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Sandia Platform Analysis

Phase I Meeting

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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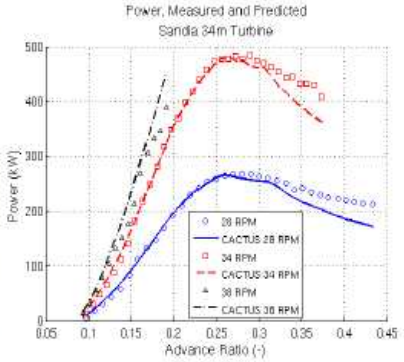
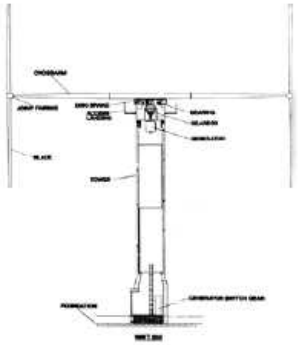
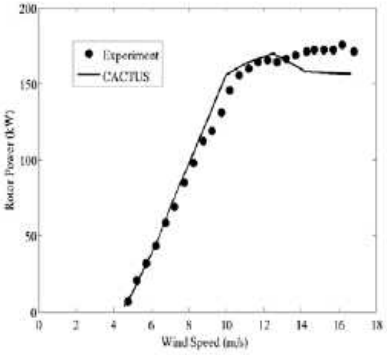
SNL Analysis Model Description

Aerodynamic Performance and Loads Simulations

- Tool: CACTUS free vortex code
- Validated against legacy VAWT performance data
- Strut drag model included
- Tower wake effects ignored
- Results fed into structural, platform, and COE analyses







SNL Analysis Model Description

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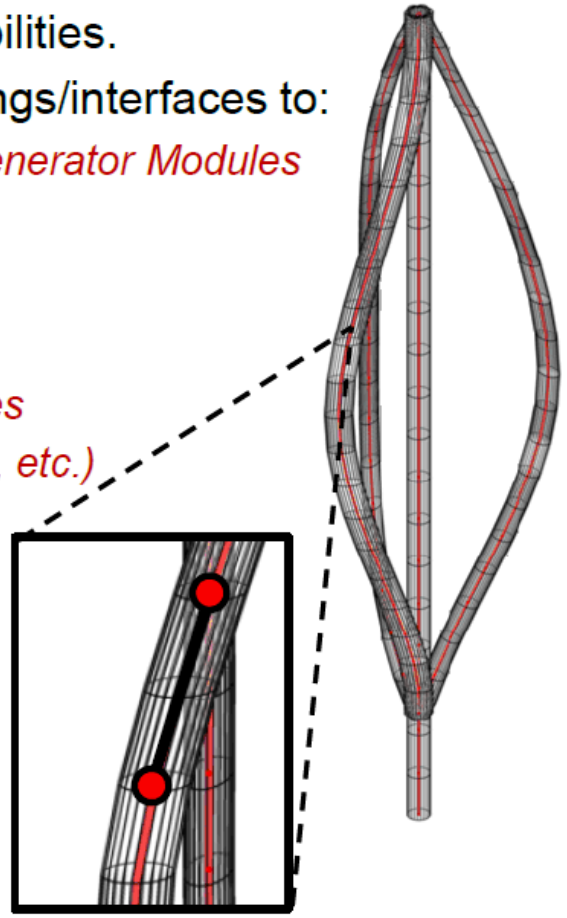
Offshore Wind ENergy Simulation (OWENS) Toolkit Structural Dynamics Design Tool Features

- ✓ Enables modal and transient analysis capabilities.
- ✓ Modular analysis framework enables couplings/interfaces to:
  - *Aerodynamics, Hydrodynamics, Drivetrain/generator Modules*
- ✓ Finite element method
  - *Flexibility and robustness in implementation*
  - *3D Timoshenko beam*
  - *Rotational effects and geometric nonlinearities*
  - *Structural couplings (bend-twist, sweep-twist, etc.)*
  - *Offset mass axes, concentrated mass, etc.*
- ✓ Mesh generator
  - Considers VAWTs of arbitrary geometry
  - Interfaces with existing design tools
  - Visualization
- ✓ Open-source, batch capability



Modal Analysis Results

- Performed a check of the SNL tool OWENS using the mass and stiffness properties from SES to compare the natural period predictions
- An additional analytic check was performed by treating the 6 system equations of motion as uncoupled:

$$\omega_i = \sqrt{k_i / m_i}$$

Summary

Comparison of Phase 1 Concepts

		Concept 1 Four-column Semi	Concept 2 Classic Spar	Concept 3 Ring Pontoon	Concept 4 Compact Semi	Concept 5 Advanced Spar	Concept 6 MC-TLP
K_{11}	N/m	1.329E+05	1.348E+05	1.329E+05	1.592E+05	1.380E+05	1.623E+05
K_{22}	N/m	1.329E+05	1.348E+05	1.329E+05	1.592E+05	1.380E+05	1.623E+05
K_{33}	N/m	1.985E+06	2.327E+06	6.599E+06	3.826E+06	2.362E+06	7.135E+07
K_{44}	(N-m)/deg	3.993E+06	1.181E+07	3.977E+06	3.485E+06	9.115E+06	2.340E+08
K_{55}	(N-m)/deg	3.995E+06	1.181E+07	3.977E+06	3.485E+06	9.115E+06	2.340E+08
K_{66}	(N-m)/deg	1.076E+06	8.189E+05	1.076E+06	1.654E+06	1.384E+06	1.118E+06
M_{11}	kg	9.809E+06	3.061E+07	8.730E+06	8.558E+06	3.251E+07	7.388E+06
M_{22}	kg	9.781E+06	3.061E+07	8.730E+06	8.558E+06	3.251E+07	7.388E+06
M_{33}	kg	1.891E+07	1.791E+07	3.365E+07	7.959E+06	2.611E+07	1.341E+07
I_{44}	kg-m^2	3.635E+09	5.210E+10	5.678E+09	1.794E+09	5.275E+10	2.337E+09
I_{55}	kg-m^2	3.651E+09	5.214E+10	5.711E+09	1.827E+09	5.278E+10	2.369E+09
I_{66}	kg-m^2	2.436E+09	6.536E+08	9.287E+08	1.305E+09	6.151E+08	1.374E+09
T_{11}	sec	54	95	51	46	96	42
T_{22}	sec	54	95	51	46	96	42
T_{33}	sec	19	17	14	9	21	3
T_{44}	sec	25	55	31	19	63	3
T_{55}	sec	25	55	31	19	63	3
T_{66}	sec	40	23	24	23	17	29

Modal Analysis Results

- Natural periods mostly compare well between the three approaches
- Pitch/roll have most discrepancy (DOF 4&5)
  - Differences in modeling turbine mass and roll/pitch inertias
- Minor discrepancies between OWENS and simple analytic method

Combined System Natural Periods [sec] - SES						
1	54.00	95.00	51.00	46.00	96.00	42.00
2	54.00	95.00	51.00	46.00	96.00	42.00
3	19.00	17.00	14.00	9.00	21.00	3.00
4	25.00	55.00	31.00	19.00	63.00	3.00
5	25.00	55.00	31.00	19.00	63.00	3.00
6	40.00	23.00	24.00	23.00	17.00	29.00

Combined System Natural Periods [sec] - OWENS						
Row	FourColumnSemi_2ndPass	ClassicSpar	RingPontoon	CompactSemi	AdvancedSpar	MultiCellularTLP
1	54.56	95.03	51.65	46.74	96.78	43.04
2	54.64	95.03	51.65	46.74	96.78	43.04
3	19.51	17.54	14.24	9.19	20.98	2.75
4	29.00	55.80	34.63	24.56	63.90	3.55
5	28.86	55.77	34.46	24.29	63.86	3.53
6	39.78	24.07	24.84	23.62	17.99	29.47

Combined System Natural Periods [sec] - Analytic						
Row	FourColumnSemi_2ndPass	ClassicSpar	RingPontoon	CompactSemi	AdvancedSpar	MultiCellularTLP
1	55.52	95.55	52.56	47.57	97.28	43.99
2	55.45	95.55	52.56	47.57	97.28	43.99
3	19.68	17.71	14.31	9.38	21.12	2.78
4	29.00	55.79	34.62	24.48	63.88	3.24
5	29.14	55.82	34.78	24.75	63.92	3.27
6	39.78	24.07	24.84	23.62	17.99	29.47

Modal Analysis Results

- Modal analyses were performed for the 6 platforms

Simulation with 15m Tower Extension													
Mode	DOF	FourColumnSemi_2ndPass		ClassicSpar		RingPontoon		CompactSemi		AdvancedSpar		MultiCellularTLP	
		[hz]	[sec]	[hz]	[sec]	[hz]	[sec]	[hz]	[sec]	[hz]	[sec]	[hz]	[sec]
1	1	0.0183	54.64	0.0105	95.03	0.0194	51.65	0.0214	46.74	0.0103	96.78	0.0232	43.04
2		0.0183	54.64	0.0105	95.03	0.0194	51.65	0.0214	46.74	0.0103	96.78	0.0232	43.04
3	2	0.0183	54.57	0.0105	95.03	0.0194	51.65	0.0214	46.74	0.0103	96.78	0.0232	43.04
4		0.0183	54.57	0.0105	95.03	0.0194	51.65	0.0214	46.74	0.0103	96.78	0.0232	43.04
5	3	0.0251	39.78	0.0179	55.80	0.0289	34.63	0.0407	24.56	0.0156	63.90	0.0339	29.47
6		0.0251	39.78	0.0179	55.80	0.0289	34.63	0.0407	24.56	0.0156	63.90	0.0339	29.47
7	4	0.0345	29.00	0.0179	55.77	0.0290	34.46	0.0412	24.29	0.0157	63.86	0.2820	3.55
8		0.0345	29.00	0.0179	55.77	0.0290	34.46	0.0412	24.29	0.0157	63.86	0.2820	3.55
9	5	0.0347	28.86	0.0415	24.07	0.0403	24.84	0.0423	23.62	0.0477	20.98	0.2833	3.53
10		0.0347	28.86	0.0415	24.07	0.0403	24.84	0.0423	23.62	0.0477	20.98	0.2833	3.53
11	6	0.0513	19.51	0.0570	17.54	0.0702	14.24	0.1088	9.19	0.0556	17.99	0.3640	2.75
12		0.0513	19.51	0.0570	17.54	0.0702	14.24	0.1088	9.19	0.0556	17.99	0.3640	2.75
13	7	0.5151	1.94	0.4552	2.20	0.4939	2.02	0.5705	1.75	0.4551	2.20	0.5980	1.67
14		0.5151	1.94	0.4552	2.20	0.4939	2.02	0.5705	1.75	0.4551	2.20	0.5980	1.67
15	8	0.5274	1.90	0.4644	2.15	0.5049	1.98	0.5842	1.71	0.4643	2.15	0.6094	1.64
16		0.5274	1.90	0.4644	2.15	0.5049	1.98	0.5842	1.71	0.4643	2.15	0.6094	1.64
17	9	1.0761	0.93	1.0931	0.91	1.0863	0.92	1.0816	0.92	1.0946	0.91	1.0810	0.93
18		1.0761	0.93	1.0931	0.91	1.0863	0.92	1.0816	0.92	1.0946	0.91	1.0810	0.93
19	10	1.4378	0.70	1.4355	0.70	1.4371	0.70	1.4400	0.69	1.4355	0.70	1.4393	0.69
20		1.4378	0.70	1.4355	0.70	1.4371	0.70	1.4400	0.69	1.4355	0.70	1.4393	0.69
21	11	1.7033	0.59	1.6985	0.59	1.7019	0.59	1.7076	0.59	1.6985	0.59	1.7063	0.59
22		1.7033	0.59	1.6985	0.59	1.7019	0.59	1.7076	0.59	1.6985	0.59	1.7063	0.59
23	12	2.0861	0.48	2.0673	0.48	2.0805	0.48	2.1044	0.48	2.0672	0.48	2.0979	0.48
24		2.0861	0.48	2.0673	0.48	2.0805	0.48	2.1044	0.48	2.0672	0.48	2.0979	0.48
25	13	2.2144	0.45	2.2004	0.45	2.2101	0.45	2.2280	0.45	2.2003	0.45	2.2231	0.45
26		2.2144	0.45	2.2004	0.45	2.2101	0.45	2.2280	0.45	2.2003	0.45	2.2231	0.45
27	14	2.3056	0.43	2.3077	0.43	2.3069	0.43	2.3063	0.43	2.3079	0.43	2.3062	0.43
28		2.3056	0.43	2.3077	0.43	2.3069	0.43	2.3063	0.43	2.3079	0.43	2.3062	0.43
29	15	2.3845	0.42	2.3845	0.42	2.3842	0.42	2.3852	0.42	2.3843	0.42	2.3847	0.42
30		2.3845	0.42	2.3845	0.42	2.3842	0.42	2.3852	0.42	2.3843	0.42	2.3847	0.42
31	16	2.9939	0.33	2.9935	0.33	2.9938	0.33	2.9942	0.33	2.9935	0.33	2.9941	0.33
32		2.9939	0.33	2.9935	0.33	2.9938	0.33	2.9942	0.33	2.9935	0.33	2.9941	0.33
33	17	3.7895	0.26	3.7866	0.26	3.7890	0.26	3.7917	0.26	3.7866	0.26	3.7911	0.26
34		3.7895	0.26	3.7866	0.26	3.7890	0.26	3.7917	0.26	3.7866	0.26	3.7911	0.26
35	18	4.1448	0.24	4.1508	0.24	4.1484	0.24	4.1467	0.24	4.1513	0.24	4.1465	0.24
36		4.1448	0.24	4.1508	0.24	4.1484	0.24	4.1467	0.24	4.1513	0.24	4.1465	0.24
37	19	4.5561	0.22	4.5561	0.22	4.5561	0.22	4.5561	0.22	4.5561	0.22	4.5561	0.22
38		4.5561	0.22	4.5561	0.22	4.5561	0.22	4.5561	0.22	4.5561	0.22	4.5561	0.22
39	20	4.9010	0.20	4.8954	0.20	4.8998	0.20	4.9055	0.20	4.8954	0.20	4.9041	0.20
40		4.9010	0.20	4.8954	0.20	4.8998	0.20	4.9055	0.20	4.8954	0.20	4.9041	0.20

Modal Analysis Results

- Showing first 8 degrees of freedom from a static modal analysis: 6 rigid body motions and first tower bending modes

DOF	FourColumnSemi_2ndPass			ClassicSpar			RingPontoon		
	Mode	[hz]	[sec]	Mode	[hz]	[sec]	Mode	[hz]	[sec]
1	sway	0.0183	54.64	surge	0.0105	95.03	sway	0.0194	51.65
2	surge	0.0183	54.57	sway	0.0105	95.03	surge	0.0194	51.65
3	yaw	0.0251	39.78	roll	0.0179	55.80	roll	0.0289	34.63
4	roll	0.0345	29.00	pitch	0.0179	55.77	pitch	0.0290	34.46
5	pitch	0.0347	28.86	yaw	0.0415	24.07	yaw	0.0403	24.84
6	heave	0.0513	19.51	heave	0.0570	17.54	heave	0.0702	14.24
7	1stTwrBend - FA	0.5151	1.94	1stTwrBend - FA	0.4552	2.20	1stTwrBend - FA	0.4939	2.02
8	1stTwrBend - SS	0.5274	1.90	1stTwrBend - SS	0.4644	2.15	1stTwrBend - SS	0.5049	1.98

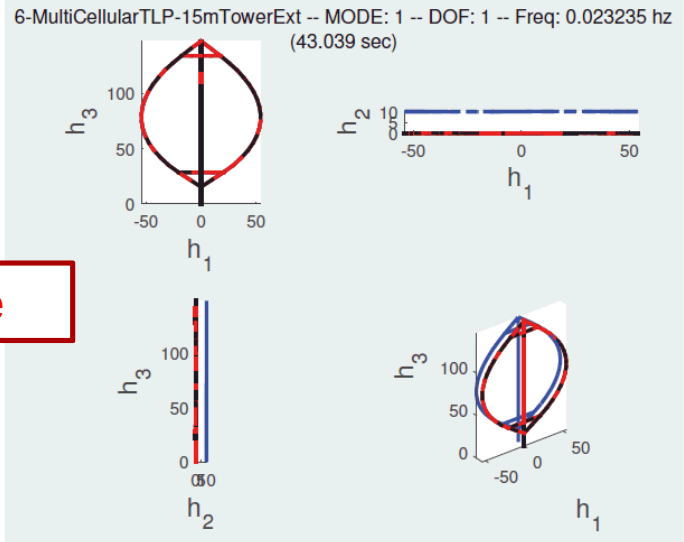
DOF	CompactSemi			AdvancedSpar			MultiCellularTLP		
	Mode	[hz]	[sec]	Mode	[hz]	[sec]	Mode	[hz]	[sec]
1	sway	0.0214	46.74	coupled sway-surge	0.0103	96.78	surge	0.0232	43.04
2	surge	0.0214	46.74	coupled surge-sway	0.0103	96.78	sway	0.0232	43.04
3	roll	0.0407	24.56	roll	0.0156	63.90	yaw	0.0339	29.47
4	pitch	0.0412	24.29	pitch	0.0157	63.86	roll	0.2820	3.55
5	yaw	0.0423	23.62	heave	0.0477	20.98	pitch	0.2833	3.53
6	heave	0.1088	9.19	yaw	0.0556	17.99	heave	0.3640	2.75
7	1stTwrBend - FA	0.5705	1.75	1stTwrBend - FA	0.4551	2.20	1stTwrBend - FA	0.5980	1.67
8	1stTwrBend - SS	0.5842	1.71	1stTwrBend - SS	0.4643	2.15	1stTwrBend - SS	0.6094	1.64

Modal Analysis - Mode Shapes

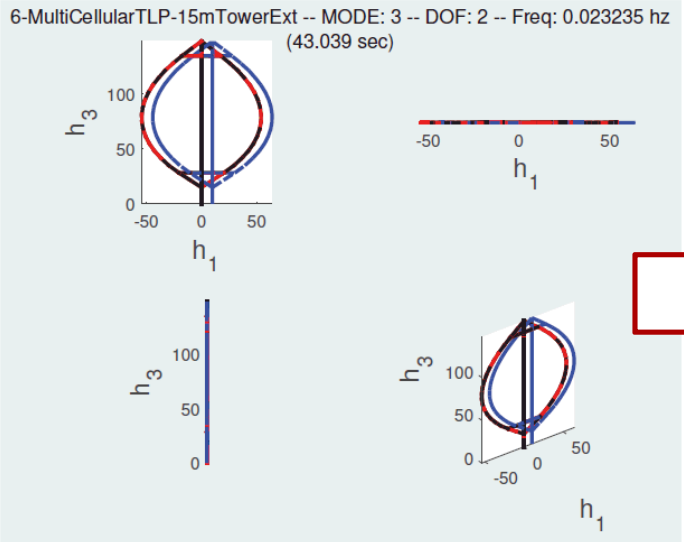
- Modal resonances were classified through observation of the mode shapes.
- As an example, the results are shown for the multi-cellular TLP

Mode Shapes – Multi-Cellular TLP

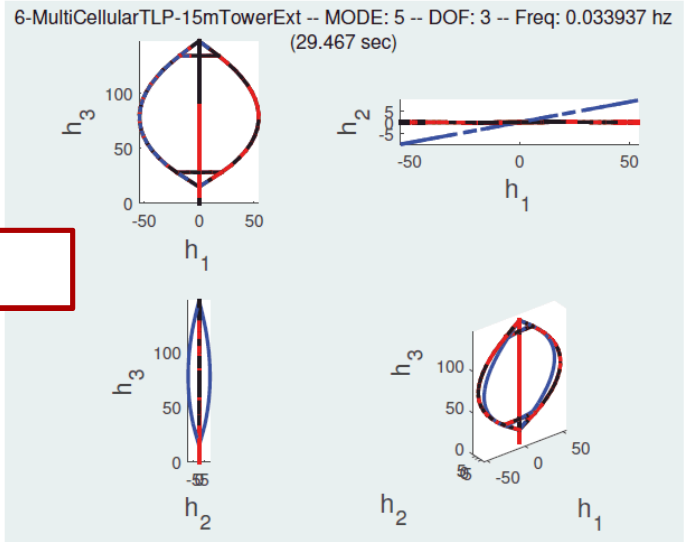
surge



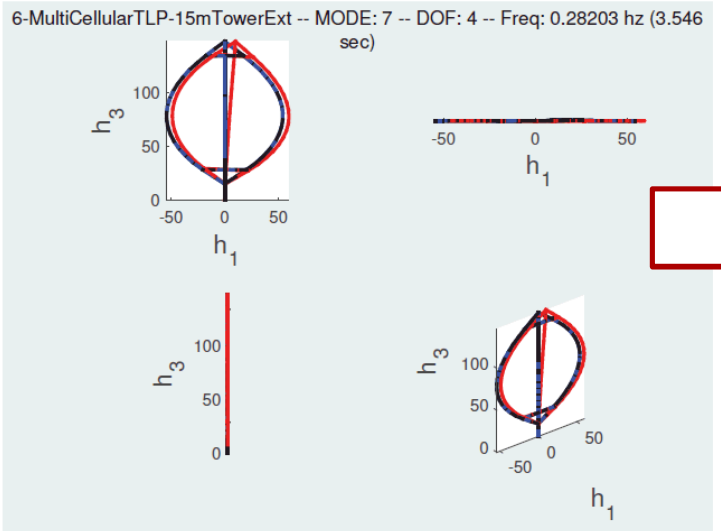
sway



yaw

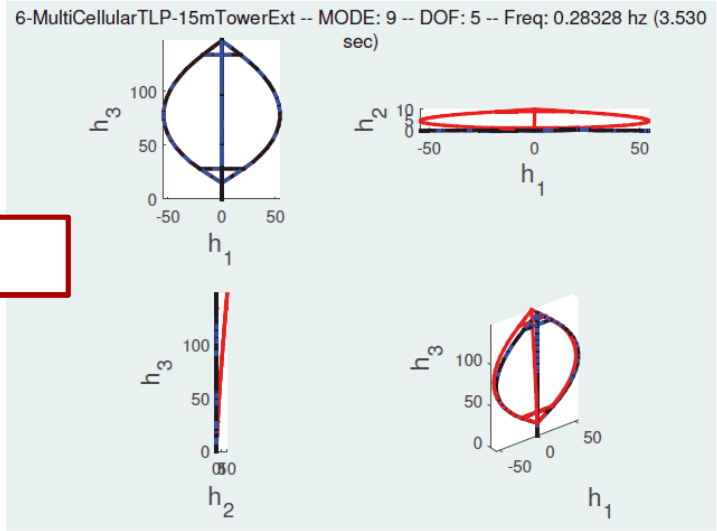


roll

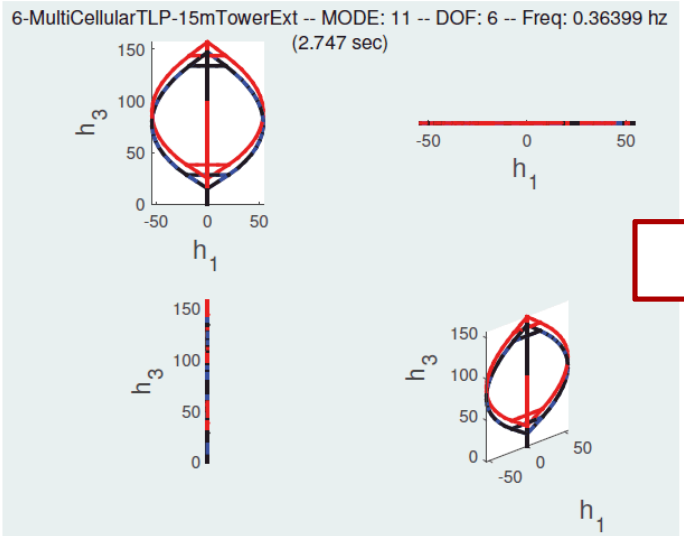


Mode Shapes – Multi-Cellular TLP

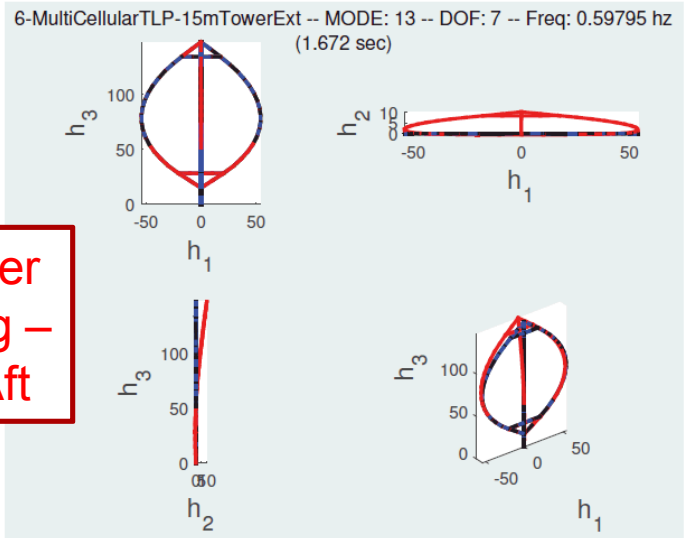
pitch



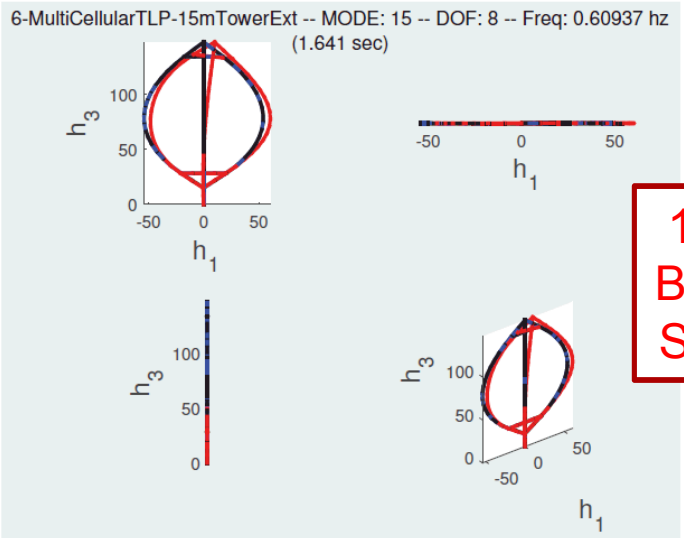
heave



1st Tower Bending – Fore-Aft



1st Tower Bending – Side-Side



Mode Shapes – Multi-Cellular TLP

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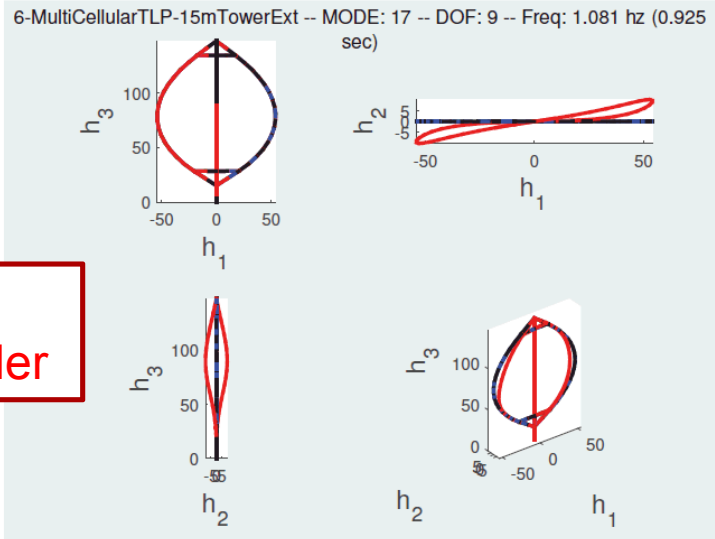
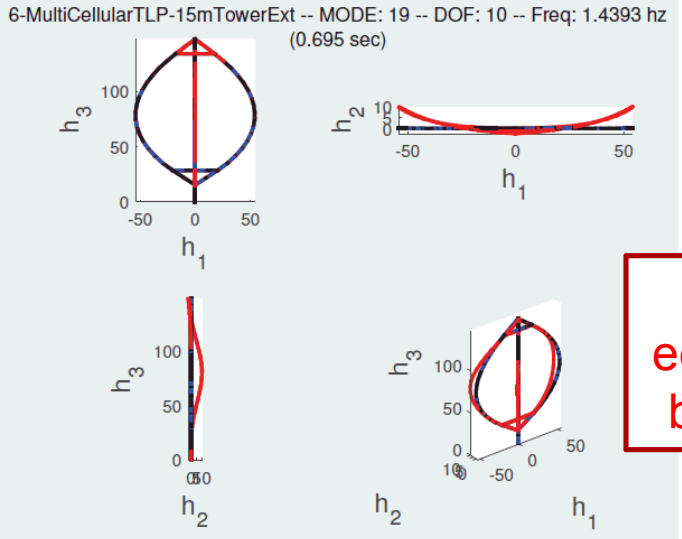
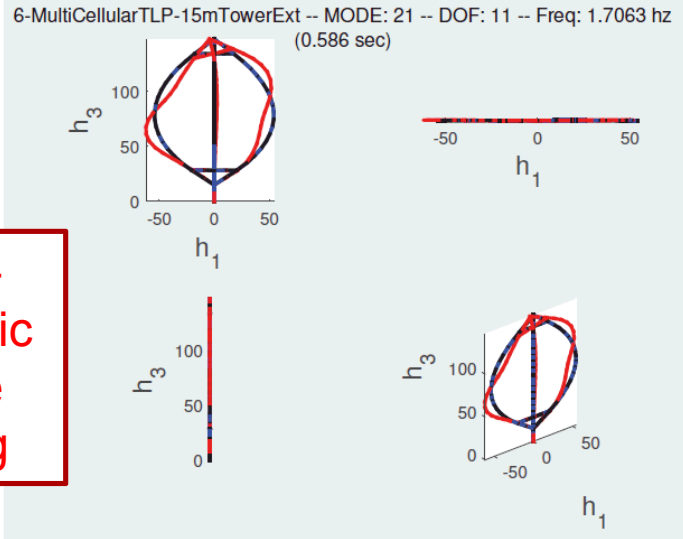
1st propeller



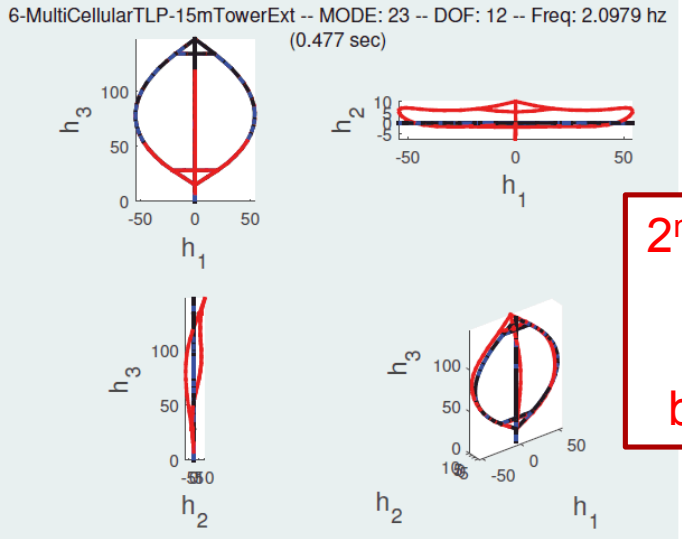
1st edgewise bending



1st anti-symmetric flatwise bending



2nd out-of-plane tower bending



Mode Shapes – Multi-Cellular TLP

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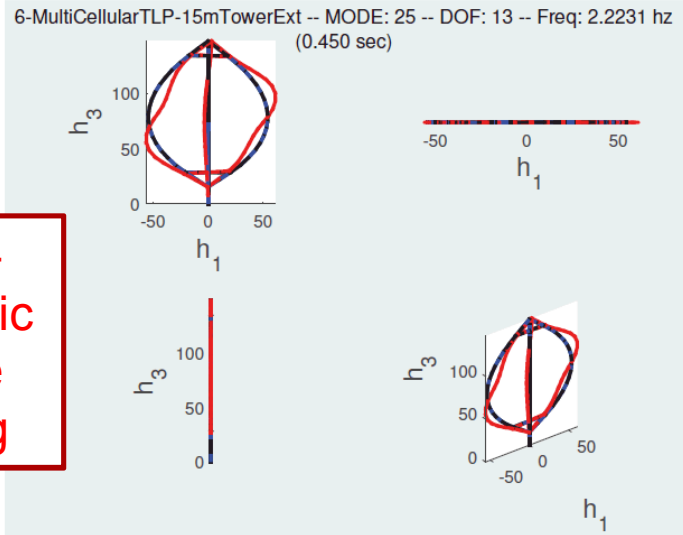
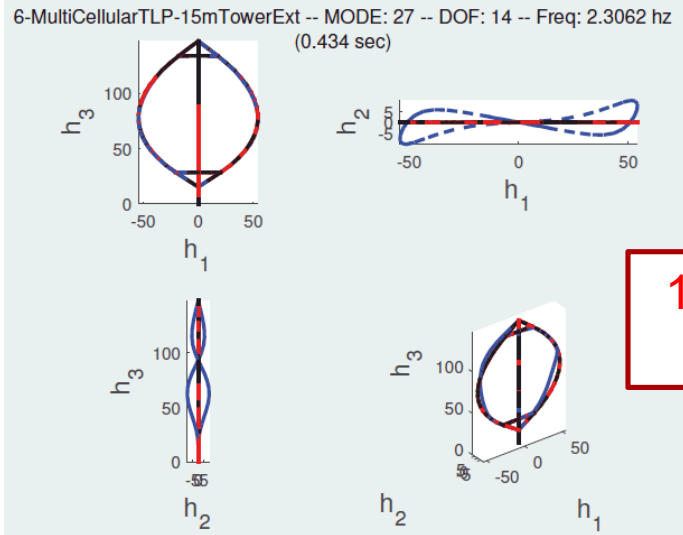
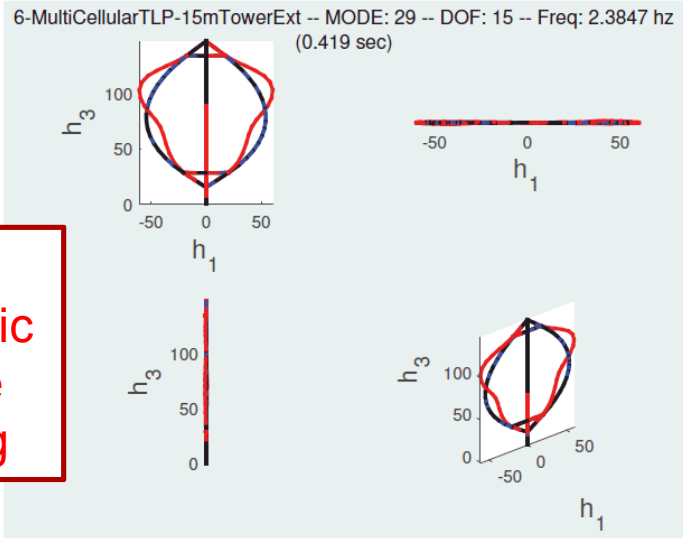
1st anti-symmetric flatwise bending



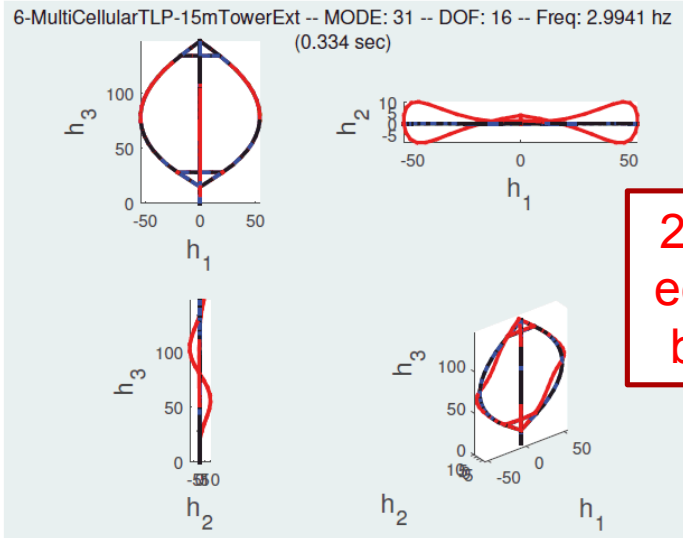
1st tower torsion



1st symmetric flatwise bending



2nd blade edgewise bending



Mode Shapes – Multi-Cellular TLP

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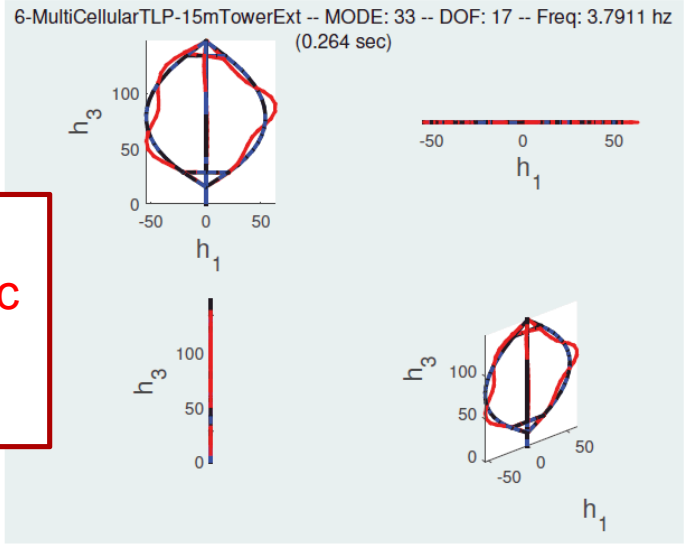
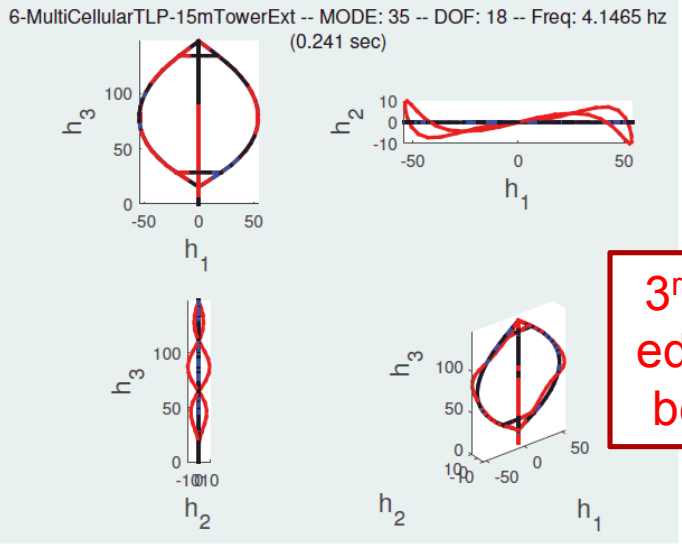
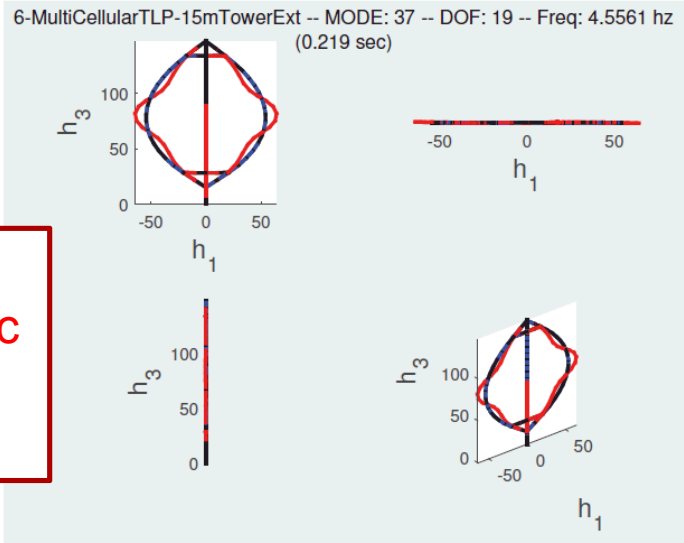
2nd anti-symmetric flatwise bending



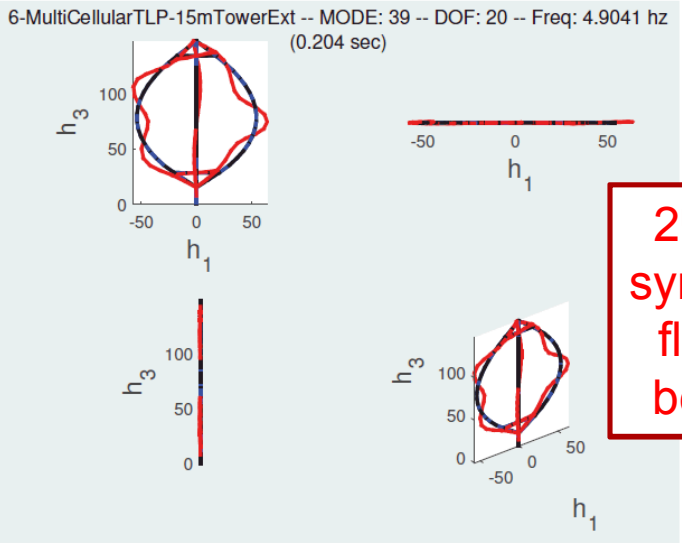
3rd blade edgewise bending



2nd symmetric flatwise bending



2nd anti-symmetric flatwise bending



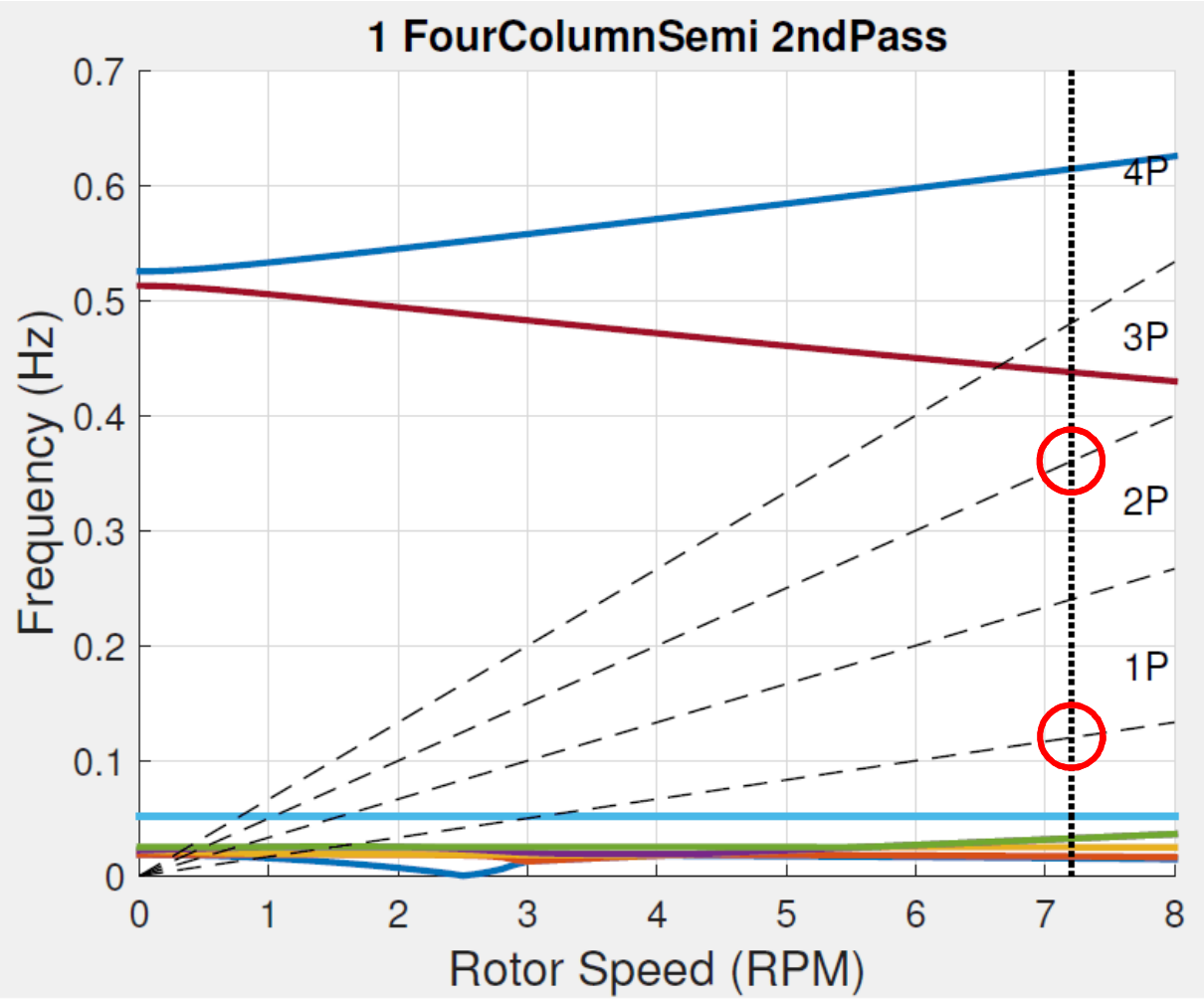
Campbell Diagram

- Comparison of the system natural frequencies (with centrifugal stiffening) for three platforms
- Frequencies are shown in a **rotating reference frame**
- Significant forcing's for a 2-bladed VAWT:
  - 1p is the most important forcing
  - 3p forcing should also be compared to the resonance conditions but is considered to contain significantly less energy

Table 1. Numerical validation of per-rev tower forcing

# of Blades	Fixed-frame (analytical)	Fixed-frame (CACTUS)	Hub-frame (analytical)	Hub-frame (CACTUS)
1	0,1,2,3,4,5	0,1,2,3,4,5	1,2,3,4,5	1,2,3,4,5
2	0,2,4,6,8,10	0,2,4,6,8,10	1,3,5,7,9	1,3,5,7,9
3	0,3,6,9,12,15	0,3,6,9,12,15	1,2,4,5,7	1,2,4,5,7
4	0,4,8,12,16,20	0,4,8,12,16,20	1,3,5,7,9	1,3,5,7,9
5	0,5,10,15,20,25	0,5,10,15	1,4,6,9,11	1,4,6,9,11
6	0,6,12,18,24,30	0,6,12	1,5,7,11,13	1,5,7,11,13
7	0,7,14,21,28,35	0,7,14	1,6,8,13,15	1,6,8,13,15

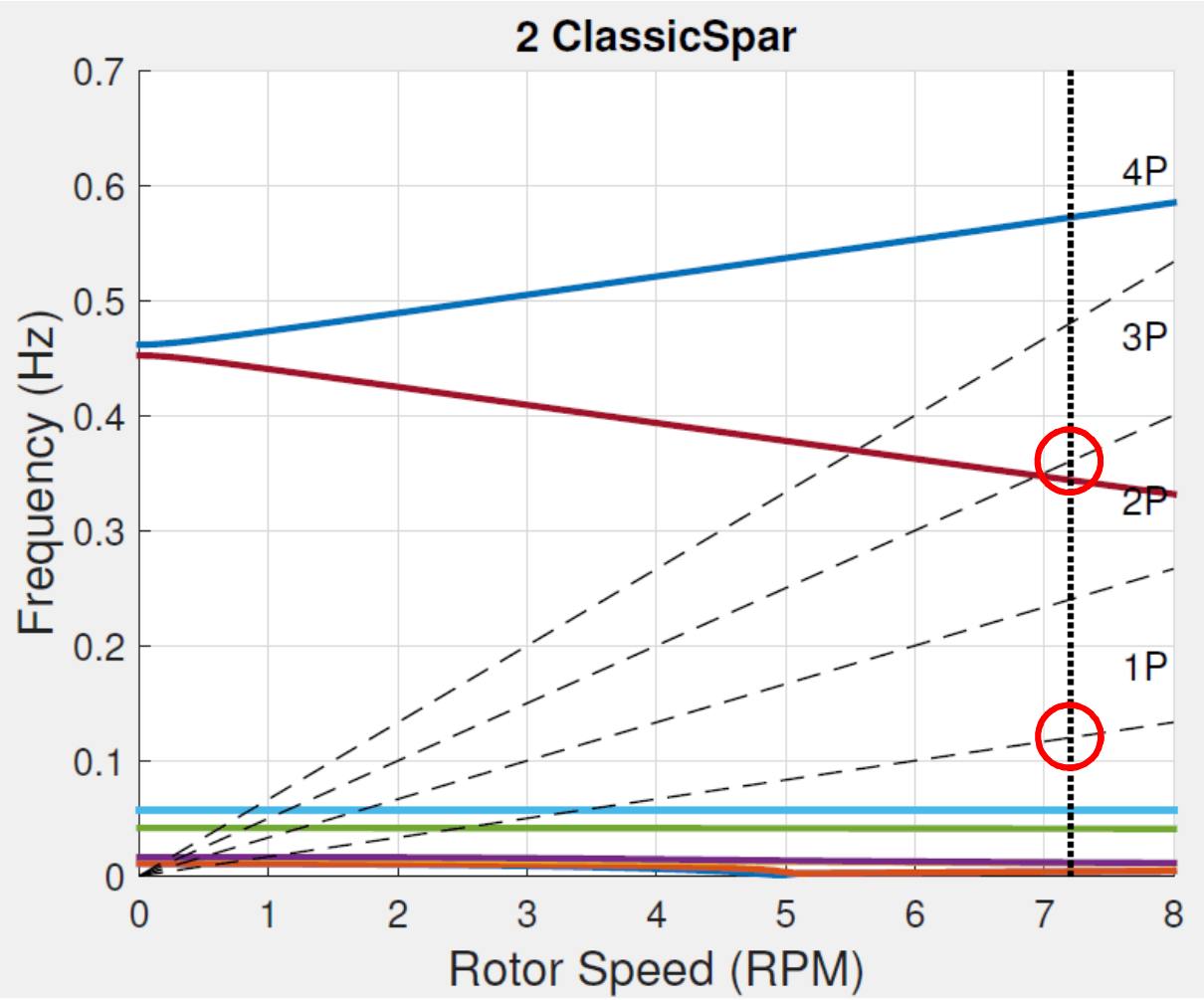
Campbell Diagram – 4-Column Semi



3p resonance is crossed at around 8.5 rpm which is far enough from the rated speed

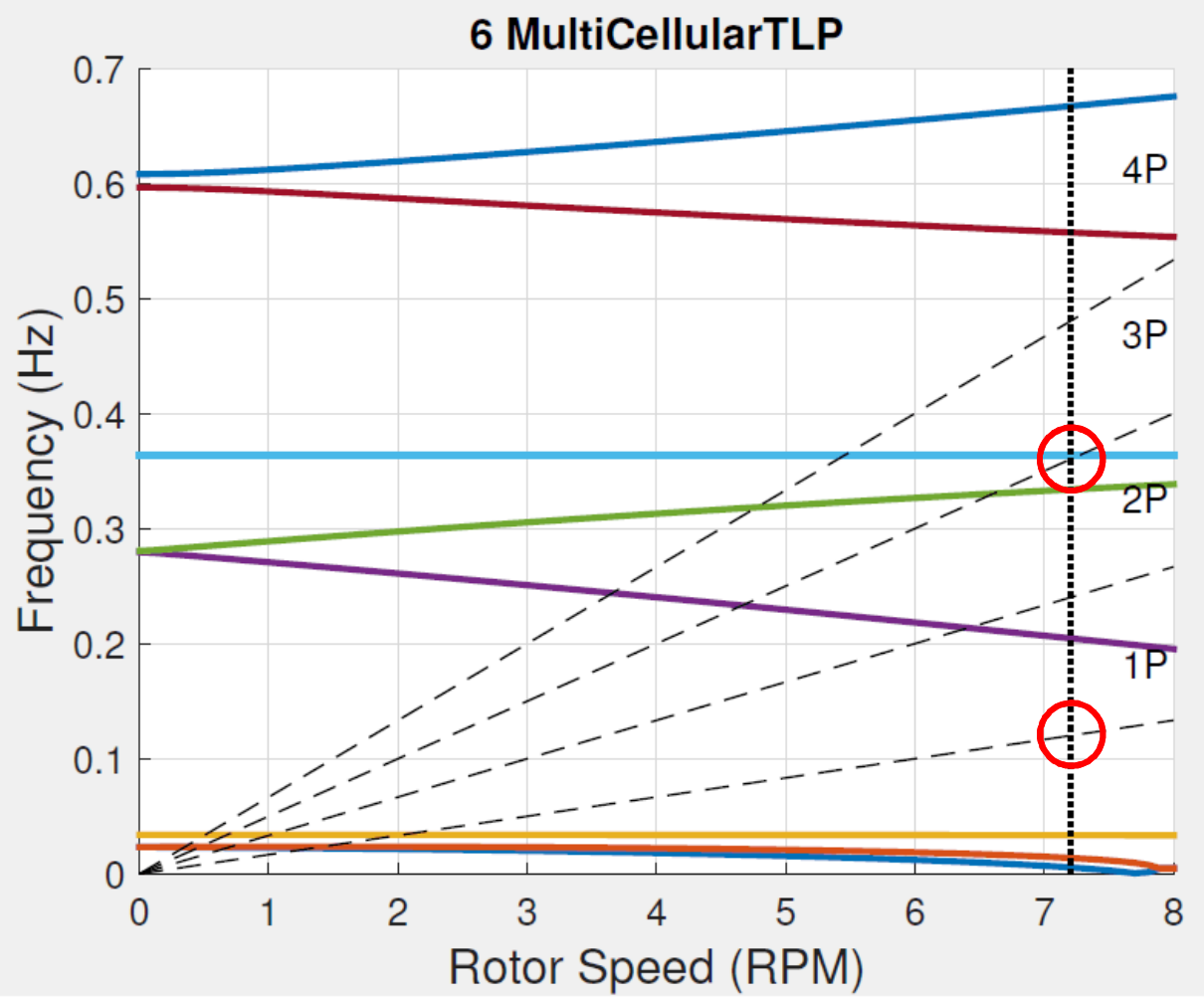
Operates without resonance crossing for the 1p forcing from 3 rpm to beyond rated

Campbell Diagram – Classic Spar



Classic Spar platform has a lower tower bending resonance frequency, which crosses the 3p forcing at 7 rpm (only 3% from rated speed)

Campbell Diagram – M.C. TLP



Roll, pitch and heave resonance modes all cross the 3p forcing.

Heave sits at the 3p forcing at rated.

1p forcing is not exciting resonance after 2 rpm

Static Deflection Analysis

- Comparison of the static deflections was performed to verify the implementation of the mass and stiffness properties in OWENS.
- Determined an inconsistency between the coordinate system intended by Sandia and used by SES
  - 10m tower extension, 5m above the mean water level is intended

Combined System Static Motions - Analytic (15m Tower Extension)						
	FourColumnSemi_2ndPass	ClassicSpar	RingPontoon	CompactSemi	AdvancedSpar	MultiCellularTLP
Surge [m]	7.85	7.74	7.85	6.55	7.56	6.43
Pitch [deg]	21.15	7.15	21.24	24.24	9.27	0.36
Yaw [deg]	6.78	8.90	6.78	4.41	5.27	6.52

Combined System Static Motions - Analytic (10m Tower Extension)						
	FourColumnSemi_2ndPass	ClassicSpar	RingPontoon	CompactSemi	AdvancedSpar	MultiCellularTLP
Surge [m]	7.85	7.74	7.85	6.55	7.56	6.43
Pitch [deg]	19.84	6.71	19.93	22.75	8.70	0.34
Yaw [deg]	6.78	8.90	6.78	4.41	5.27	6.52

Combined System Static Motions - SES						
Pitch [deg]	19.8	6.7	19.9	22.8	8.7	0.3
Yaw [deg]	6.8	8.9	6.8	4.4	5.3	6.5

Static Deflection Analysis

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- Static deflection comparison to displacement limits

Combined System Static Motions - Analytic (15m Tower Extension)						
	FourColumnSemi_2ndPass	ClassicSpar	RingPontoon	CompactSemi	AdvancedSpar	MultiCellularTLP
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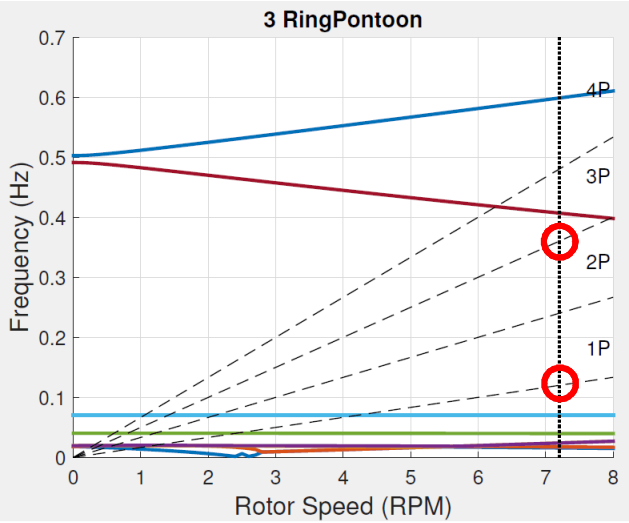
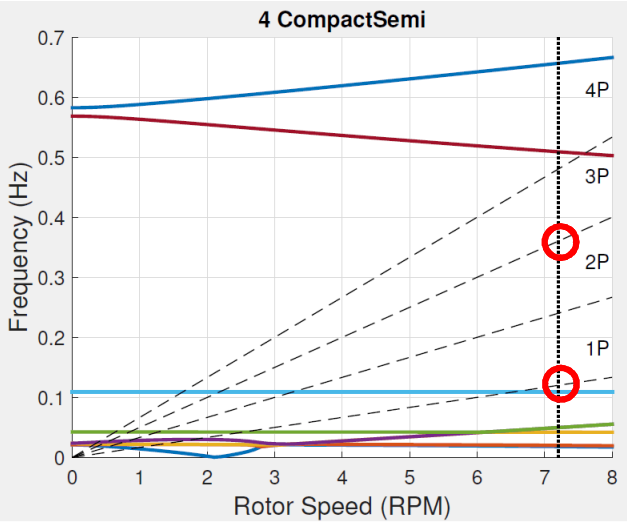
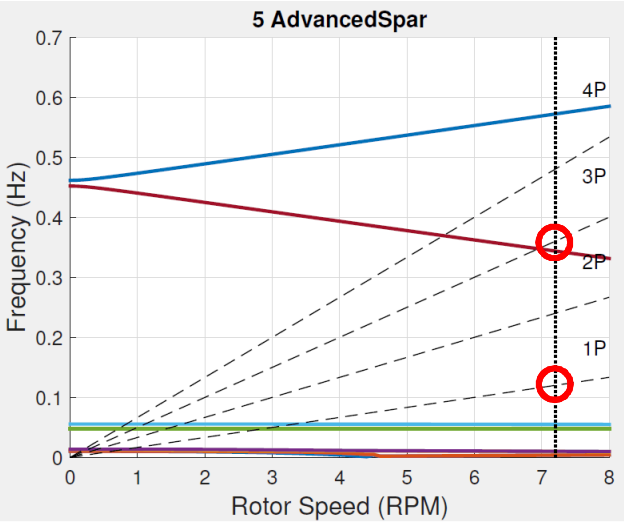
BACKUP SLIDES

Campbell Diagram - additional







Dynamic Analysis

- Transient
- 1-case (2-blade), FFT of each of the 6 load cases