.2109	30.1182	0.093
15	3rd Torsion	44.8623	43.4578	1.405	35.3975	34.5078	0.890
16	6th SS	53.2770	48.9445	4.332	35.6336	34.5830	1.051
17	6th FA	53.2770	48.9071	4.370	35.6636	35.3740	0.290
18	4th Torsion	62.2312	58.6564	3.575	52.9449	50.5171	2.428

Barge-Supported Turbine Modes

Mode Number	Mode Type	Frequency (Hz)			
		BModes			ADAMS
		Platform Inertia Only	Platform Inertia + Hydrostatic & Mooring Stiffness	Full Platform Model	Full Platform Model
1	Surge	0.0000	0.0081	0.0076	0.0076
2	Sway	0.0000	0.0081	0.0076	0.0076
3	Yaw	0.0000	0.0206	0.0198	0.0198
4	Roll	0.0000	0.1106	0.0978	0.0966
5	Pitch	0.0000	0.1109	0.0980	0.0968
6	Heave	0.0000	0.2576	0.1283	0.2463
7	1st SS	0.7349	0.7671	0.5489	0.5374
8	1st FA	0.7494	0.7820	0.5556	0.5440
9	1st Torsion	1.4836	1.4836	1.4826	1.4890
10	2nd SS	1.9943	1.9962	1.9270	1.9327
11	2nd FA	2.3652	2.3666	2.2942	2.2950
12	3rd SS	4.7559	4.7562	4.7011	4.7742
13	3rd FA	5.0799	5.0801	5.0293	5.2260
14	1st Axial	8.5014	8.5017	8.2186	8.2759
15	4th SS	11.3835	11.3835	11.3542	11.3138
16	4th FA	11.5280	11.5280	11.4983	11.5167
17	2nd Torsion	17.9683	17.9683	17.9679	17.9639
18	5th SS	21.7584	21.7584	21.7406	21.3760



Monopile-Supported Turbine: Structural Idealization



Monopile-Supported Turbine: Comparison of Modal Frequencies

Mode Number	Mode Type	Frequency (Hz)		Difference (Hz)
		BModes	ADAMS	
1	1st SS	0.2513	0.2457	0.01
2	1st FA	0.2530	0.2472	0.01
3	1st Torsion	1.2752	1.2777	0.00
4	2nd SS	1.3680	1.3549	0.01
5	2nd FA	1.5316	1.5056	0.03
6	3rd SS	2.7425	2.7810	0.04
7	3rd FA	3.0874	3.1788	0.09
8	4th SS	5.9778	6.0090	0.03
9	4th FA	6.0506	6.2269	0.18
10	1st Axial	6.7671	6.5515	0.22
11	2nd Torsion	10.3875	10.3448	0.04
12	5th SS	11.4049	11.2947	0.11
13	5th FA	11.4758	11.4022	0.07
14	6th SS	17.9595	17.6518	0.31
15	6th FA	17.9704	17.7208	0.25
16	2nd Axial	18.1887	18.0404	0.15

Spar-Buoy-Supported Turbine: Comparison of Modal Frequencies

Mode Number	Mode Type	Frequency (Hz)			Difference (Hz)
		BModes (no gravity)	Bmodes (with gravity)	ADAMS	
1	Surge	0.0085	0.0085	0.0084	0.0001
2	Sway	0.0089	0.0089	0.0089	0.0000
3	Heave	0.0324	0.0325	0.0180	0.0145
4	Roll	0.0711	0.0376	0.0377	0.0001
5	Pitch	0.0712	0.0377	0.0378	0.0001
6	Yaw	0.1649	0.1649	0.1649	0.0000
7	SS-1	0.5000	0.4893	0.4861	0.0032
8	FA-1	0.5104	0.5103	0.5103	0.0000
9	Twist	1.693	1.695	1.700	0.0051
10	SS-2	2.067	2.065	0.7647	1.3003
11	FA-2	2.569	2.568	2.562	0.0062
12	SS-3	6.029	6.026	3.720	2.3057
13	FA-3	6.360	6.329	6.326	0.0031
14	Axial	8.033	7.678	7.669	0.0087

Future Plans

- Introduce Timoshenko beam element
- Provide for curved blade modeling.
- Couple BModes with CFD.

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Thank You for Your Attention

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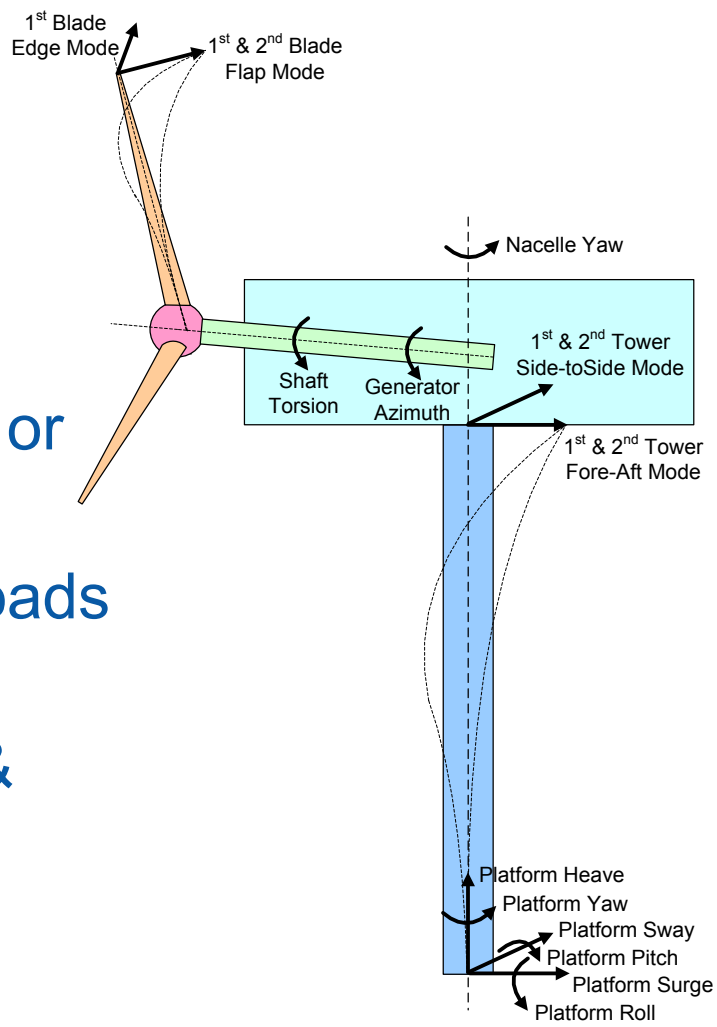
What are Analysis Codes?

- Codes developed for direct application in the design process
- Preprocessors, simulators, & post-processors
- Primary (simulation) codes are:
  - Multi-physics models (aero-hydro-servo-elastic)
  - Full system models (foundation + substructure + tower + nacelle + drivetrain + rotor)
  - Developed uniquely to the wind turbine application (not general purpose)
- Codes developed to run on standard PCs (not supercomputers)
- Codes whose accuracy is only as good as their inputs:
  - Inputs must be tuned with test data to ensure accurate outputs

FAST

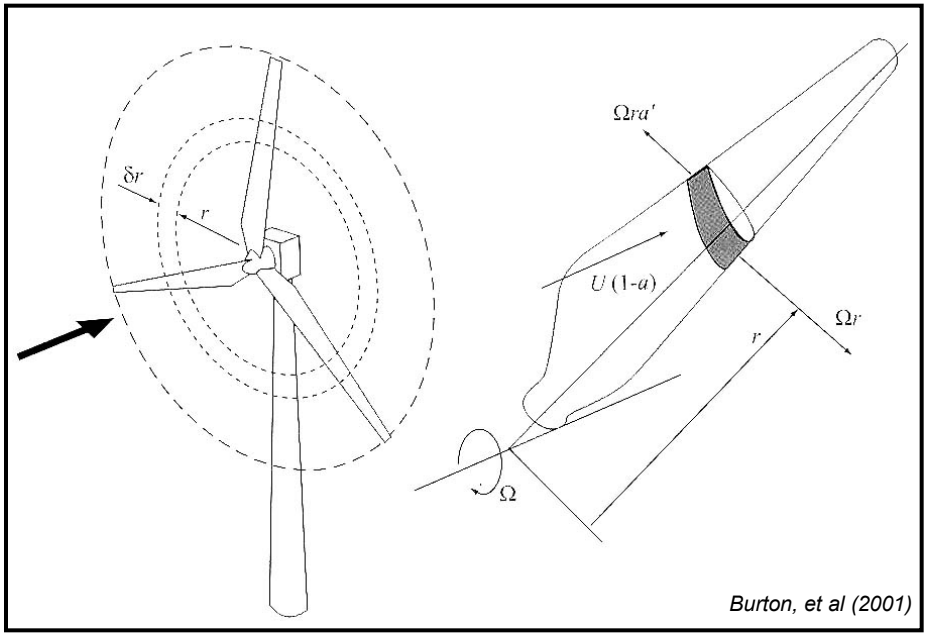
- Computes structural & controller responses as part of the aero-hydro-servo-elastic solution
- Combined modal & multi-body representation through 24 DOFs
- Controls through subroutines, DLLs, or Simulink®
- Nonlinear time-domain solution for loads analysis
- Linearization with MBC for controls & stability analysis
- Preprocessor for building turbine models in **MSC.ADAMS**
- Evaluated by GL WindEnergie



FAST DOFs for a 3-Bladed Turbine

AeroDyn

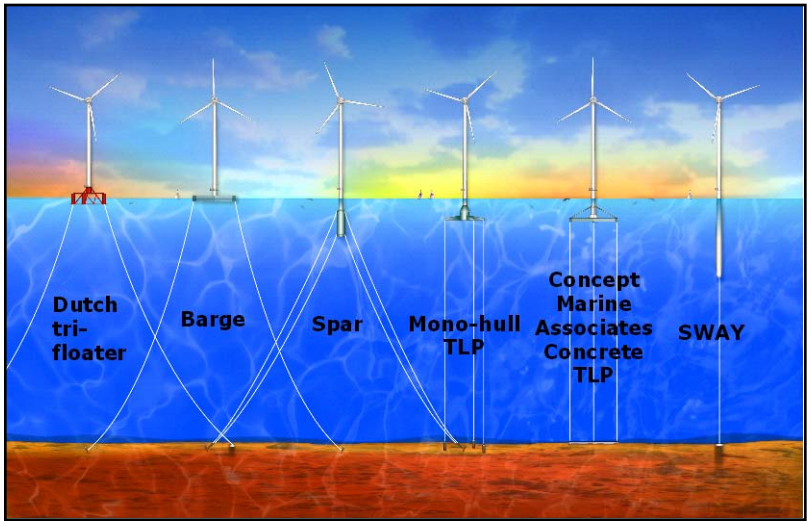
- Computes aerodynamics (lift, drag, pitch) as part of the aero-elastic solution
- Wind-inflow input:
  - Uniform, unsteady
  - Turbulent (**TurbSim**)
- Wake modeling:
  - BEM (quasi-steady)
  - GDW (dynamic)
- Dynamic stall modeling:
  - Beddoes-Leishman (semi-empirical)



BEM Discretization

HydroDyn

- Computes wave-kinematics & hydrodynamics as part of the hydro-elastic solution
- Wave & current input:
  - Regular or irregular linear waves
  - Steady sub-surface, near-surface, & depth-independent currents
- Hydrodynamics:
  - Morison's equation for monopiles
  - Linear radiation/diffraction theory for floaters (with frequency-domain input from WAMIT or equivalent)
- Moorings:
  - Quasi-static (nonlinear catenary equations)



Floating Wind Turbine Concepts

Coupled Modes

- Each natural mode has coupled flap + lag + twist + axial motion
- Types of coupling:
  - Dynamic couplings. Caused by
    - Geometric offsets of section c.m., tension center, and shear center from the pitch axis
    - Blade twist and precone
    - Blade rotation
    - Blade curving (built-in or induced by deformation)
  - Material couplings. Caused by material cross-stiffness.
- Sophisticated modeling required to capture these couplings accurately.

Assumptions & Limitations

- Straight Euler-Bernoulli beam
- Isotropic properties (no cross-stiffnesses)
- Rotary inertia effects included, but shear deformation effects ignored.
- Moderate deformations, but small strains.
- For tower modal analysis, tower head (nacelle+rotor) and platform are modeled as 6-dof rigid-body inertias.
- Foundation (soil) is modeled as a distributed spring.

Future Plans

- Integrate BModes with CFD (collaboration with NASA)
- Integrate with AeroDyn
- Integrate with FAST
- Introduce Timoshenko beam element
- Provide for composites
- Extend formulation for curved blades.