National Renewable Energy Laboratory
Innovation for Our Energy Future

Overview of BModes

TurbSim & Design Codes Workshop

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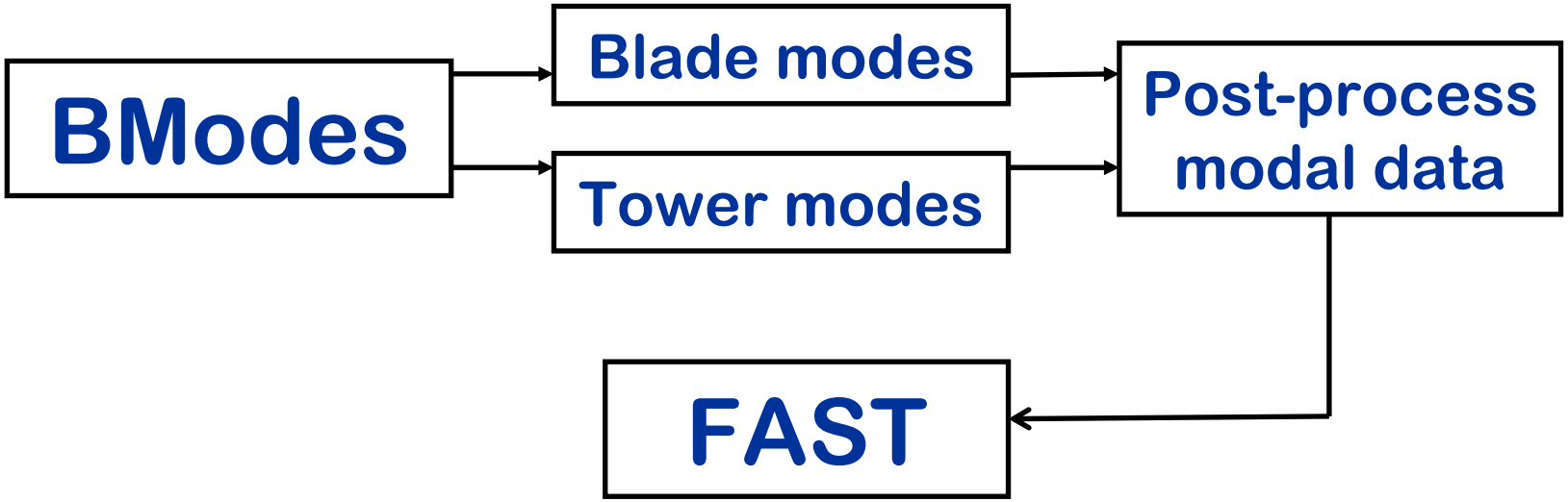
Background

- Modal-based codes, such as FAST, need modes of main flexible components (towers and blades) to build wind turbine models.
- BModes developed to provide such modes.



BModes Application

Blades

- Given:
  - Blade distributed geometric & structural properties
  - Rotational speed
  - Pitch control setting, precone
  - Tip mass inertia properties
- Computes:
  - Modal frequencies
  - Coupled mode shapes

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.

BModes Application

Towers

- Tower configurations that BModes can model:
  - Land-based tower
    - with tower head inertia
    - with or without tension-wires support
  - Offshore tower : supported by
    - floating-platform
      - Barge + mooring lines
      - spar-buoy + mooring lines
      - TLP
    - monopile (no multi-pod supports)

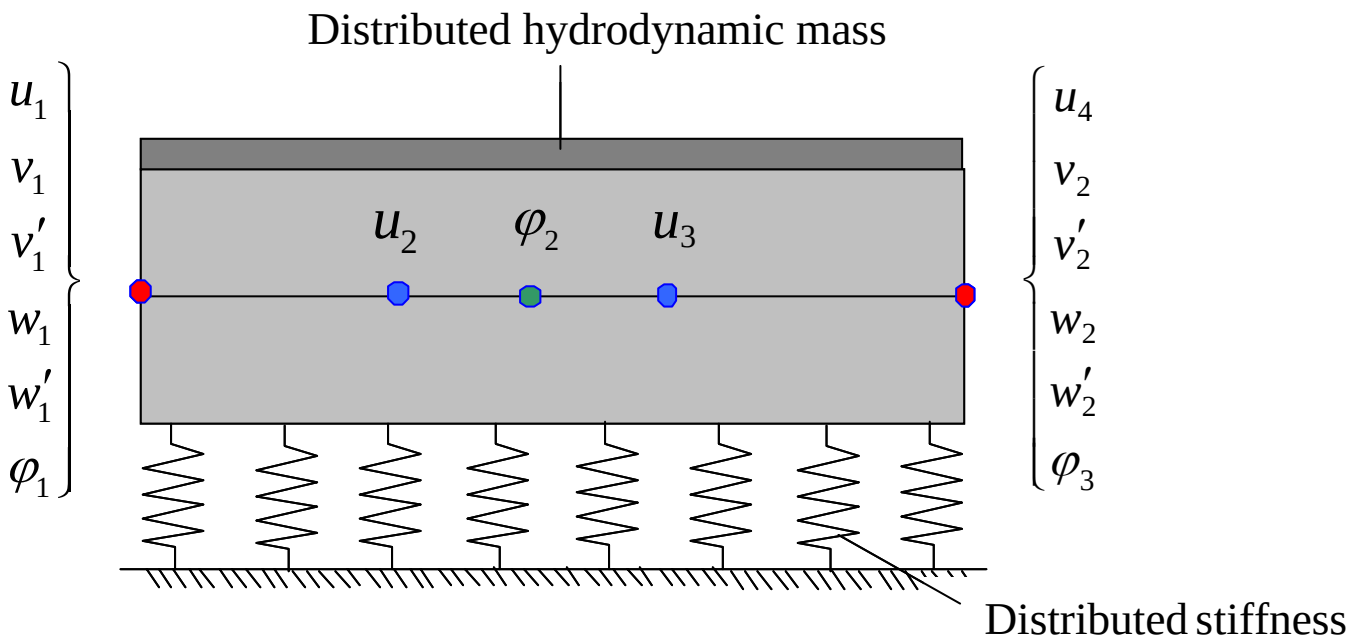
BModes Application

Towers (cont'd)

- Given:
  - Elastic tower distributed geometric & structural properties
  - Tower-head inertias and c.m. offsets from tower top
  - Tension-wires stiffness and geometric layout (*)
  - Floating-platform hydrodynamic & hydrostatic properties + mooring lines 6x6 stiffness matrix (*)
  - Monopile foundation elastic properties (*)
  - Hydrodynamic added mass on submerged part of the elastic tower (*)
- Computes:
  - Modal frequencies & coupled modes
    (coupled → fore-aft + side-side + twist + axial motion)

Salient Features of BModes

- Uses 15-dof finite element with two external and three internal nodes



Salient Features of BModes (cont'd)

- Uses quasi-coordinates:

- Quasi-coordinates give rise to spatial-integral terms.

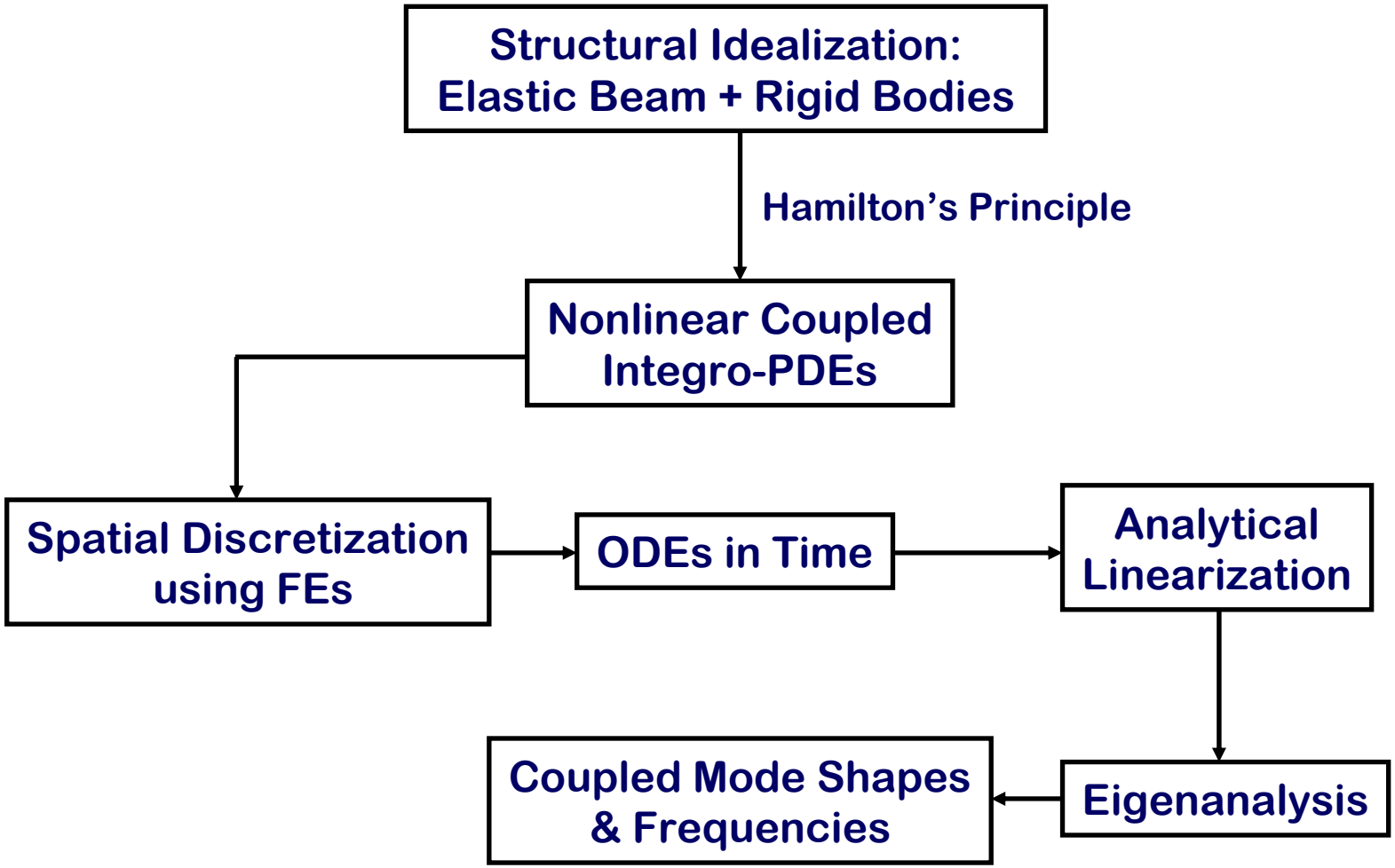
Salient Features of BModes (cont'd)

- Rotational effects (centrifugal, Coriolis, tennis-racket, etc) included accurately
- Finite-element assembly specialized to handle spatial-integral terms
- Arbitrary distributed beam properties
- Provision for precone & pitch control setting
- Potential to handle a complex range of boundary conditions
- Linearized equations derived analytically

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.

Technical Approach



BModes

Other Applications

- Experimental validation or code-to-code verification of blade & tower components
- Parameters identification (model updating)
- Modal reduction
- Physical interpretation of dynamic couplings
- Aid modal-based stability analysis
- Modal-based fatigue analysis

BModes Verification

- For blades:
  BModes verified extensively using models ranging from a rotating string to realistic blades.
- For towers:
  Verification in progress.

Sample Results for Blades

Spinning Uniform Cable

Comparison of Flap Modal Frequencies

Cable 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	0.0	0.00	0.00	0.00	0.00	0.00
2	2.0	2.00	4.90	4.91	7.75	7.76
6	6.0	6.01	14.70	14.72	23.24	23.27
10	10.0	10.02	24.49	24.53	38.73	38.79
15	15.0	15.03	36.74	36.80	58.09	58.18
20	20.0	20.04	48.99	49.07	77.46	77.58
25	25.0	25.04	61.24	61.33	96.82	96.97
30	30.0	30.05	73.48	73.60	116.19	116.37

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

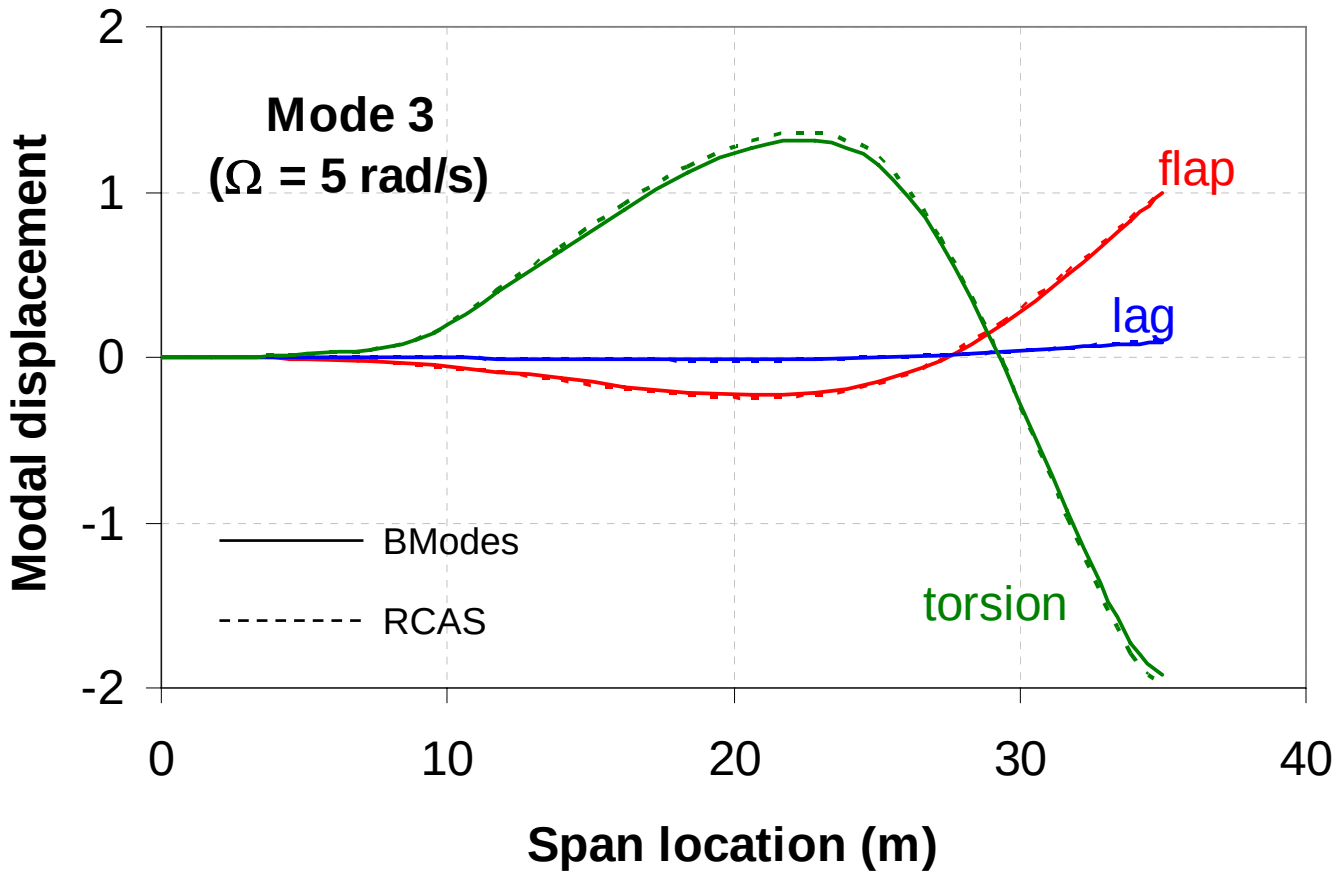
WindPact 1.5 MW Turbine Blade

Comparison of Flap 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 Results
for
Towers
(NREL 5MW Turbine)

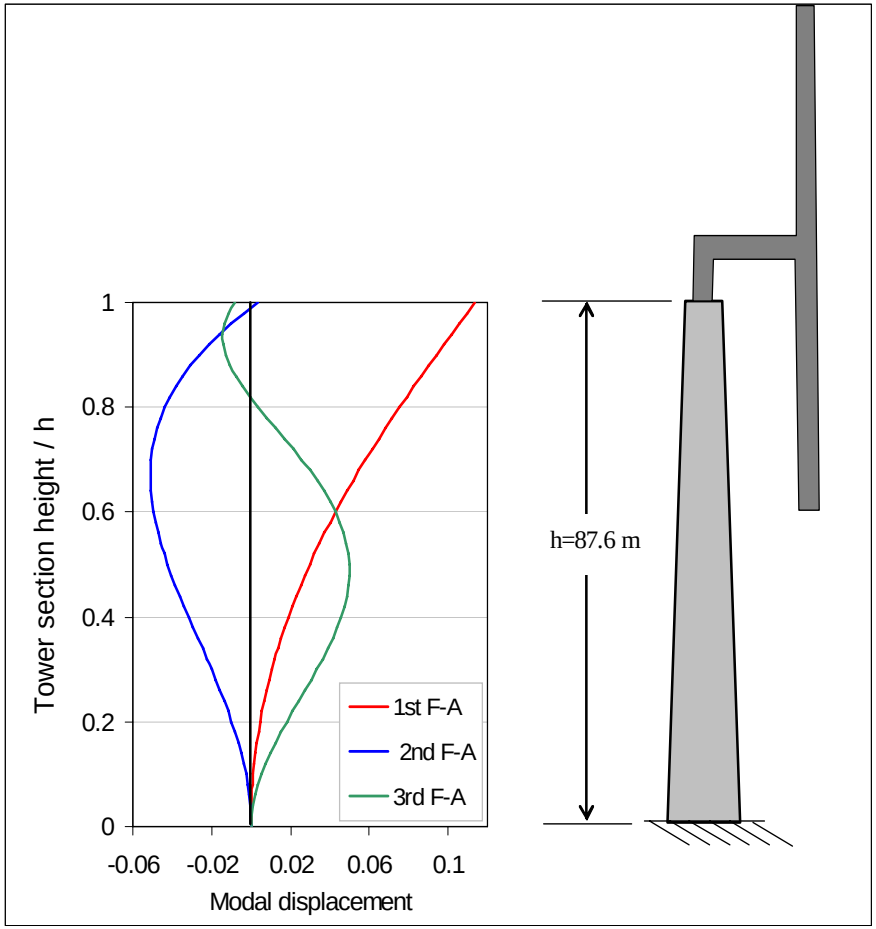
Land-Based Tower

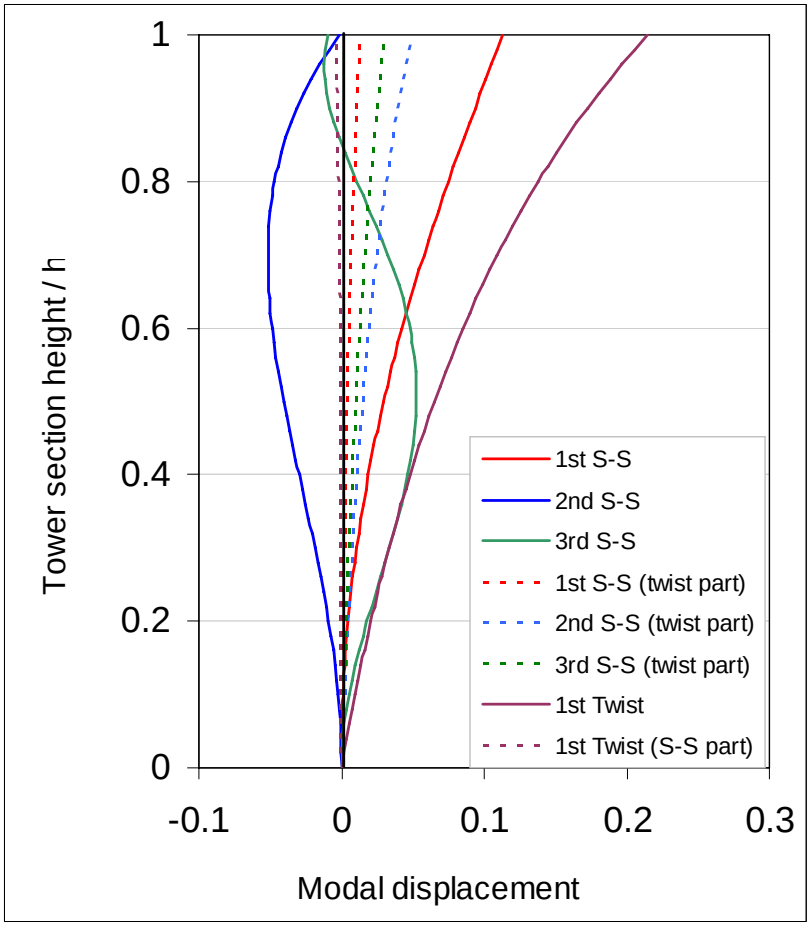
Modal Frequencies

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

Land-Based Tower

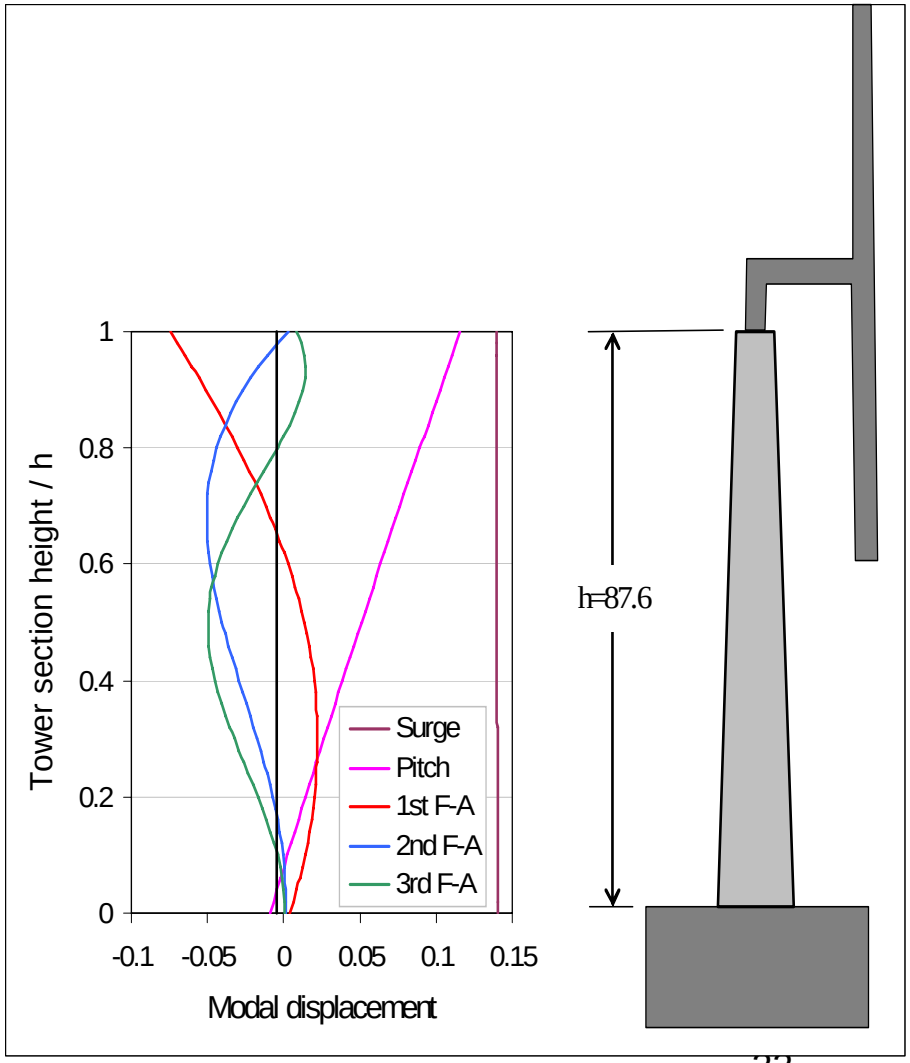
Mode Shapes



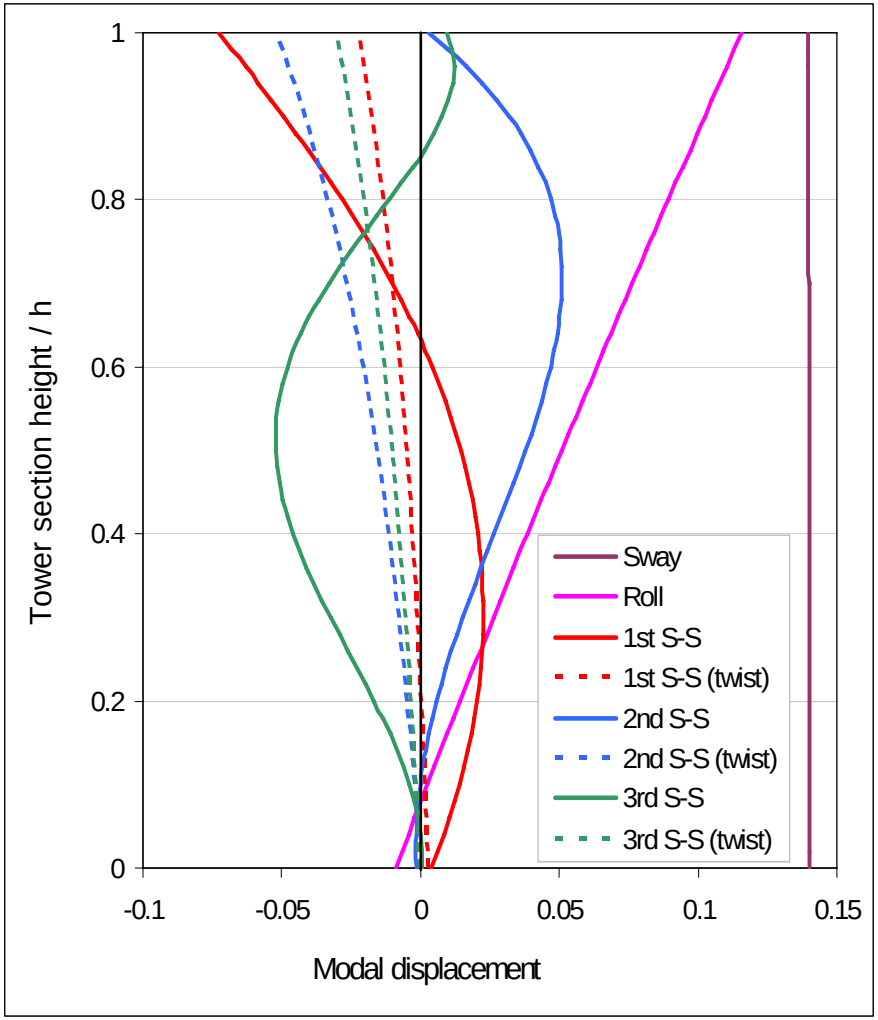


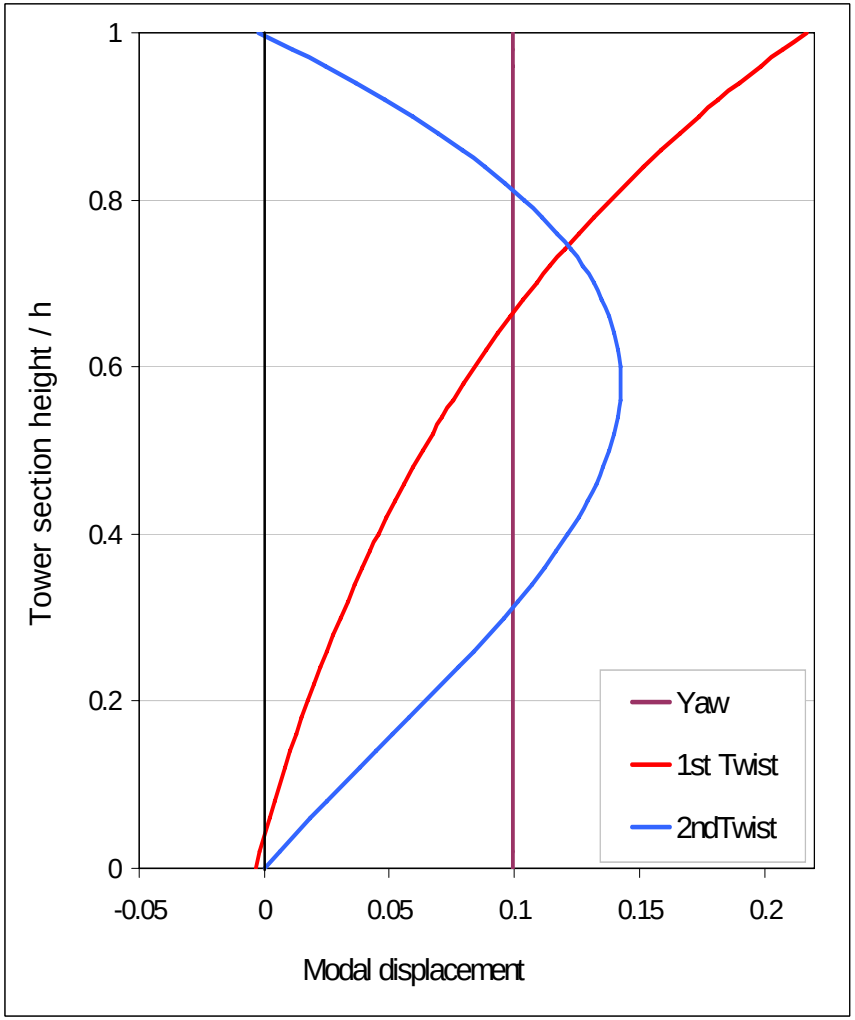
Barge-Supported Turbine Modes

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

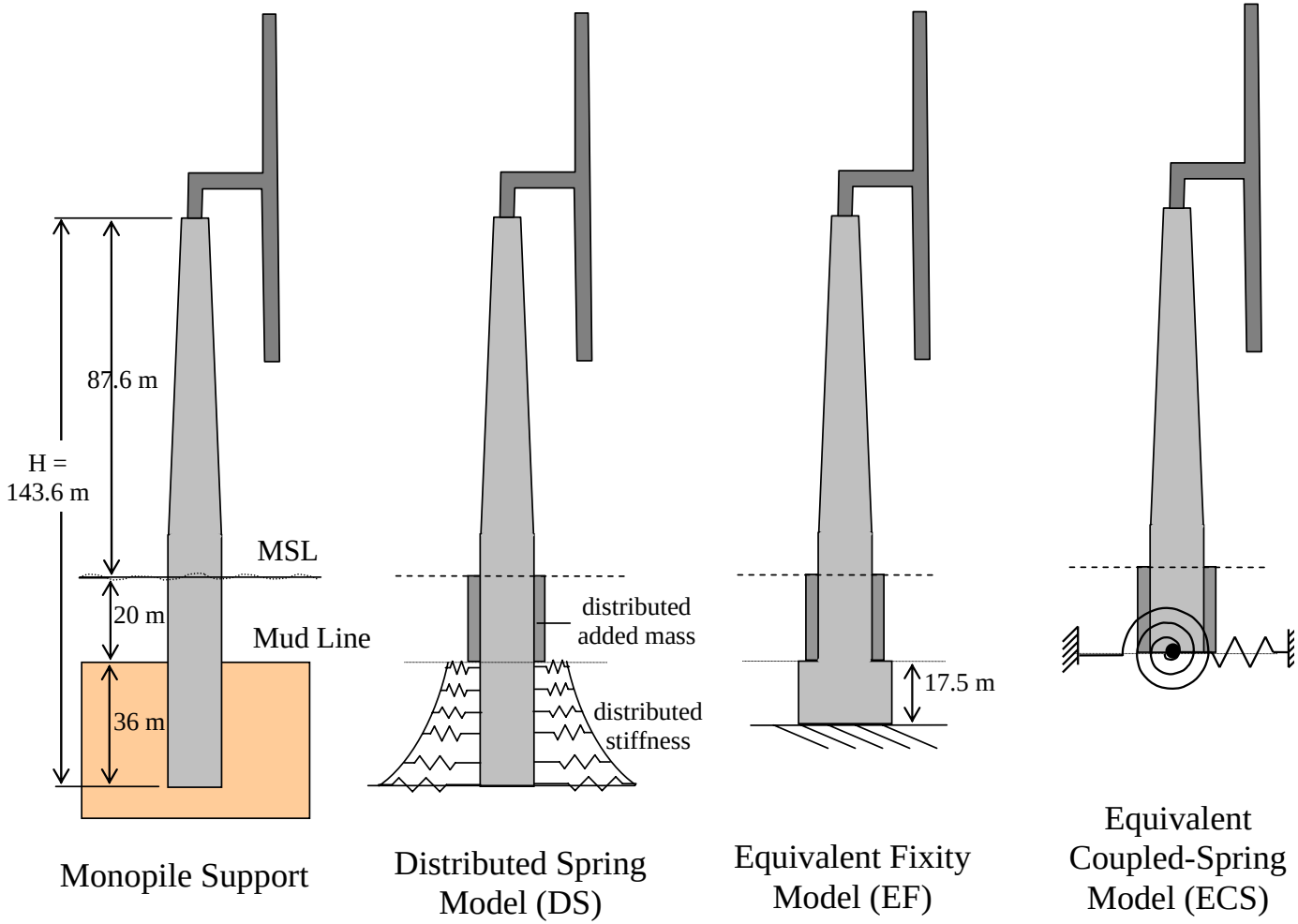


Barge-Supported Turbine Modes





Monopile-Supported Turbine:
Equivalent Models



Monopile-Supported Turbine Modal Frequencies

DS Model

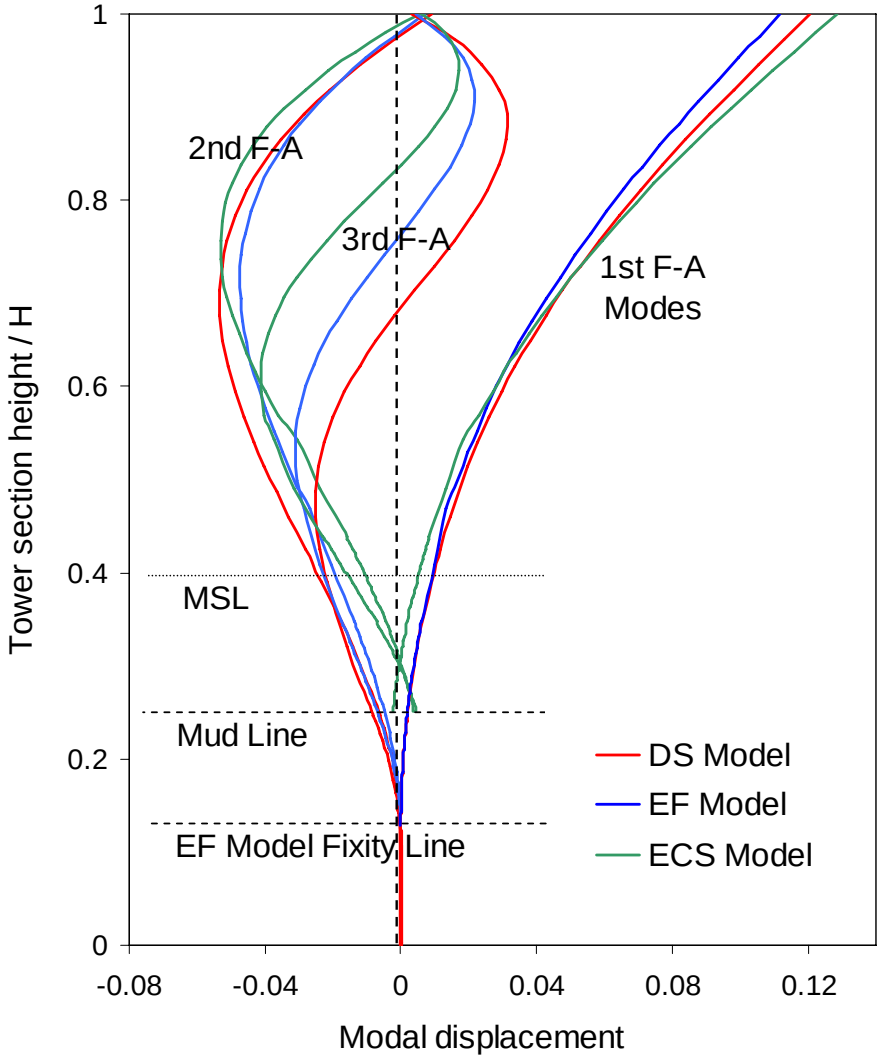
Mode Number	Mode Type	Frequency (Hz)		Difference (Hz)
		BModes	ADAMS	
1	1st SS	0.2513	0.2457	0.01
2	1st FA	0.2530	0.2472	0.01
3	1st Torsion	1.2752	1.2777	0.00
4	2nd SS	1.3680	1.3549	0.01
5	2nd FA	1.5316	1.5056	0.03
6	3rd SS	2.7425	2.7810	0.04
7	3rd FA	3.0874	3.1788	0.09
8	4th SS	5.9778	6.0090	0.03
9	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
17	3rd Torsion	21.1075	21.1944	0.09

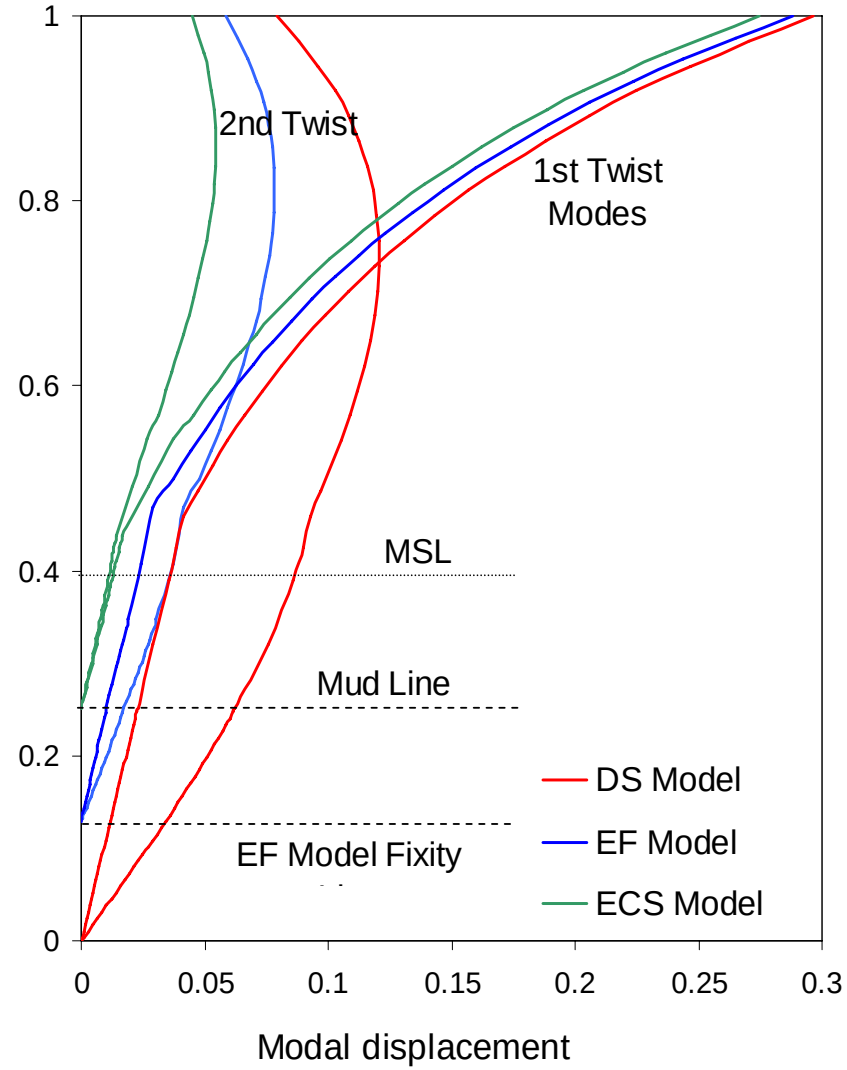
All Models

Mode Number	Mode Type	Frequency (Hz)		
		Distributed Stiffness	Apparent Fixity	Equivalent Stiffness
1	1st SS	0.2513	0.2513	0.2584
2	1st FA	0.253	0.2530	0.2604
3	1st Torsion	1.2752	1.3039	1.3223
4	2nd SS	1.368	1.3672	1.5051
5	2nd FA	1.5316	1.5307	1.7468
6	3rd SS	2.7425	2.7430	3.3313
7	3rd FA	3.0874	3.0895	3.6600
8	4th SS	5.9778	6.0125	7.1579
9	4th FA	6.0506	6.1083	7.6287
10	1st Axial	6.7671	7.0695	7.8420
11	2nd Torsion	10.3875	11.6387	13.1516
12	5th SS	11.4049	11.7126	13.1865
13	5th FA	11.4758	13.1636	15.9651
14	6th SS	17.9595	18.7032	16.6629
15	6th FA	17.9704	18.7399	16.6988
16	2nd Axial	18.1887	22.2298	25.9700
17	3rd Torsion	21.1075	23.3796	25.9937

Monopile-Supported Turbine

Mode Shapes





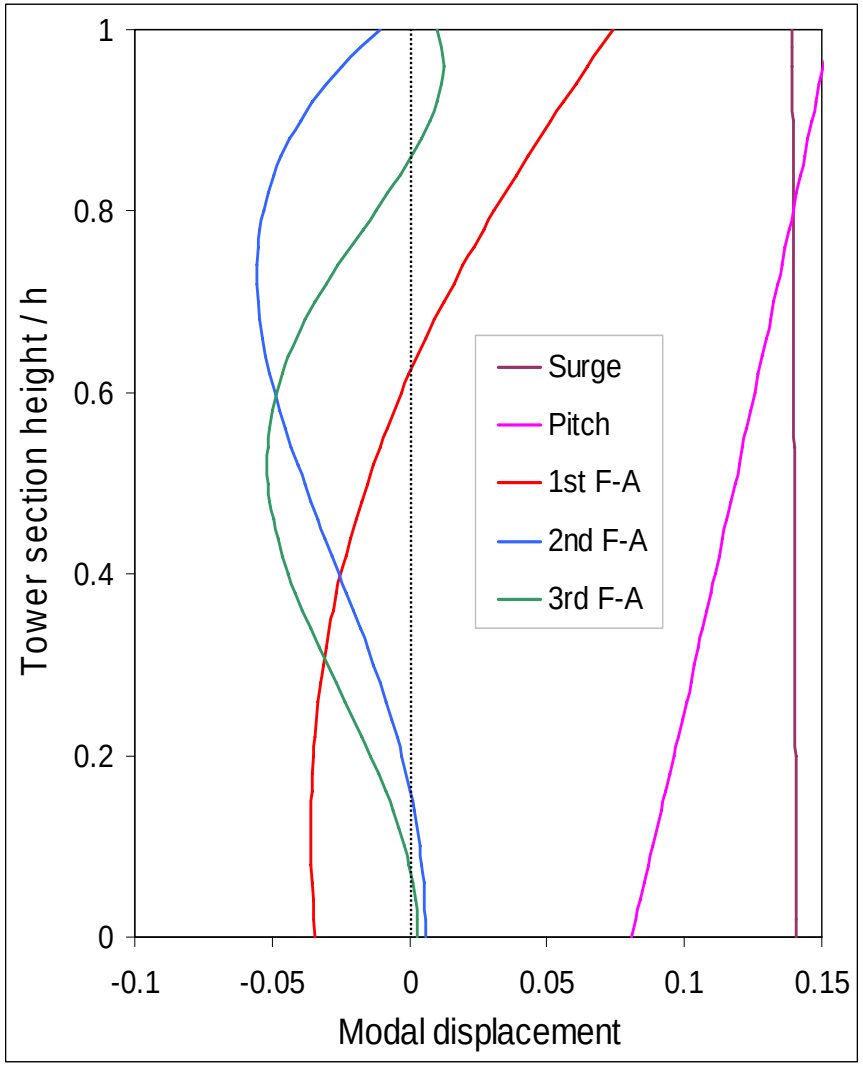
Spar-Buoy-Supported Turbine

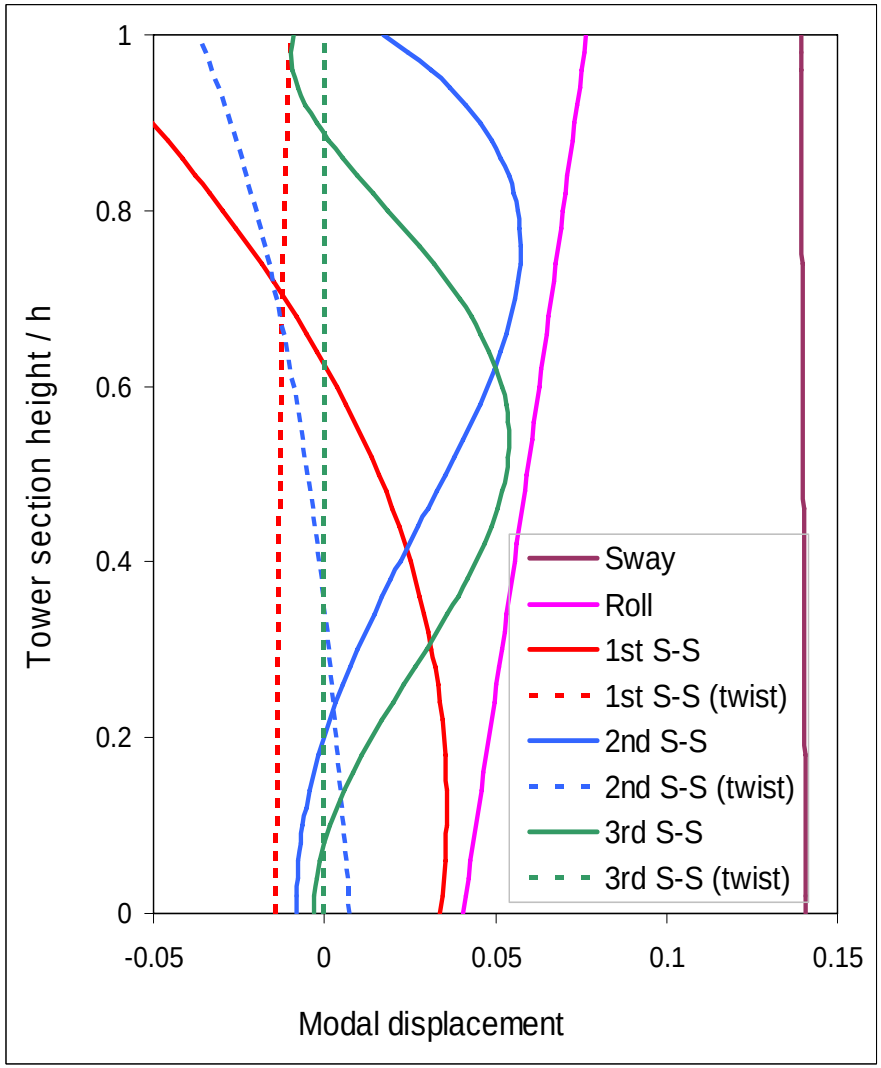
Modal Frequencies

Mode Number	Mode Type	Frequency (Hz)		
		BModes	ADAMS	Diff (Hz)
1	Surge	0.0085	0.0084	0.000
2	Sway	0.0089	0.0089	0.000
3	Heave	0.0324	0.0180	0.014
4	Roll	0.0711	0.0377	0.033
5	Pitch	0.0712	0.0378	0.033
6	Yaw	0.1649	0.1649	0.000
7	SS-1	0.5000	0.4861	0.014
8	FA-1	0.5103	0.5103	0.000
9	Twist	1.693	1.700	0.007
10	SS-2	2.067	0.7647	1.302
11	FA-2	2.569	2.562	0.008
12	SS-3	6.02919	3.720	2.309
13	FA-3	6.360	6.326	0.034
14	Axial	8.033	7.669	0.363

Spar-Buoy-Supported Turbine

Mode Shapes





Future Plans

- Complete verification. Release BModes-3 along with new user's manual.
- Integrate BModes with CFD (collaboration with NASA).
- Provide for composites.
- Integrate with FAST.
- Extend formulation for curved blades
- Introduce Timoshenko beam element.

Questions?

Current version of BModes is available on NWTC website

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