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Modal Dynamics and Stability of Large Multi-megawatt Deepwater Offshore Vertical-axis Wind Turbines:
Initial Support Structure and Rotor Design Impact Studies

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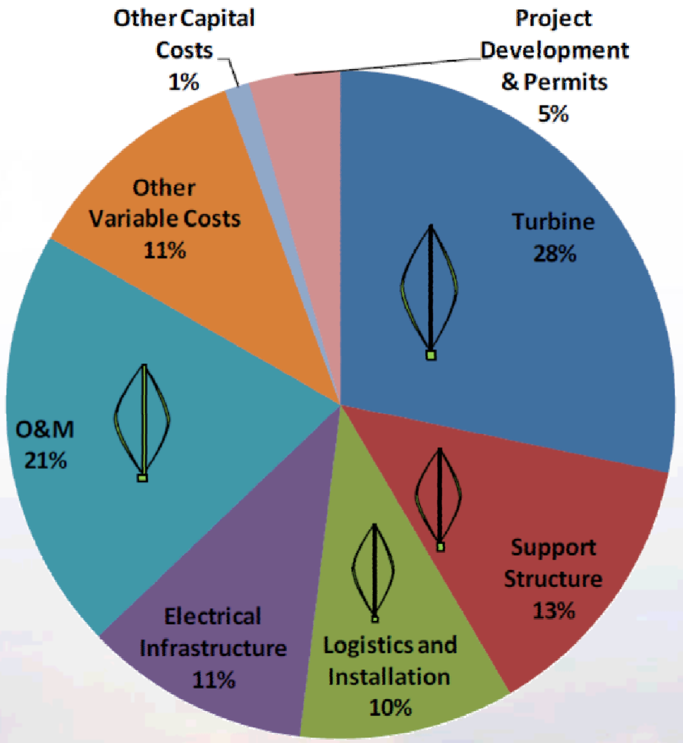
Outline

- **Motivation**
- **Offshore Wind Energy Simulation Toolkit**
- **Tower Resonance & Per-rev Excitations**
- **Impact Studies**
  - Support structure
  - Turbine size
  - Turbine configuration
- **Conclusions and Future Work**

Cost Breakdown: Offshore Wind Project

- Rotor cost 28% of lifetime project cost
- 20% reduction in COE for viability
- Other critical costs:
  - *Operations & Maintenance (O&M)*
  - *Logistics & Installation*
  - *Support Structure*
- VAWT may reduce these costs



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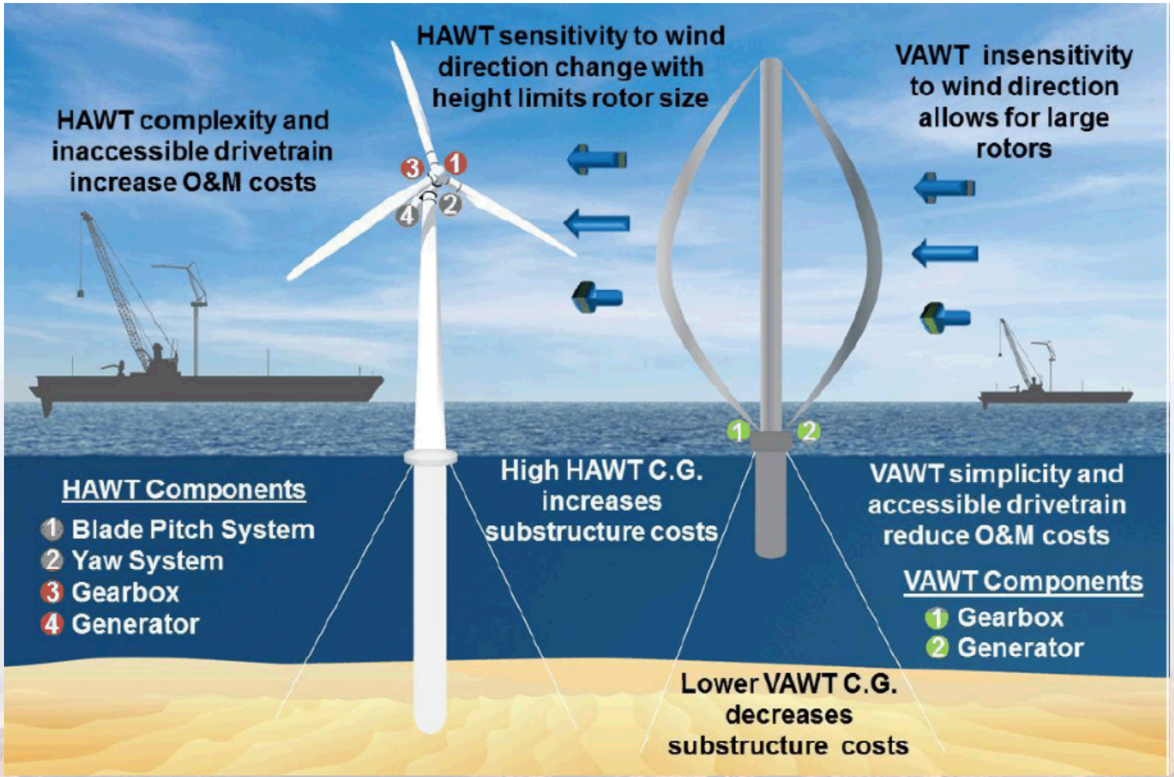
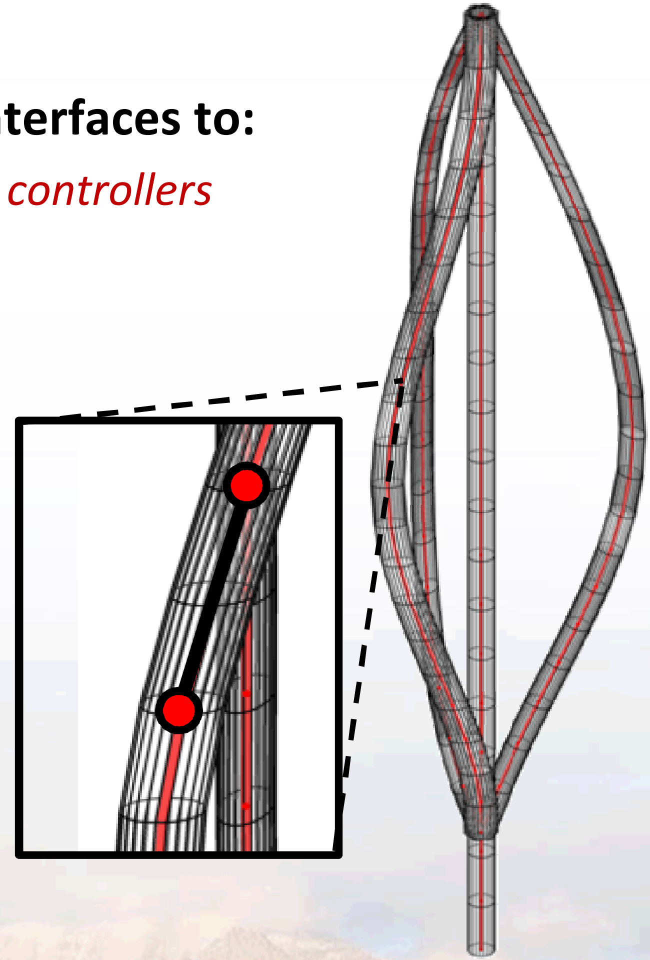
VAWT vs. HAWT for Offshore Wind

- **Offshore wind requires significant reduction in COE**
  - *Reduction in O&M costs*
  - *Increased energy capture*



Design Tool Features

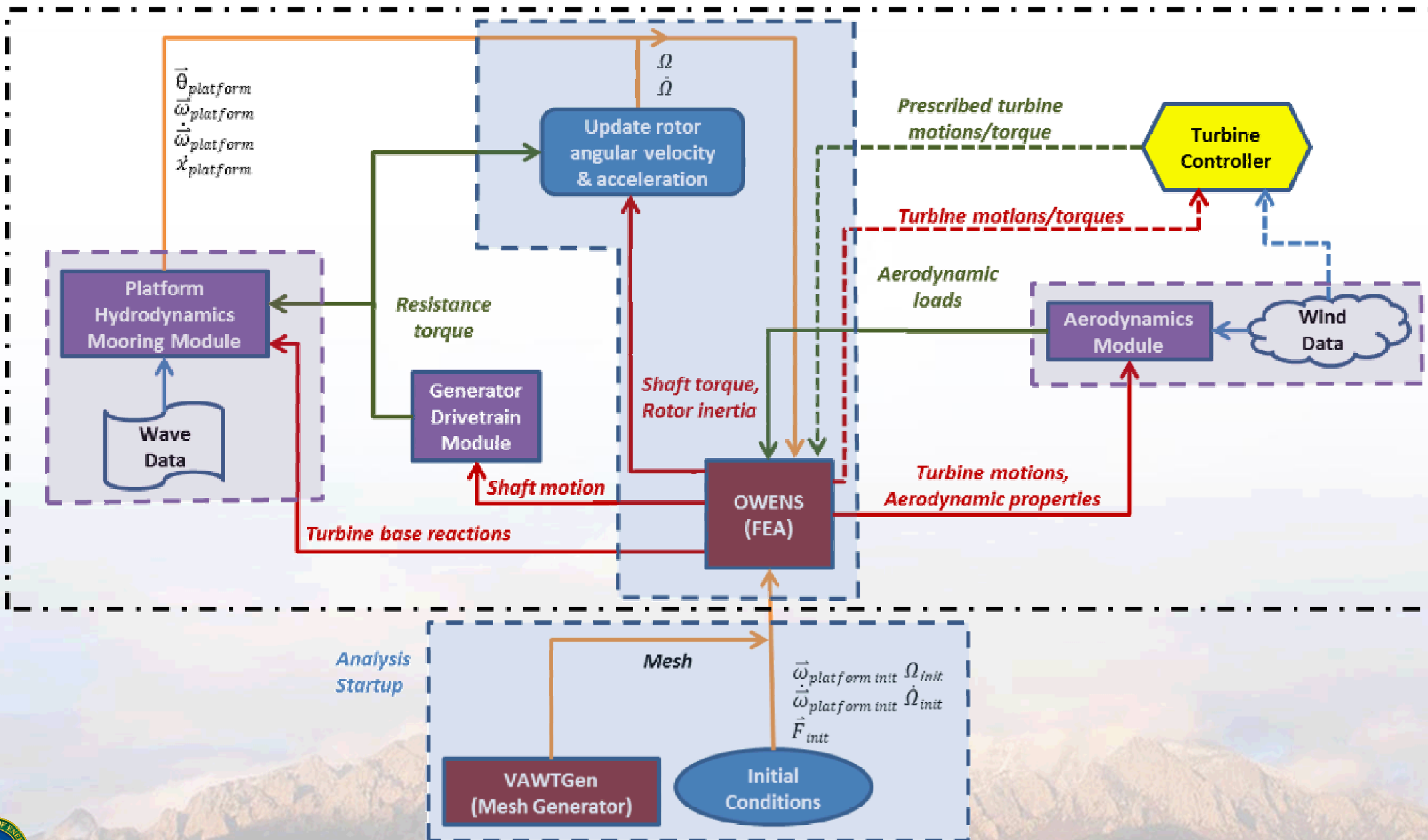
- **Enables modal and transient analysis capabilities.**
- **Modular analysis framework enables couplings/interfaces to:**
  - *Aerodynamics, Hydrodynamics, Drivetrain/generator, controllers*
- **Finite element method**
  - *Flexibility and robustness in implementation*
  - *3D Timoshenko beam*
  - *Rotational 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**



Analysis Framework:

Offshore Wind ENergy Simulation (OWENS) Toolkit

Coupled Aeroelastic / Hyrdrodynamic Analysis:



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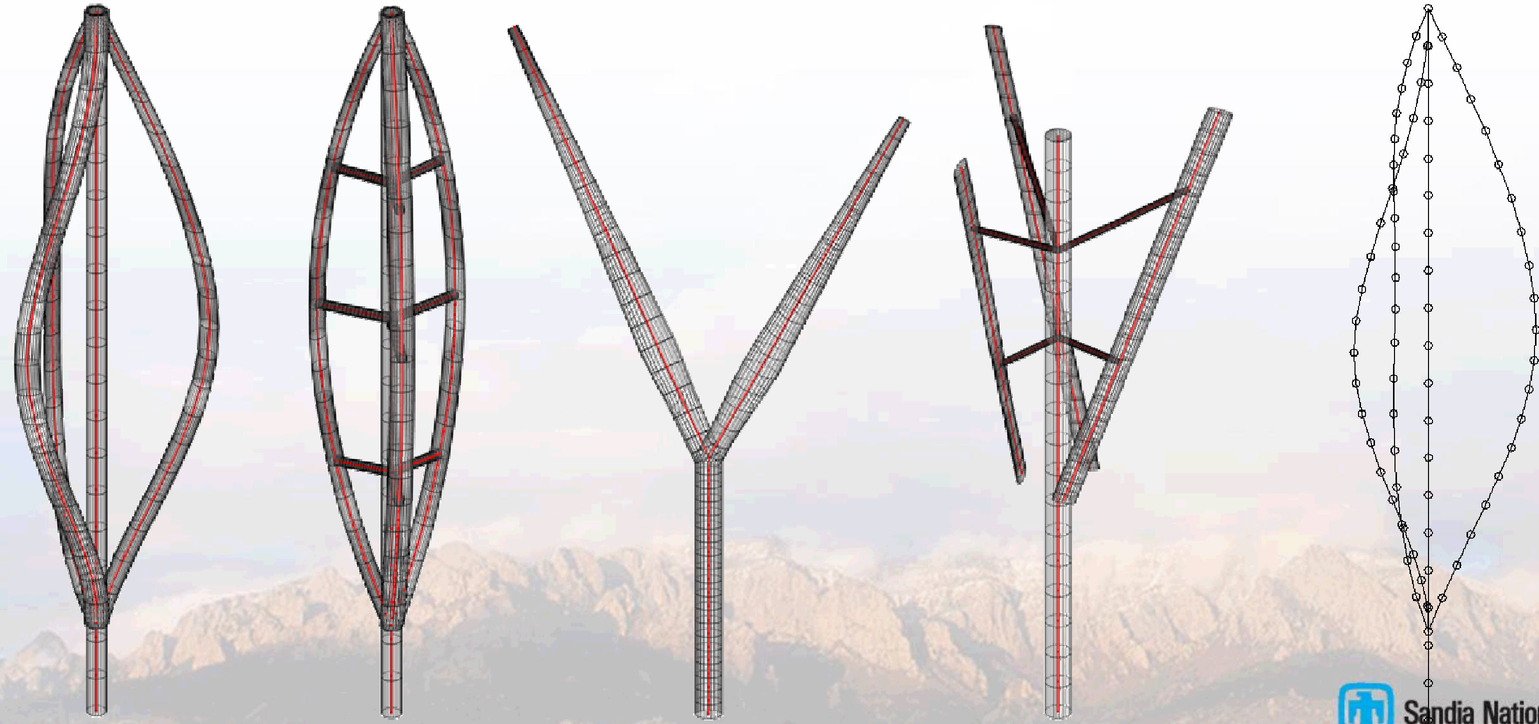
VAWTGen Mesh Generator

- Components specified in existing wind energy tool file formats
- Streamlines with existing blade design tools
- Components positioned and oriented arbitrarily about tower axis.
- Any number of blades and struts.
- Automatically locates and specifies joint constraints.



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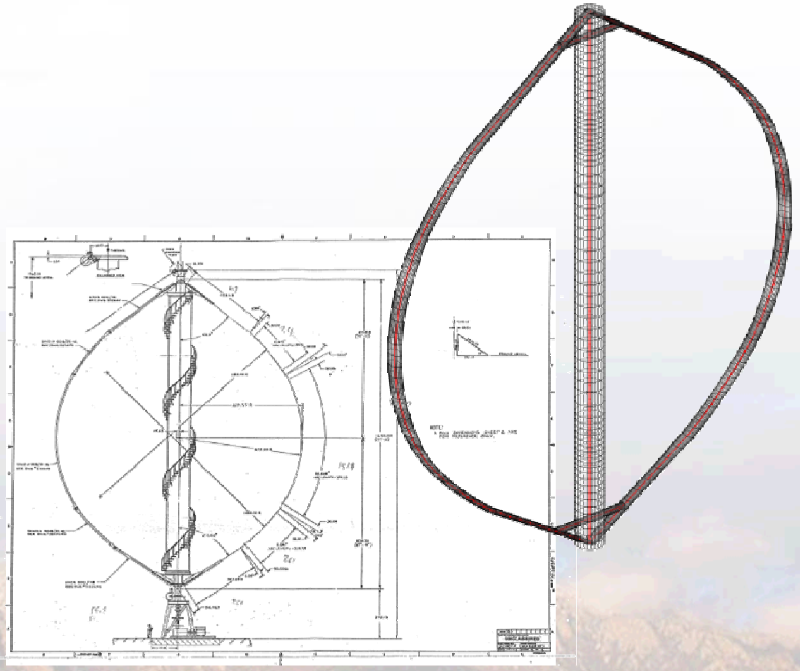
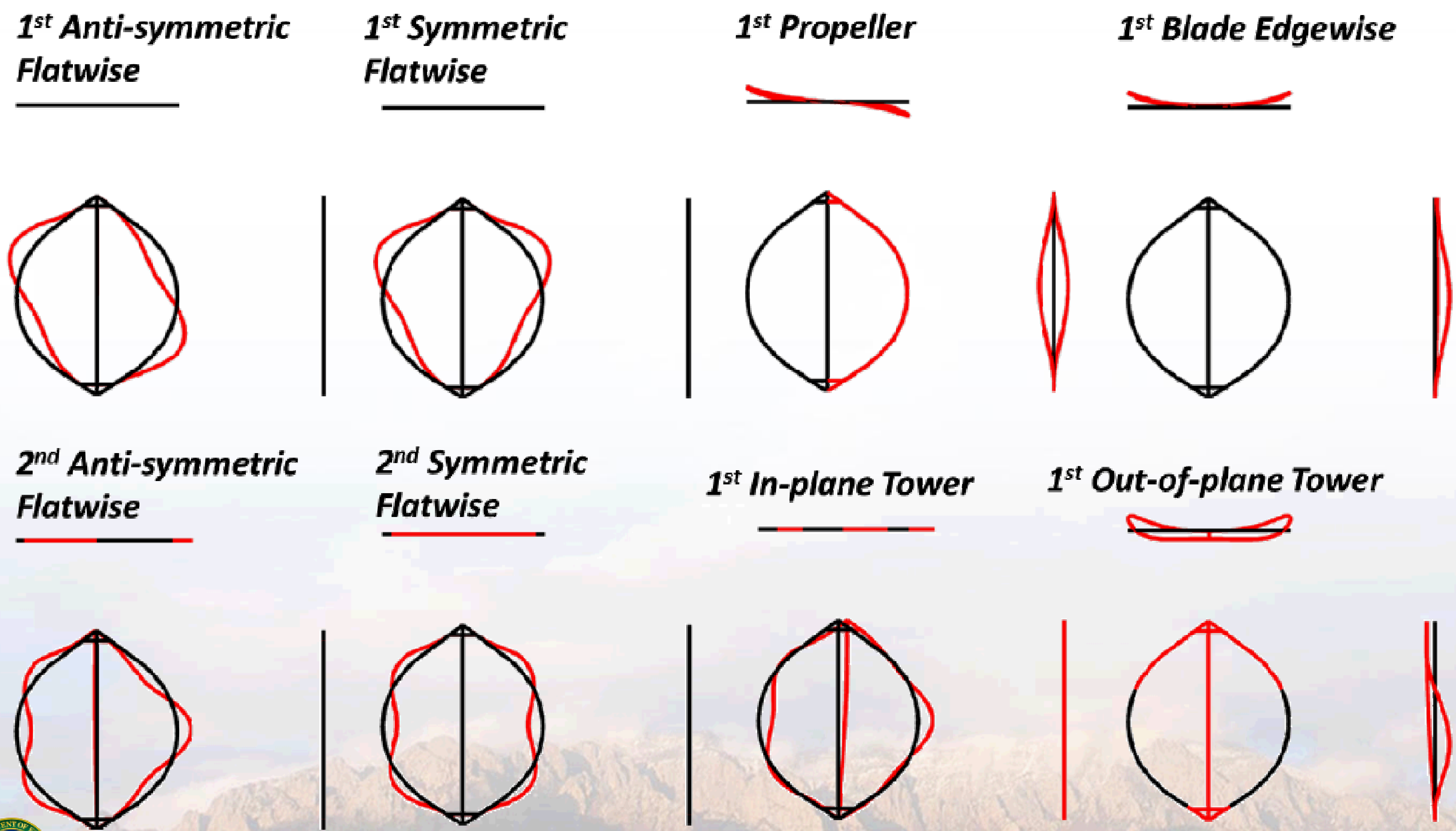
Verification & Validation

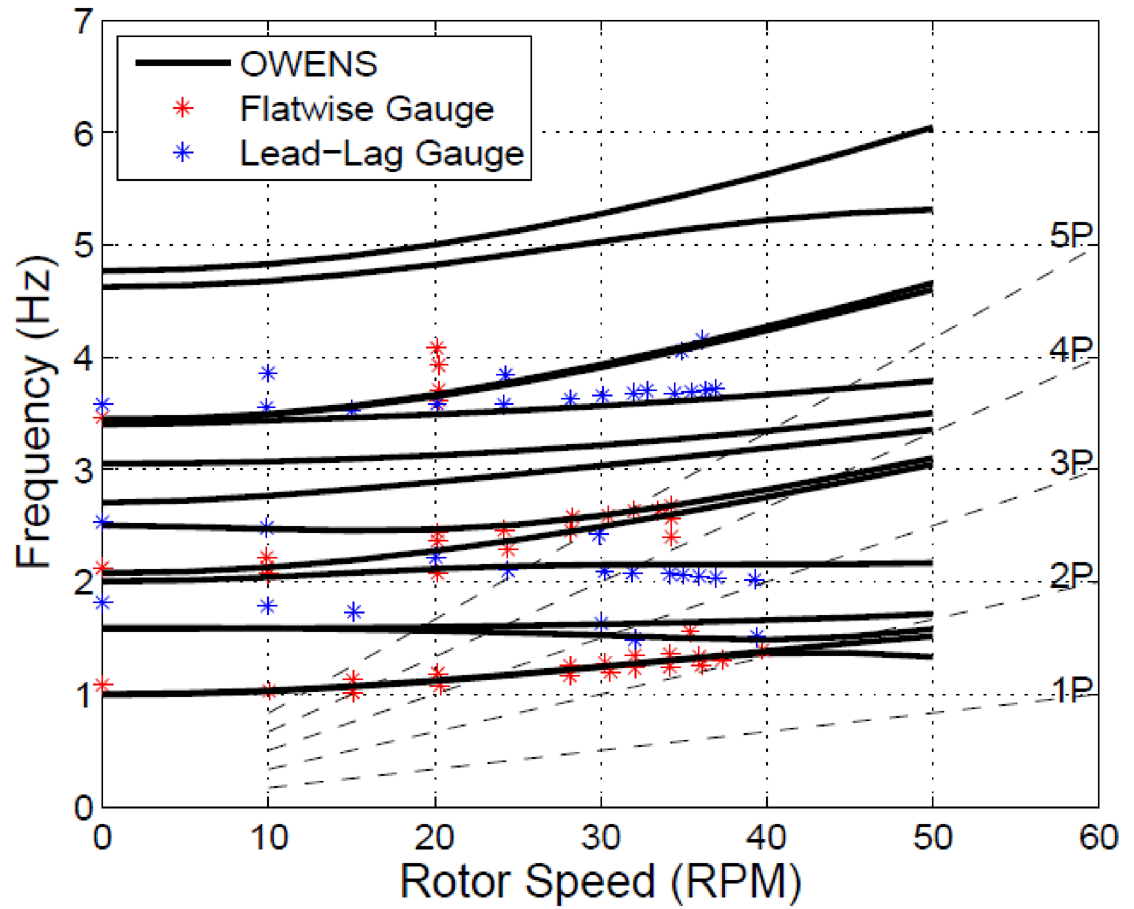
- **Analytical Verification**
  - Uncoupled vibrations
  - Rotational effects - “whirling shaft problem”
- **Numerical Verification**
  - Assumed modes method
  - ANSYS Code-to-code comparison
- **Validation**
  - Sandia 34-meter VAWT
  - Parked frequencies/mode shapes
  - Campbell diagram



34-meter Mode Shapes



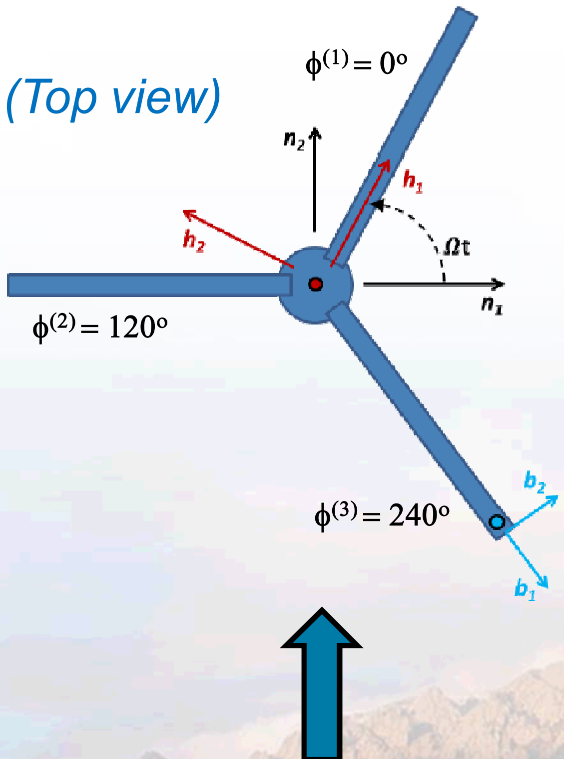
Rotating Sandia 34-m VAWT: Campbell Diagram



Tower Resonance in VAWTs

- Historically an issue for VAWT designs
- Previous work employed experimentally observed trends

(Top view)



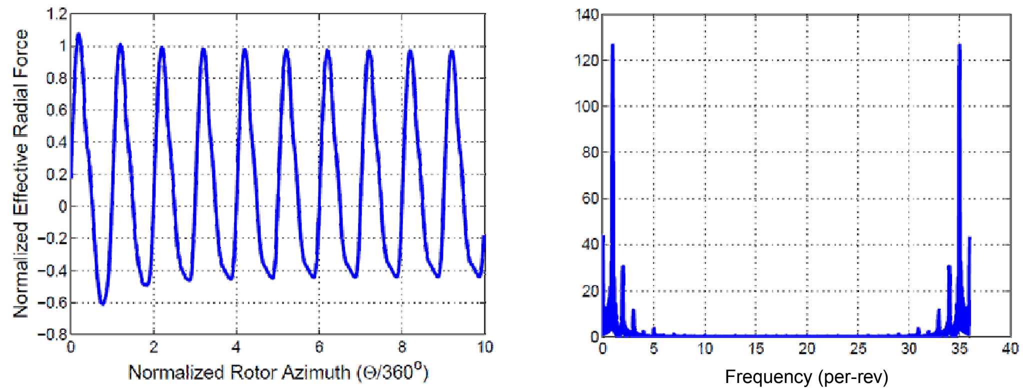
Inflow

Effective harmonic forcing on blade "m":

$$F^{(m)} = \sum_n F_n \cos n\theta \, \hat{b}_1$$

$$\theta = \Omega t + \bar{\phi}^{(m)}$$

CACTUS Load Output:



Tower Resonance in VAWTs (2)

- Sum over blades for effective tower forcing
  - Inertial frame vs. rotating frame

Hub frame:

$$\left[C_H^B\left(\bar{\phi}^{(m)}\right)\right] = \begin{bmatrix} \cos\bar{\phi}^{(m)} & \sin\bar{\phi}^{(m)} & 0 \\ -\sin\bar{\phi}^{(m)} & \cos\bar{\phi}^{(m)} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$F_{Hi}^{(m)}\left(\tilde{t}\right) = C_H^{B^T} F_i^{(m)}\left(\tilde{t}\right)$$

Inertial frame:

$$\left[C_N^B\left(2\pi\tilde{t} + \bar{\phi}^{(m)}\right)\right] = \begin{bmatrix} \cos\left(2\pi\tilde{t} + \bar{\phi}^{(m)}\right) & \sin\left(2\pi\tilde{t} + \bar{\phi}^{(m)}\right) & 0 \\ -\sin\left(2\pi\tilde{t} + \bar{\phi}^{(m)}\right) & \cos\left(2\pi\tilde{t} + \bar{\phi}^{(m)}\right) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$F_{Ni}^{(m)}\left(\tilde{t}\right) = C_N^{B^T}\left(\tilde{t}\right) F_i^{(m)}\left(\tilde{t}\right)$$

  - Frames have different frequency content
    - *Important realization for analysts and experimentalists*
- Employ Fourier transform, examine frequency content as a function of # of blades
- Analytical expression for tower forcing frequency content

Tower Resonance in VAWTs (3)

- Verification using CACTUS aerodynamics software
- Convenient look up tables for designers

Critical per-rev tower excitation look up table (rotating frame):

# of Blades	Per-Rev Sensitivity	Example Configuration
1	1,2,3,4	
2	1,3,5,7	**SNL 34-m, SNL 14-m, DTU Deep Wind**
3	2,4,5,7	**VAWT Power VP60**
4	3,5,7,9	
5	4,6,9,11	
6	5,7,11,13	**Lux**
7	6,8,13,15	
8	7,9,15,17	
9	8,10,17,19	
10	9,11,19,21	

Support Configurations

- **Land –based**
- **Monopile**
  - 20 and 30 meter
- **Floating platform**
  - Spar Buoy (U. of Maine)
  - ITI Energy Barge

Platform Physical and Hydrodynamic Mass Properties:

	Spar Buoy	ITI Barge	Ratio
Mass (kg)	5.47E+06	5.45E+06	1.0
CM (above SWL) (m)	-68.4	0.282	-242.5
Pitch MOI (kg-m^2)	2.32E+09	7.27E+08	3.2
Roll MOI (kg-m^2)	2.32E+09	7.27E+08	3.2
Yaw MOI (kg-m^2)	6.52E+07	1.45E+09	0.1
Added Mass in Surge (kg)	6.00E+06	7.49E+05	8.0
Added Mass in Sway (kg)	6.00E+06	7.49E+05	8.0
Added Mass in Heave (kg)	2.26E+05	1.86E+07	0.0
Added Pitch MOI (kg-m^2)	7.18E+09	1.26E+09	5.7
Added Roll MOI (kg-m^2)	7.18E+09	1.26E+09	5.7
Added Yaw MOI (kg-m^2)	0.00E+00	1.18E+08	0.0

Platform/Turbine Rigid Body Frequencies (Hz):

	Spar Buoy	ITI Barge
Sway	0.0084	0.0076
Surge	0.0084	0.0076
Heave	0.0330	0.1283
Pitch	0.0241	0.0980
Roll	0.0241	0.0980
Yaw	0.0270	0.0198

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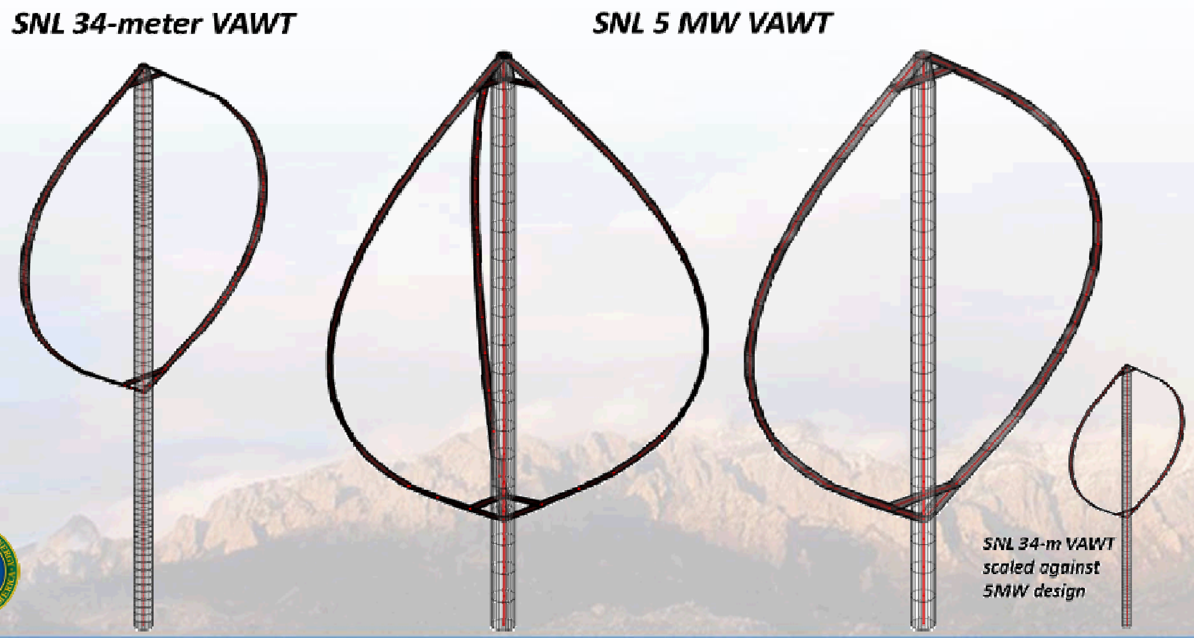
VAWT Configurations

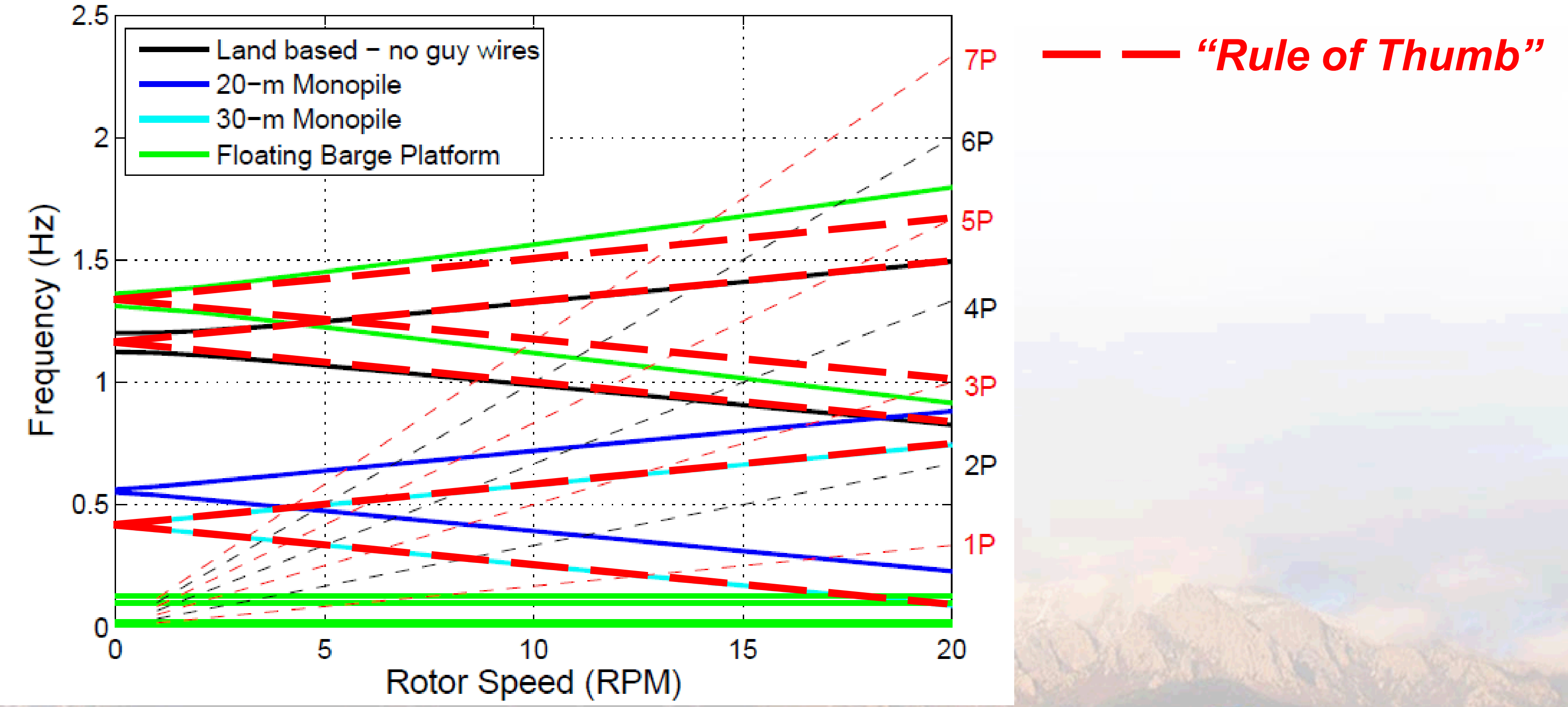
- Sandia 34-meter VAWT
- Sandia 5 MW VAWT
  - *2 and 3 blades*

	SNL 34-meter	SNL 3 blade 5MW	SNL 2 blade 5 MW
Rating	500 kW	5 MW	5 MW
Configuration	Darrieus	Darrieus	Darrieus
Height (m)	42.5	132.1	132.1
Height to Diameter	1.25	1.22	1.22
Mass (kg)	3.10E+04	6.50E+05	6.50E+05
Min Chord (m)	0.91	1.92	2.88
Max Chord (m)	1.22	2.57	3.86
Blade Material	6063-T5 Al	Fiberglass	Fiberglass



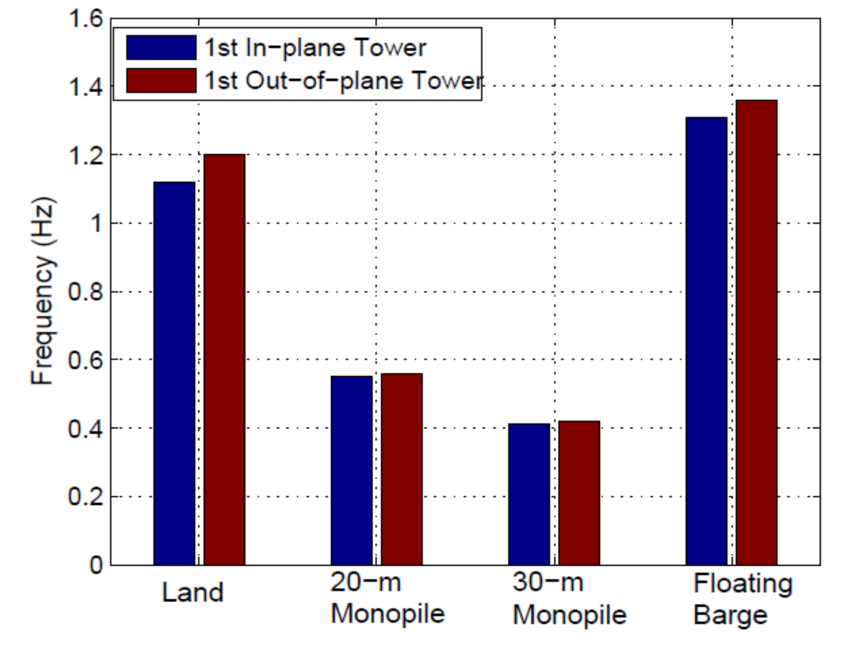
SNL 34-m VAWT Support Study

- Land-based, 20 & 30-m Monopile, Scaled barge platform
- Blade modes not significantly affected
- Notable difference in tower mode response

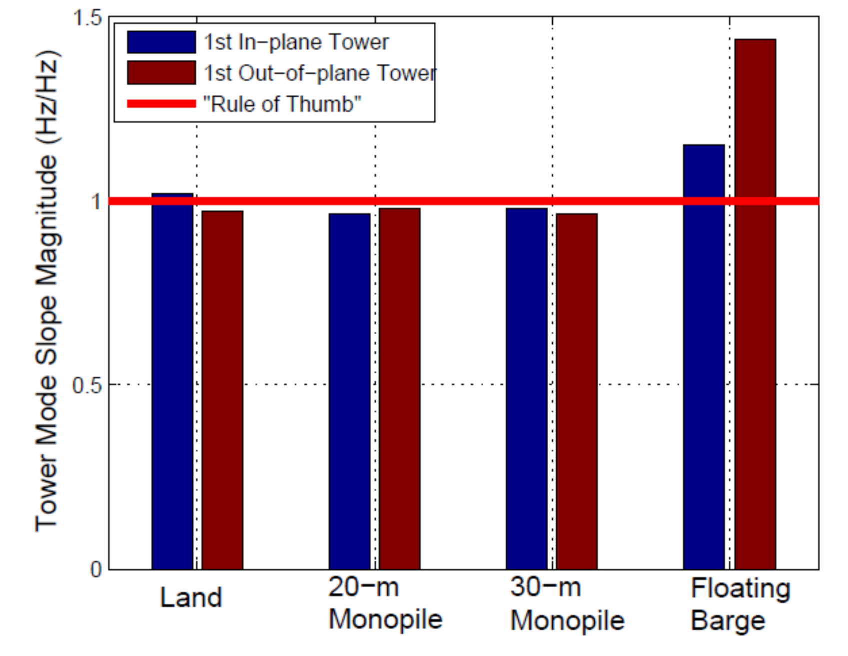


SNL 34-m VAWT Support Study (2)

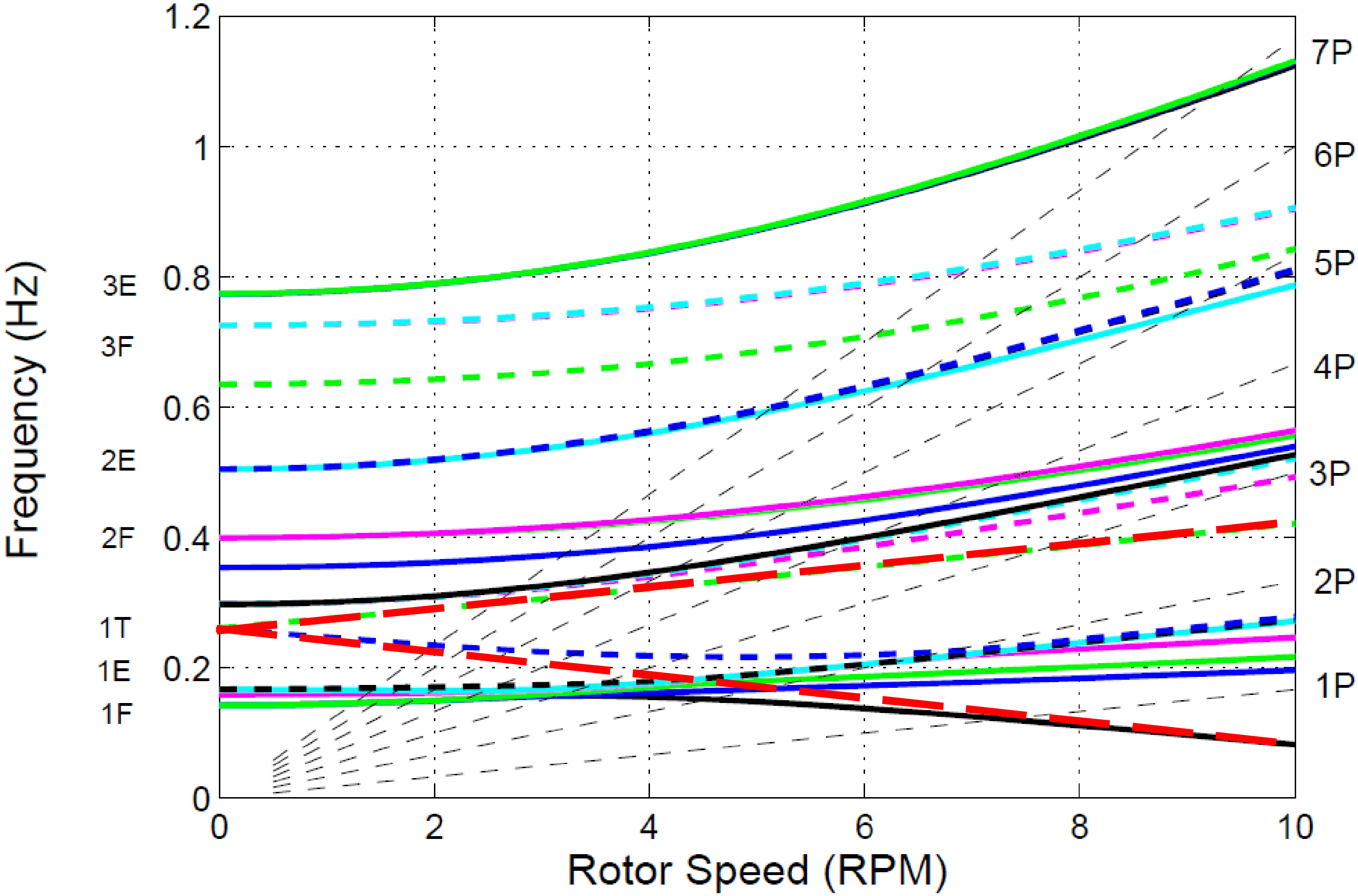
Summary of Parked Tower Frequencies:



Summary of Tower Mode Slopes:

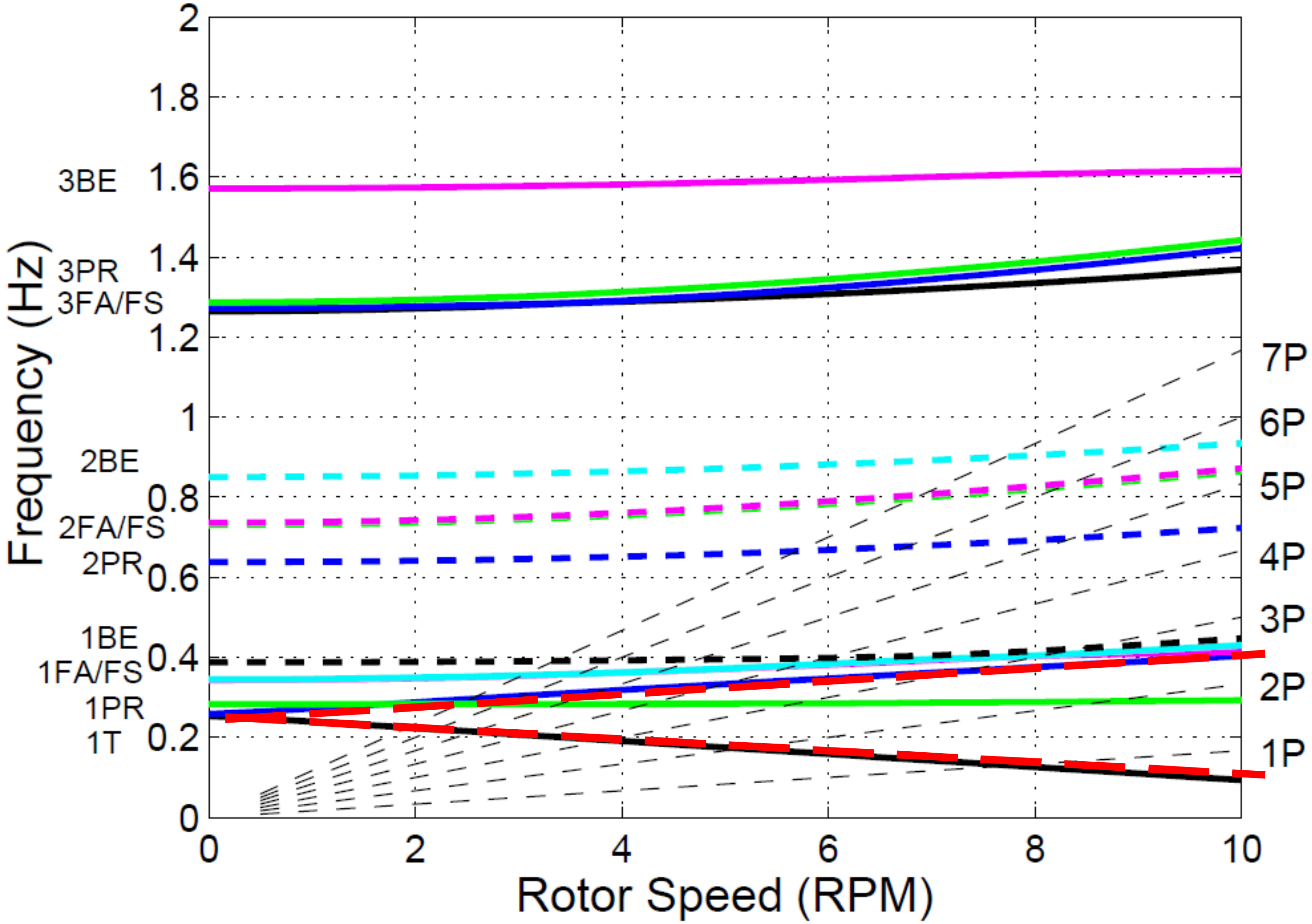


SNL 5 MW VAWT (3 bladed - land)



- Low frequency
- "Frequency veering"/ Mode localization
- Stress-stiffening effects in blade modes

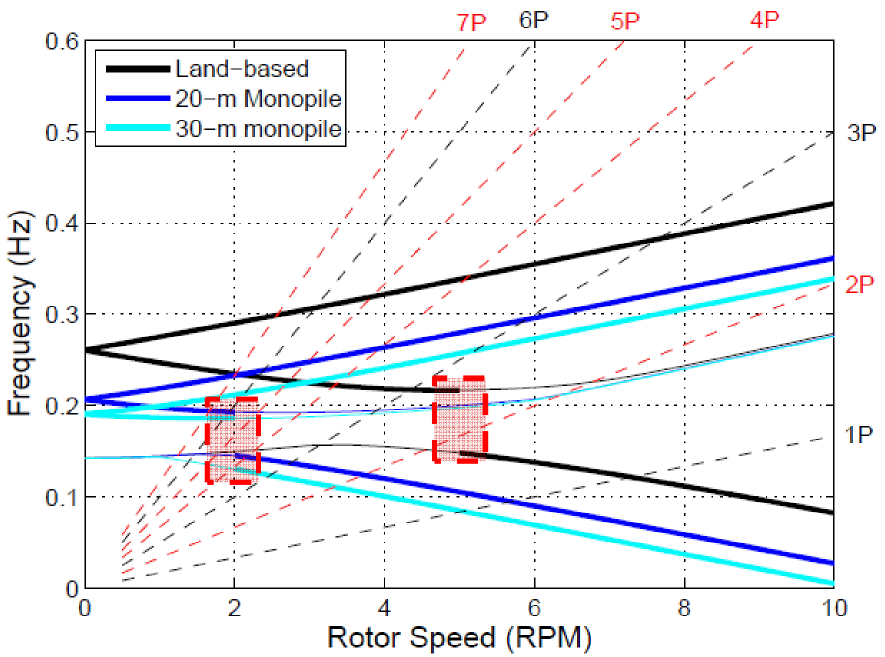
SNL 5 MW VAWT (2 bladed - land)



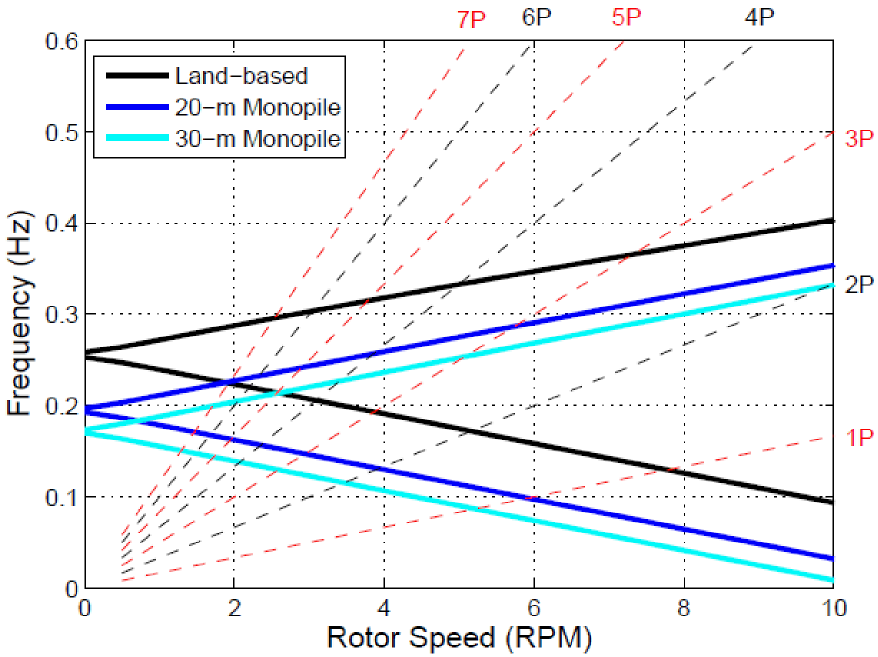
- Low frequency
- Stiffer blade modes (larger blades)
- No “frequency veering”

SNL 5 MW – Monopile Support

3-bladed:

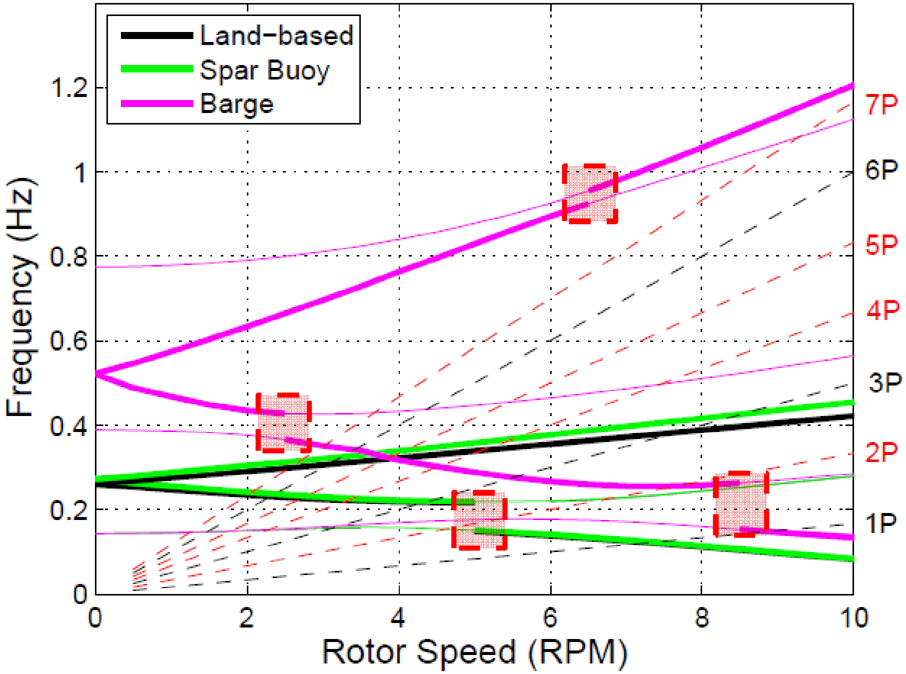


2-bladed:

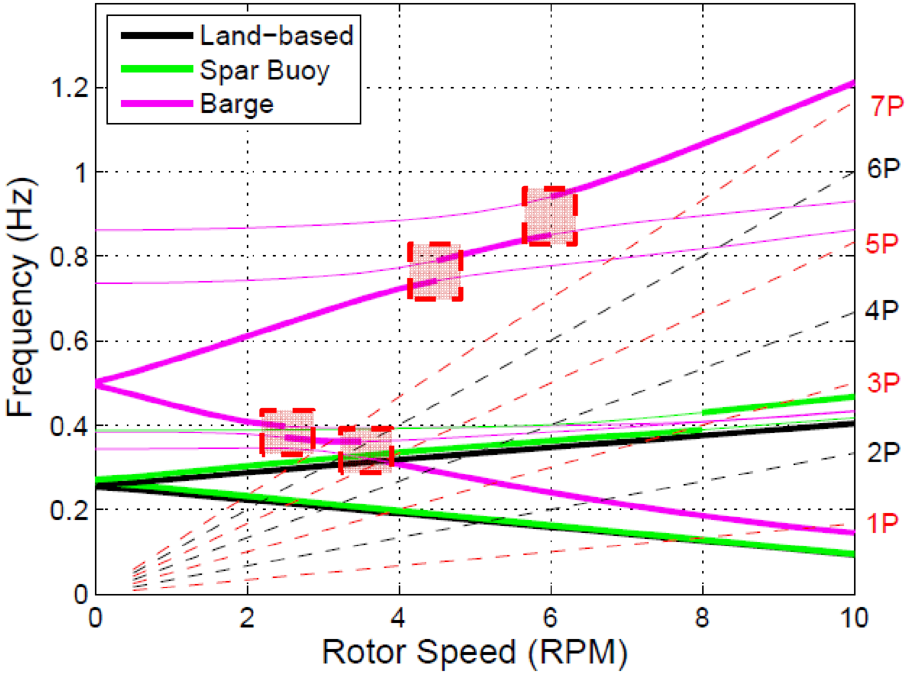


SNL 5 MW – Floating Support

3-bladed:



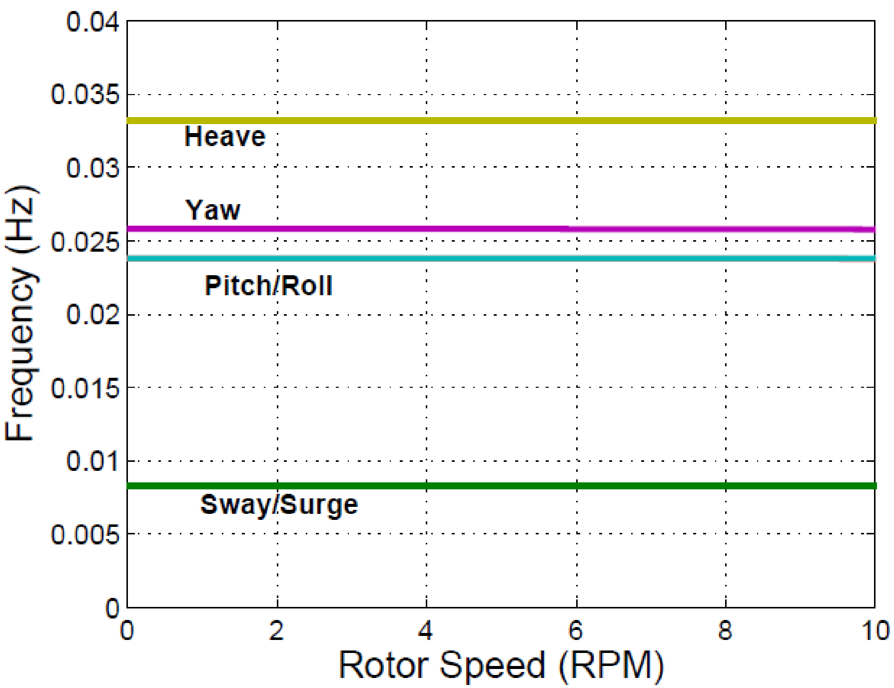
2-bladed:



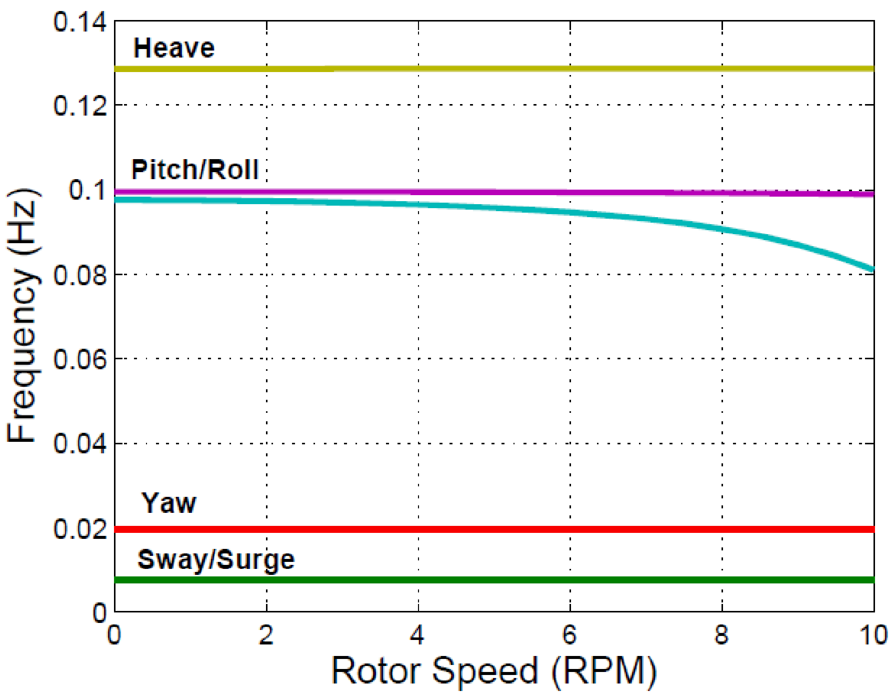
SNL 5 MW – Floating Support

Rigid Body Modes

3-bladed:

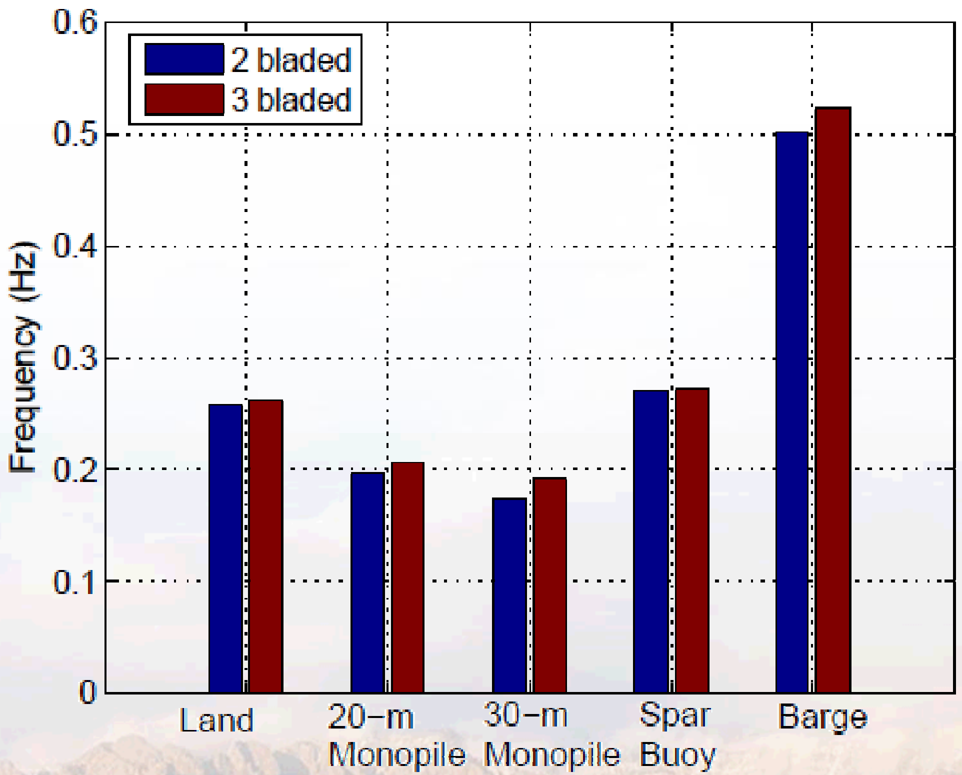


2-bladed:



SNL 5 MW Support Summary

- **Parked Tower Mode Frequencies**



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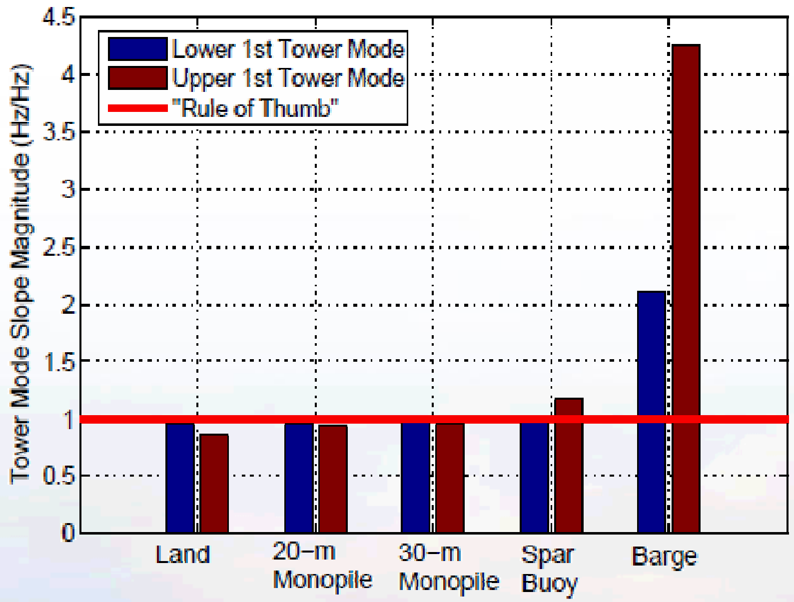
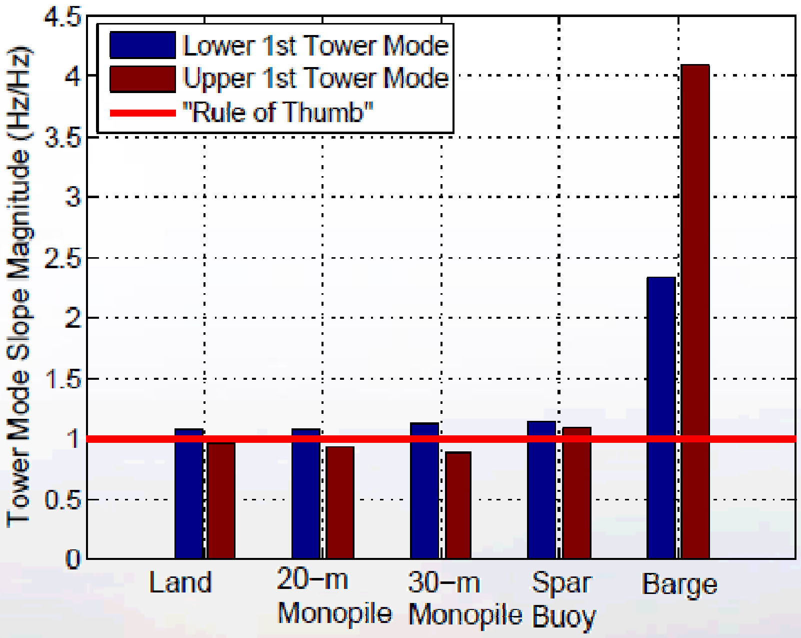
SNL 5 MW Support Summary (2)

- Tower Mode Frequency Slope

3-bladed:



2-bladed:



Conclusions

- Developed greater understanding of critical per-rev excitations for VAWT tower modes
- Low frequency modes of multi-MW VAWT designs and "frequency veering" require careful analysis and interpretation of results
- Monopile supports lower frequency of tower modes and reduce rotor speed at which resonance can occur
- Floating supports may alleviate resonance concerns, but rigid body modes should be examined

Conclusions (2)

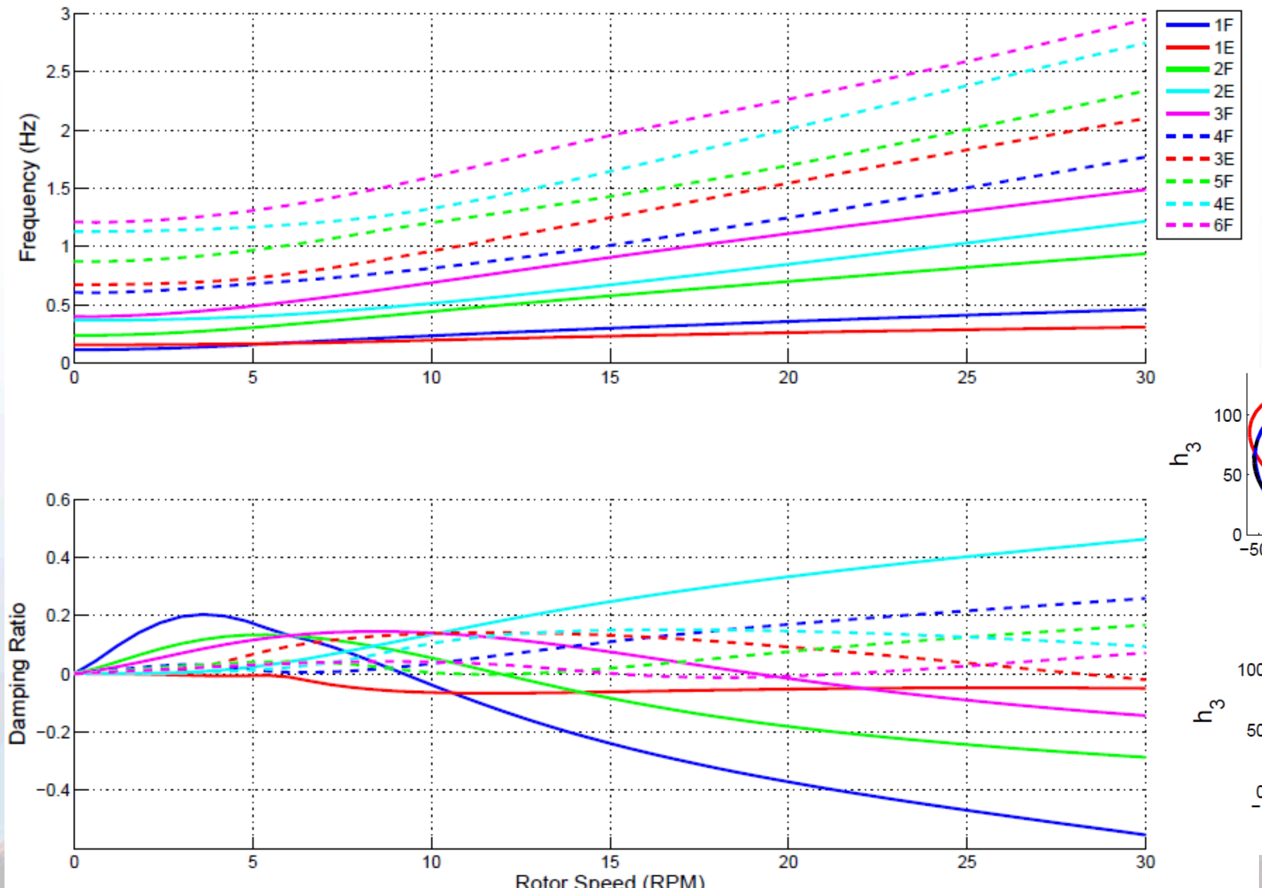
- Barge and spar platforms provide a range influence on structural modes and may mediate resonance concern in offshore VAWTs

- System level design studies and cost modeling needed to determine best rotor design, rotor operating speed, and platform designs.

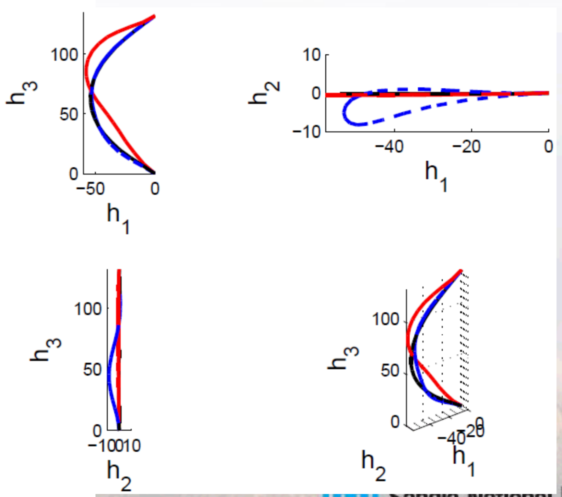
- Previous initial design “rules of thumb” do not appear to be well suited for floating VAWT configurations

Future Work

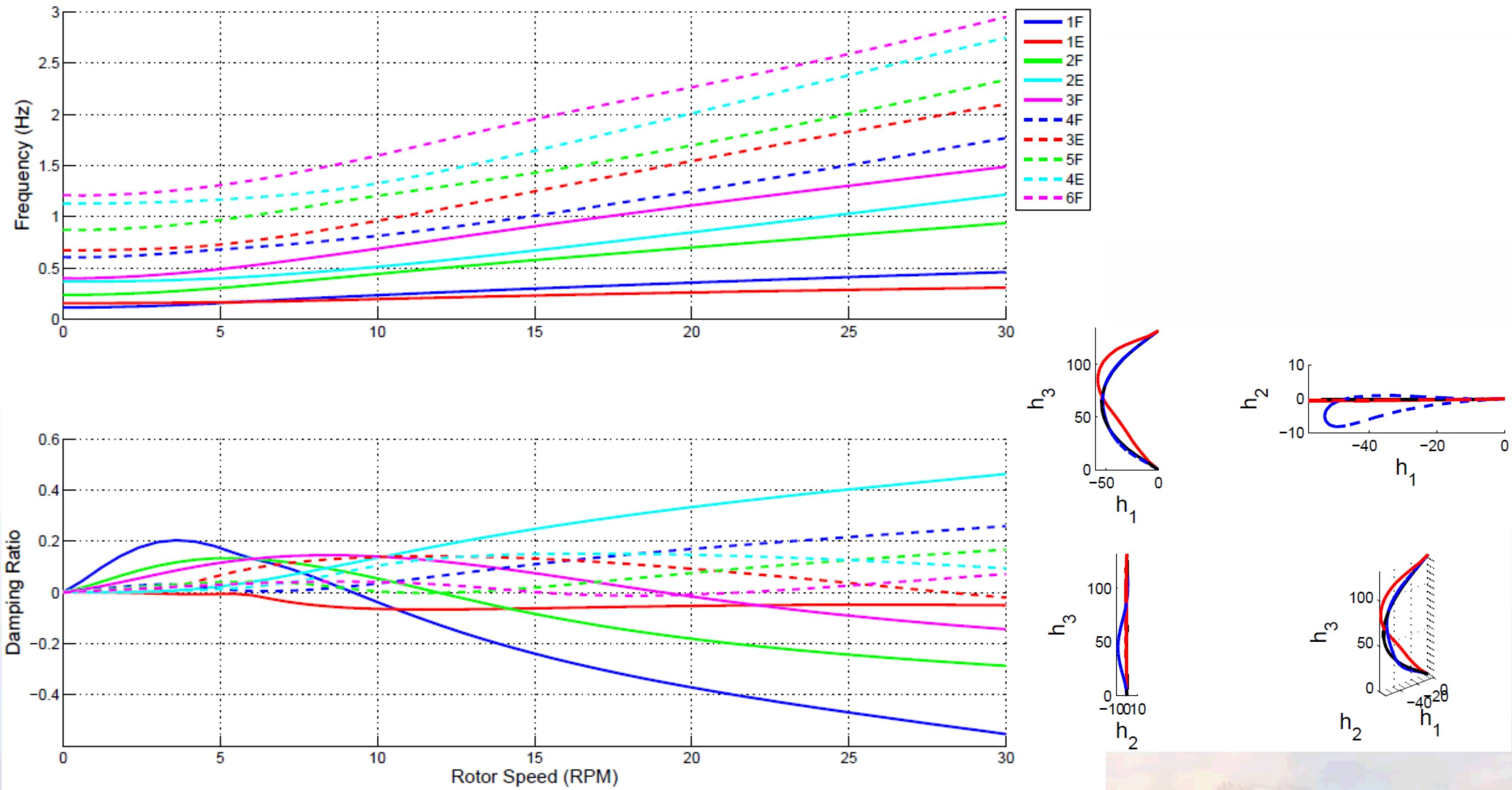
- Investigations to examine the severity of resonance concerns in multi-MW VAWT designs



in multi-



Initial Aeroelastic Stability Study



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