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The Development of Modal Testing Technology for Wind Turbines: A Historical Perspective

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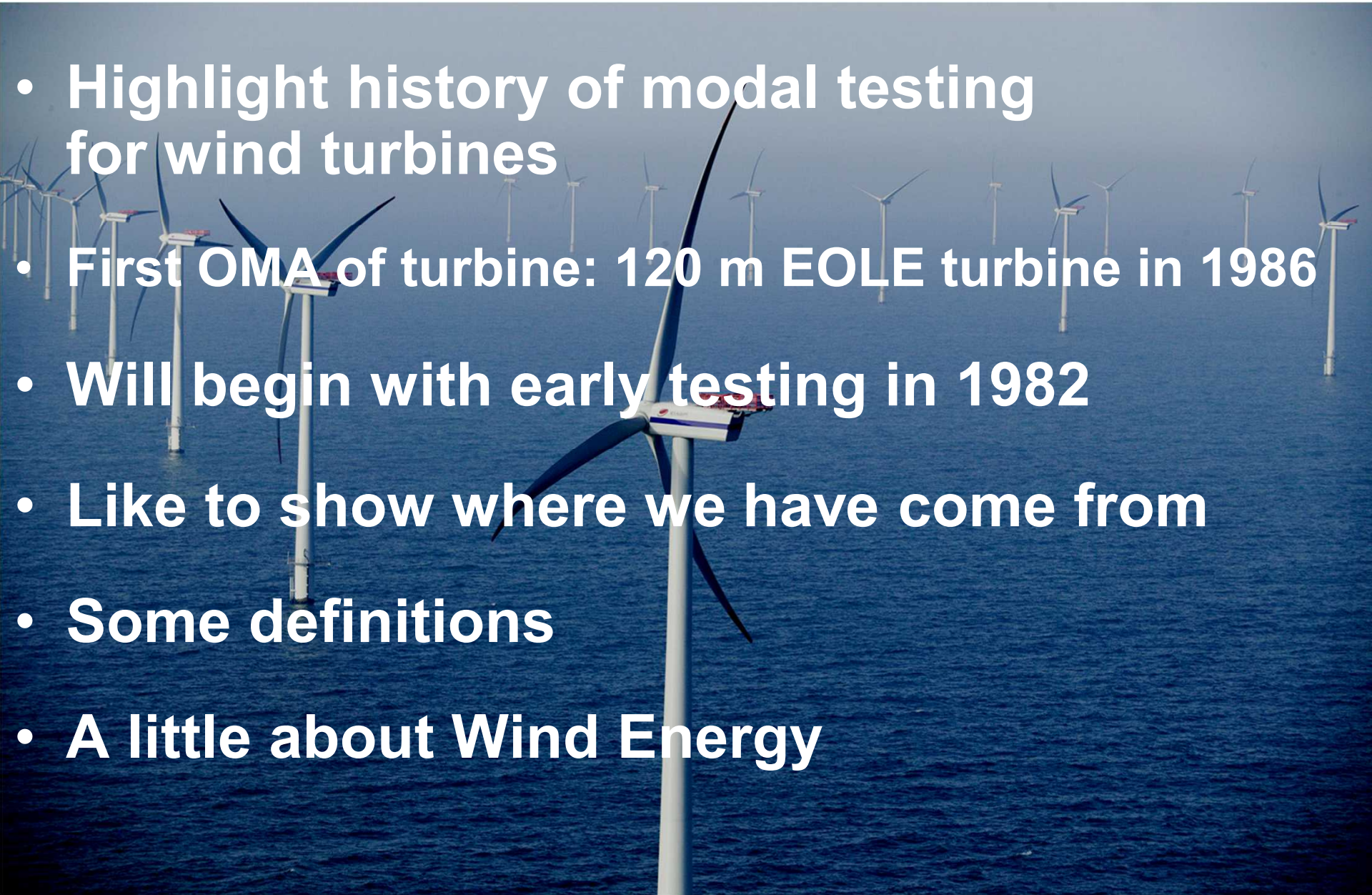
*Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

Introduction



- Highlight history of modal testing for wind turbines
- First OMA of turbine: 120 m EOLE turbine in 1986
- Will begin with early testing in 1982
- Like to show where we have come from
- Some definitions
- A little about Wind Energy

Wind Power Basics

$$WindPower = \frac{1}{2}\rho A C_P V_\infty^3$$

Wind Power output is proportional to wind speed cubed.

$$C_{P\max} \cong 0.3 \text{ (Drag)}$$

$$C_{P\max} \cong 0.59 \text{ (Lift)}$$

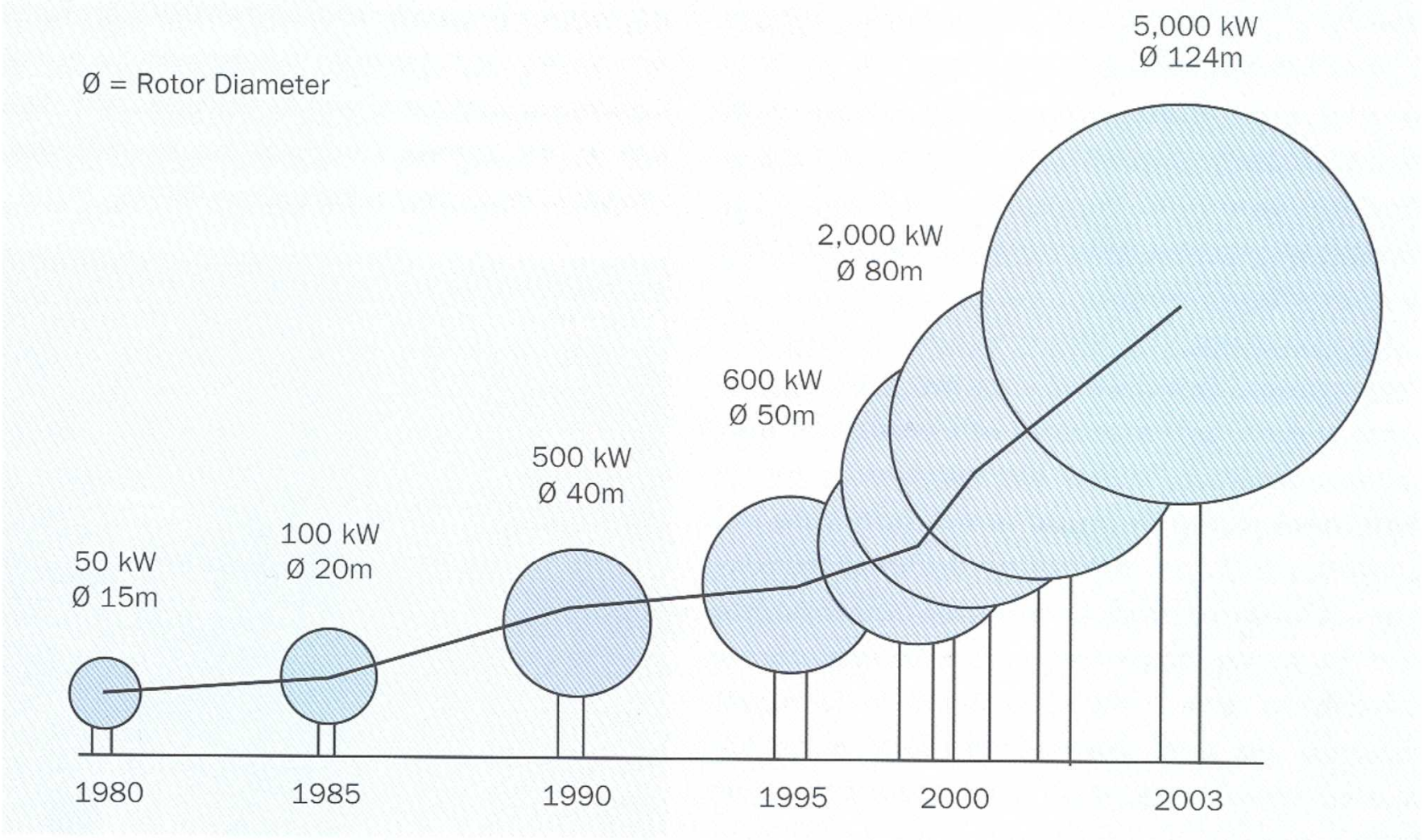
Effectively, the maximum drag-driven power coefficient is 0.15 because only the down-wind motion of the blade produces power

Lift-driven machines are only limited by the **Betz Limit** (the maximum energy extraction coefficient)

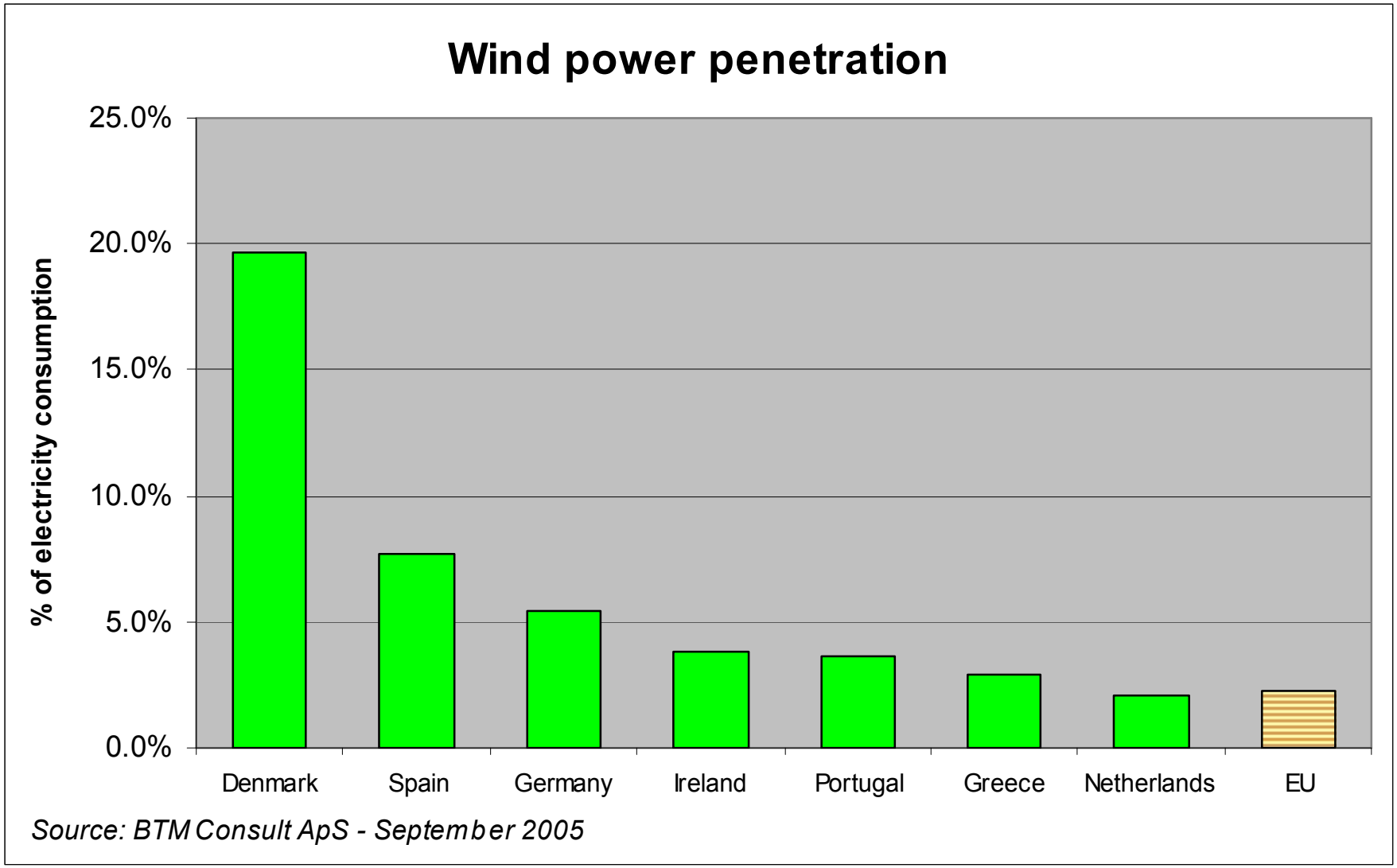
Some Machines Currently on the Market

These four suppliers account for 75% of the world market

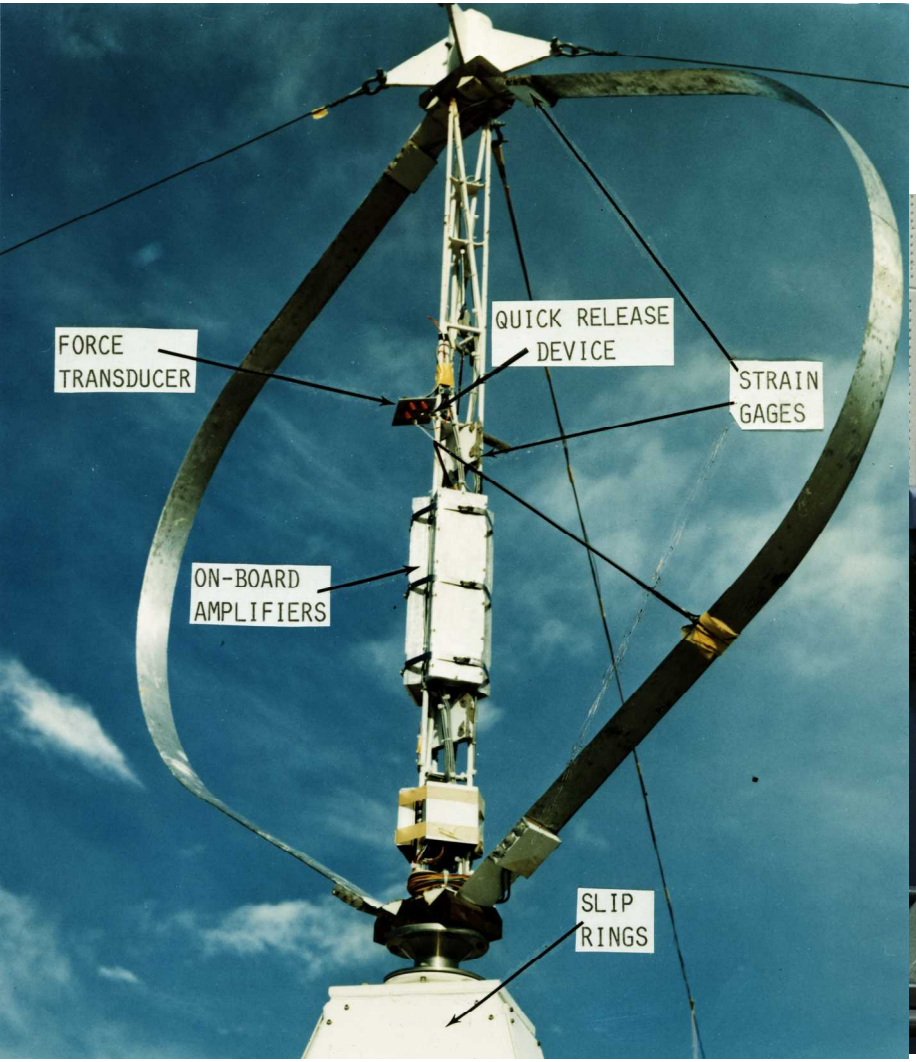
Bigger with Time

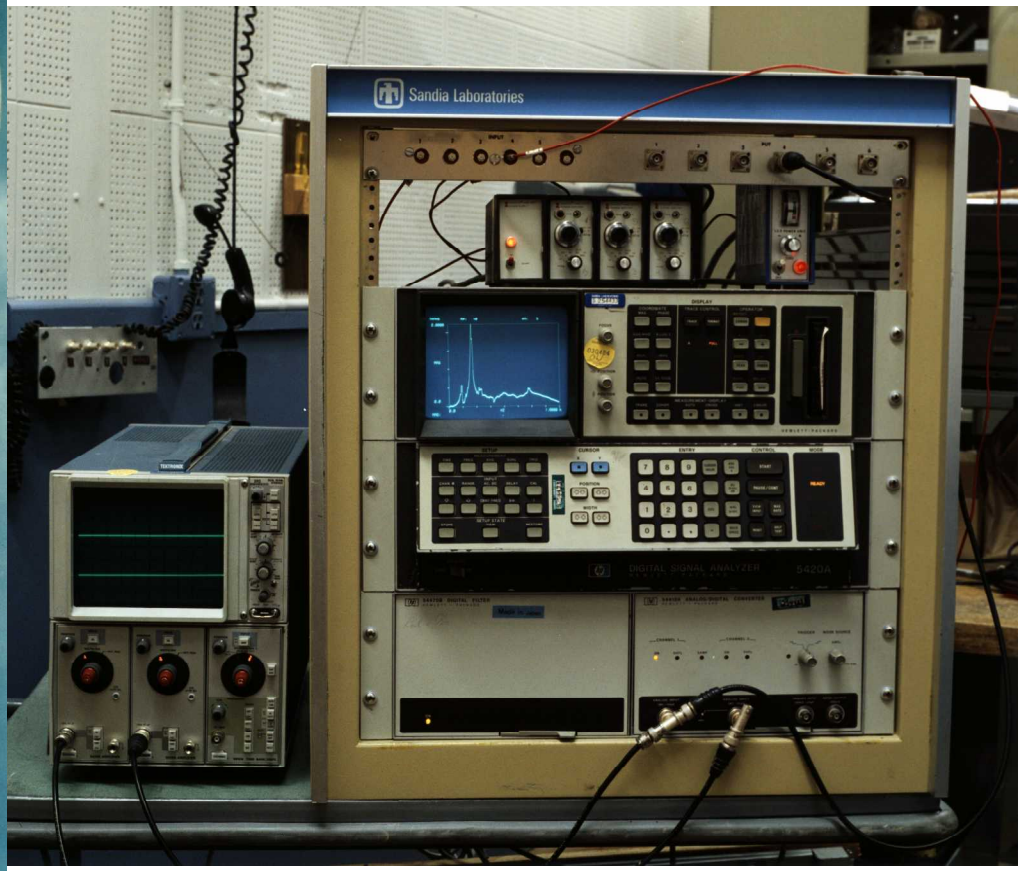


Penetration of Wind Power Electricity in Leading Countries

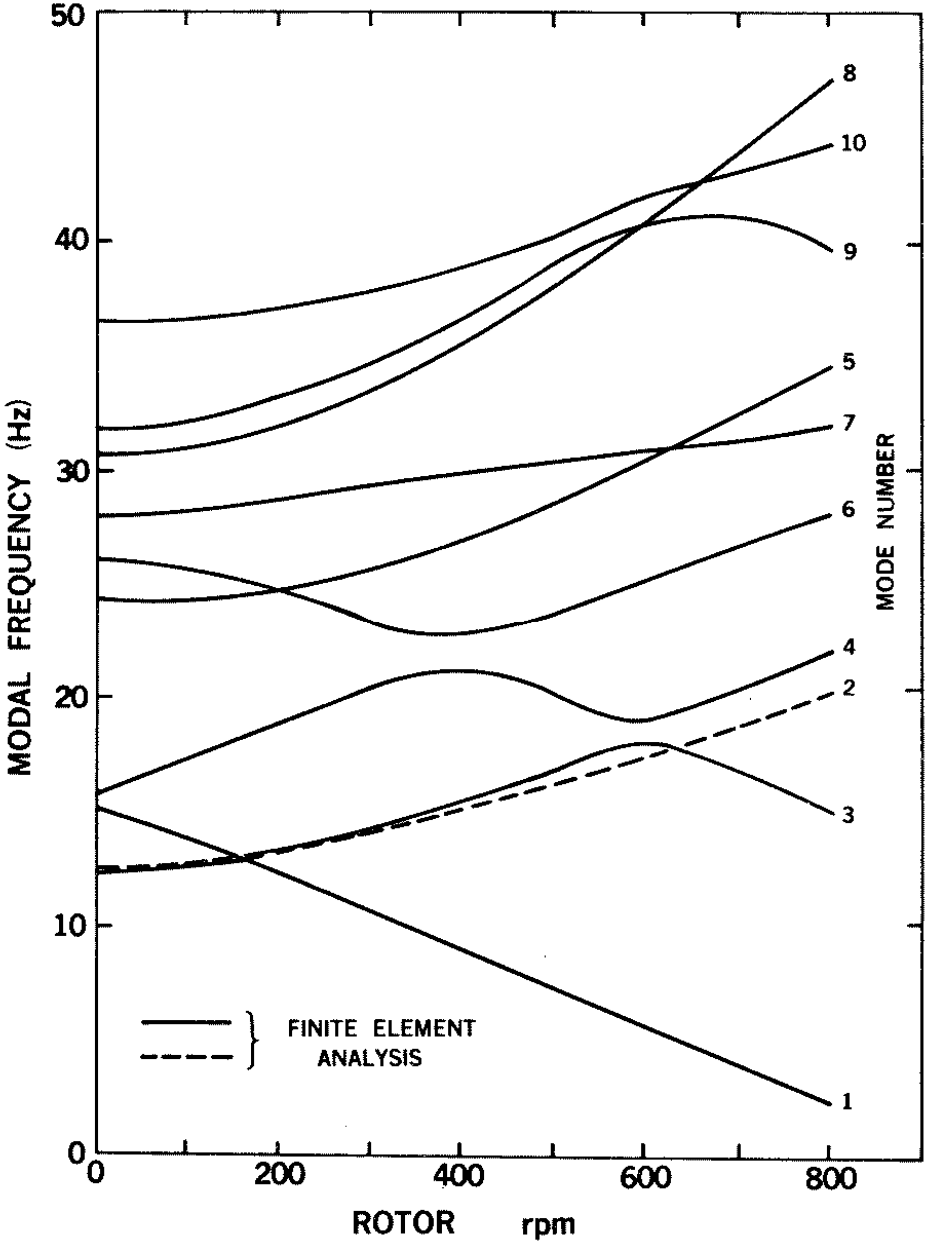


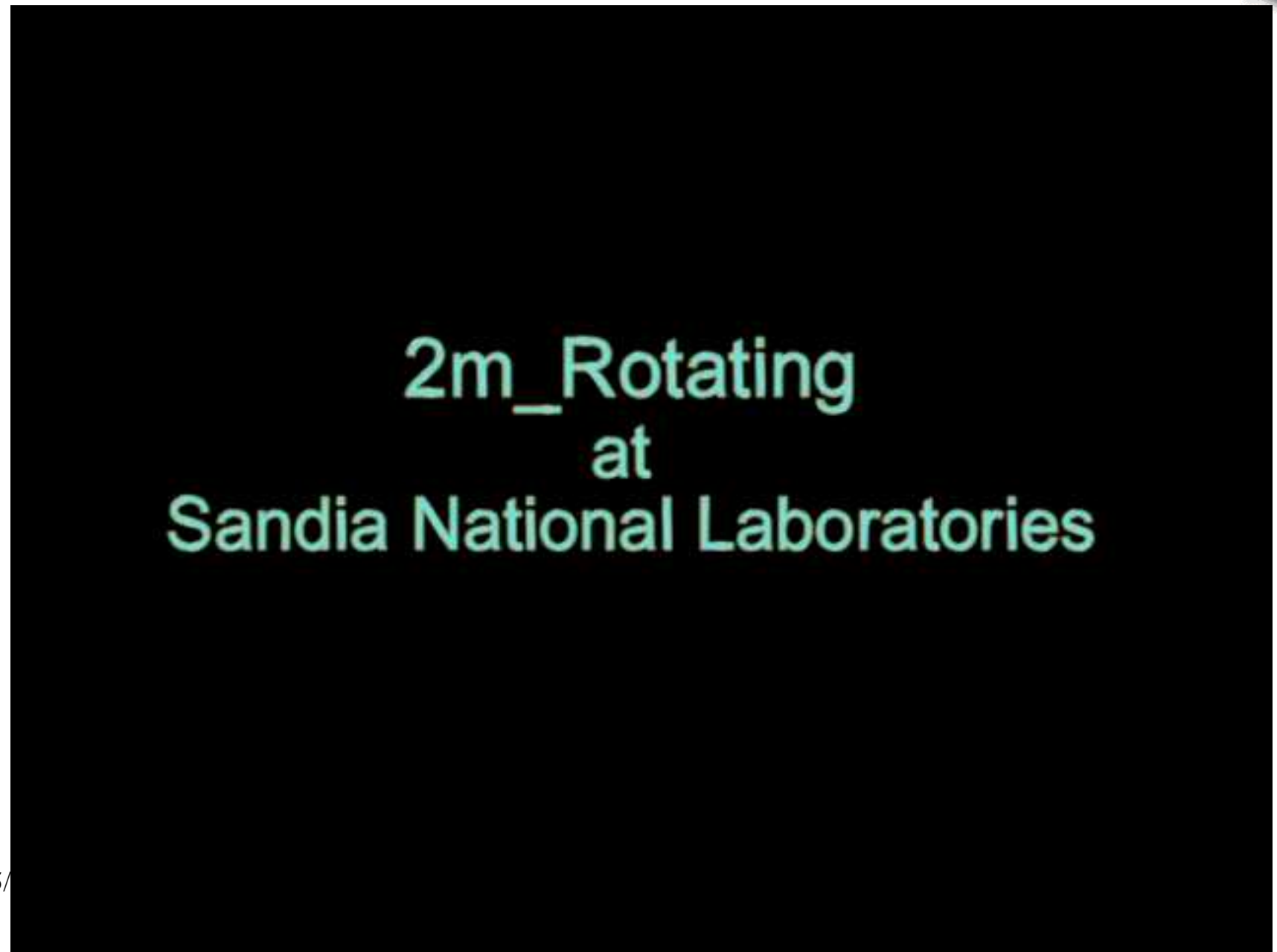
Back to 1982 !!
(when modal testing was tough)





Modal parameters (rotation speed)




2m_Rotating
at
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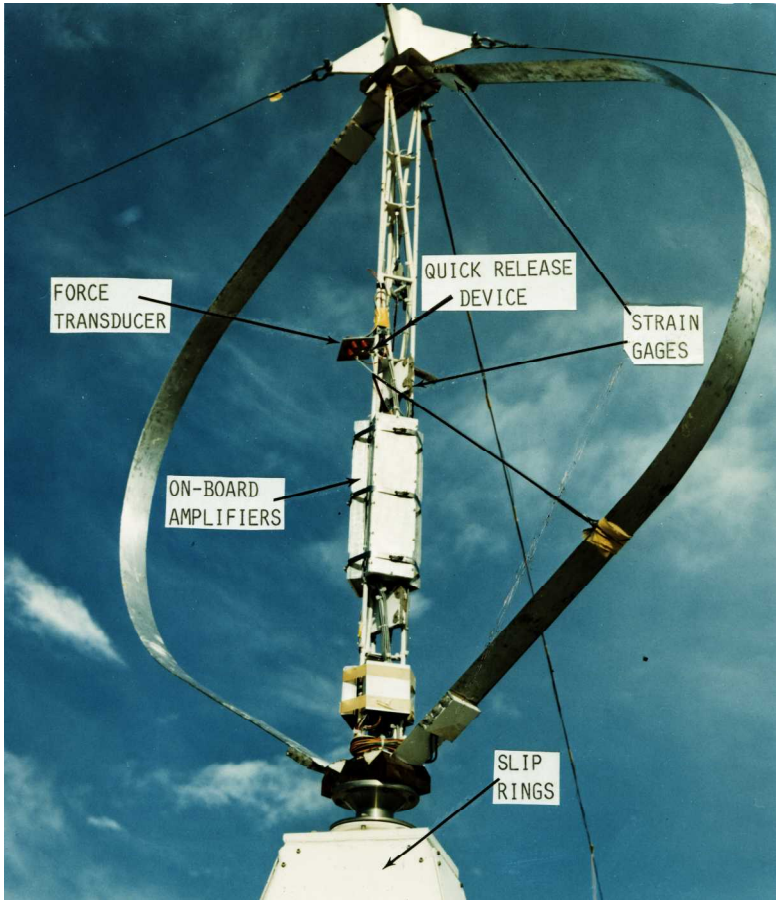
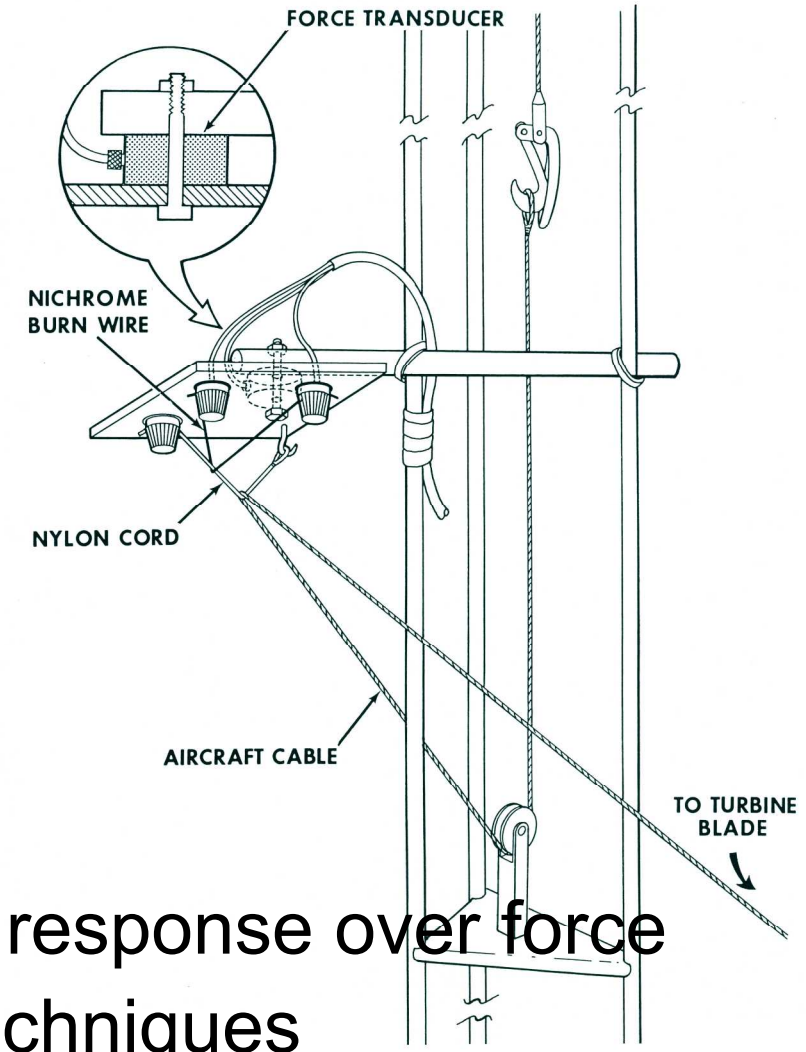
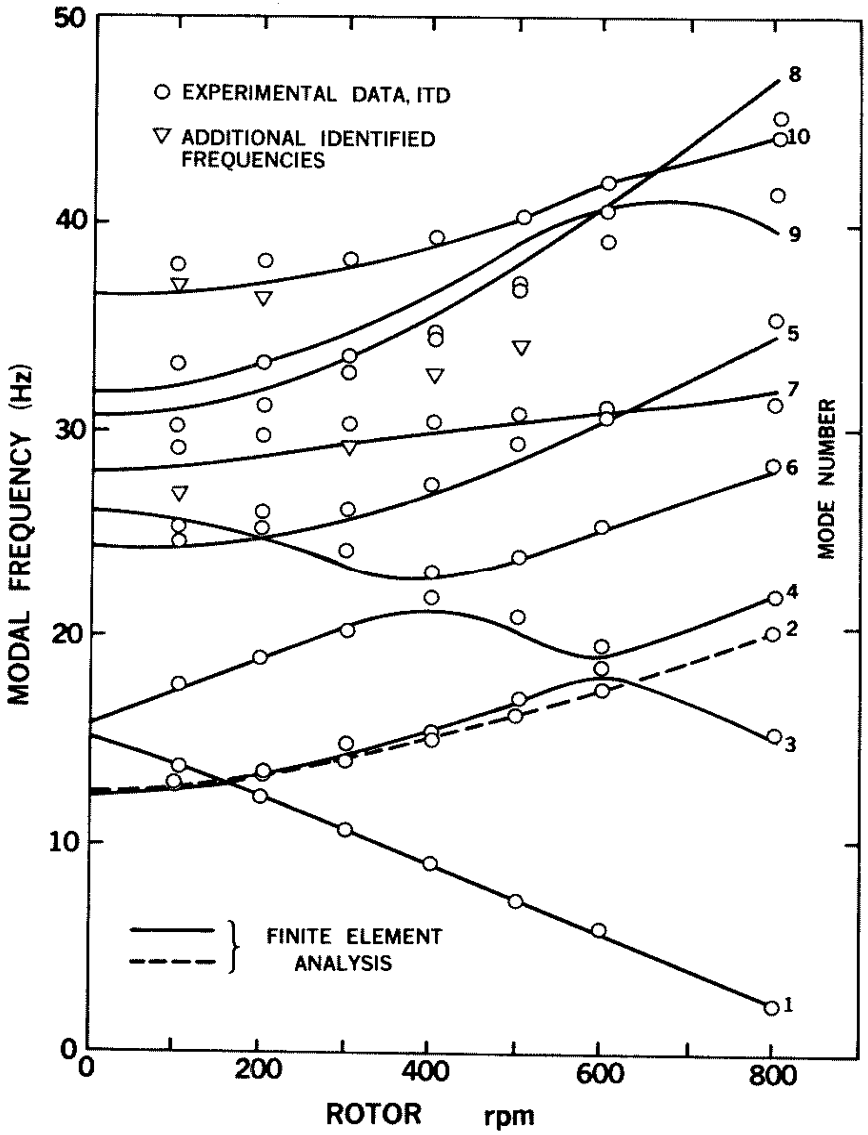
Force Input Device





- Step input produces FRFs, response over force
- Extract modes in tradition techniques

Comparison of Test versus Analysis



Extremely difficult

Time Consuming

Two channels

Reload Excitation

Move forward to 1986

120 meter tall

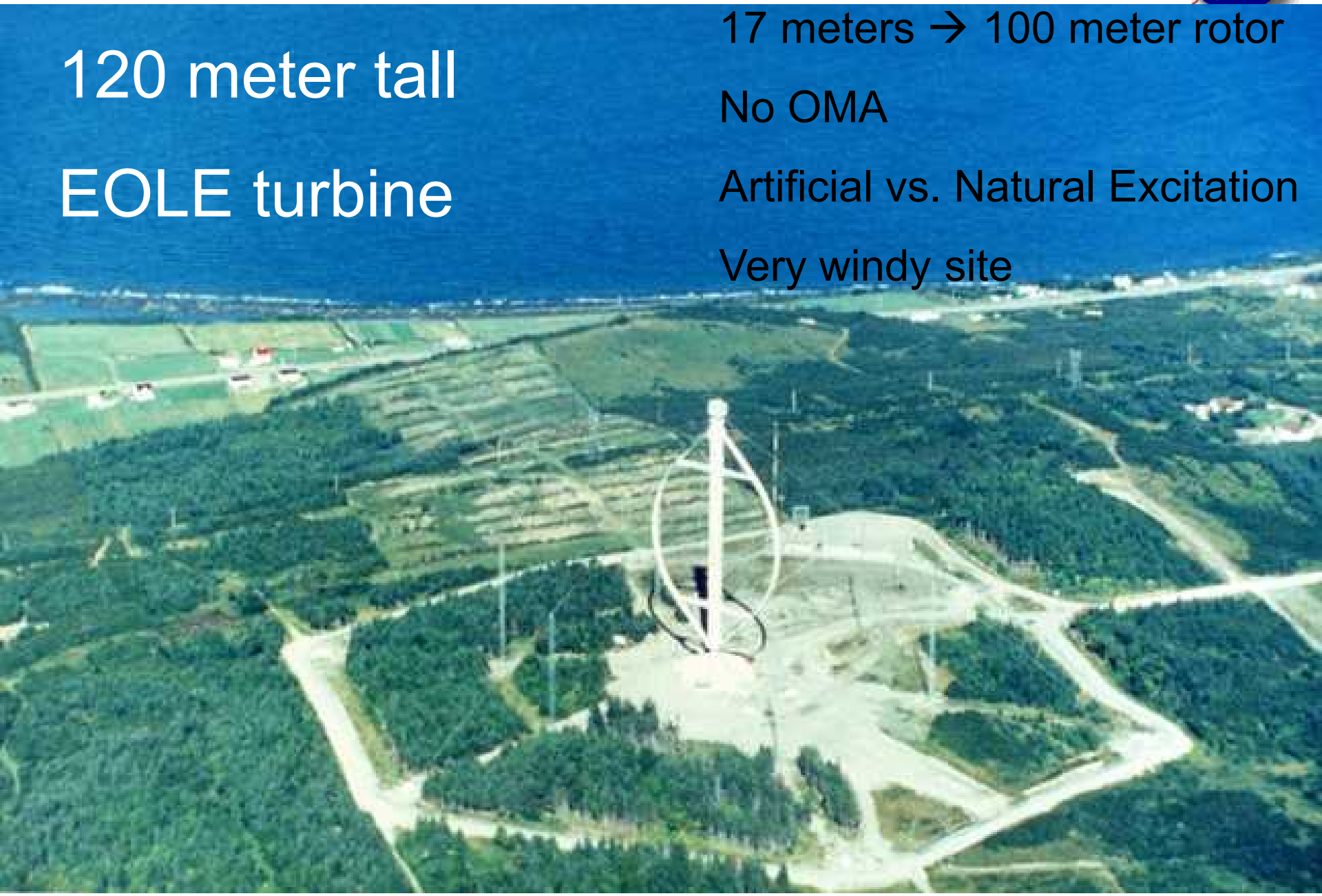
EOLE turbine

17 meters → 100 meter rotor

No OMA

Artificial vs. Natural Excitation

Very windy site



Attaching cable for Step Input

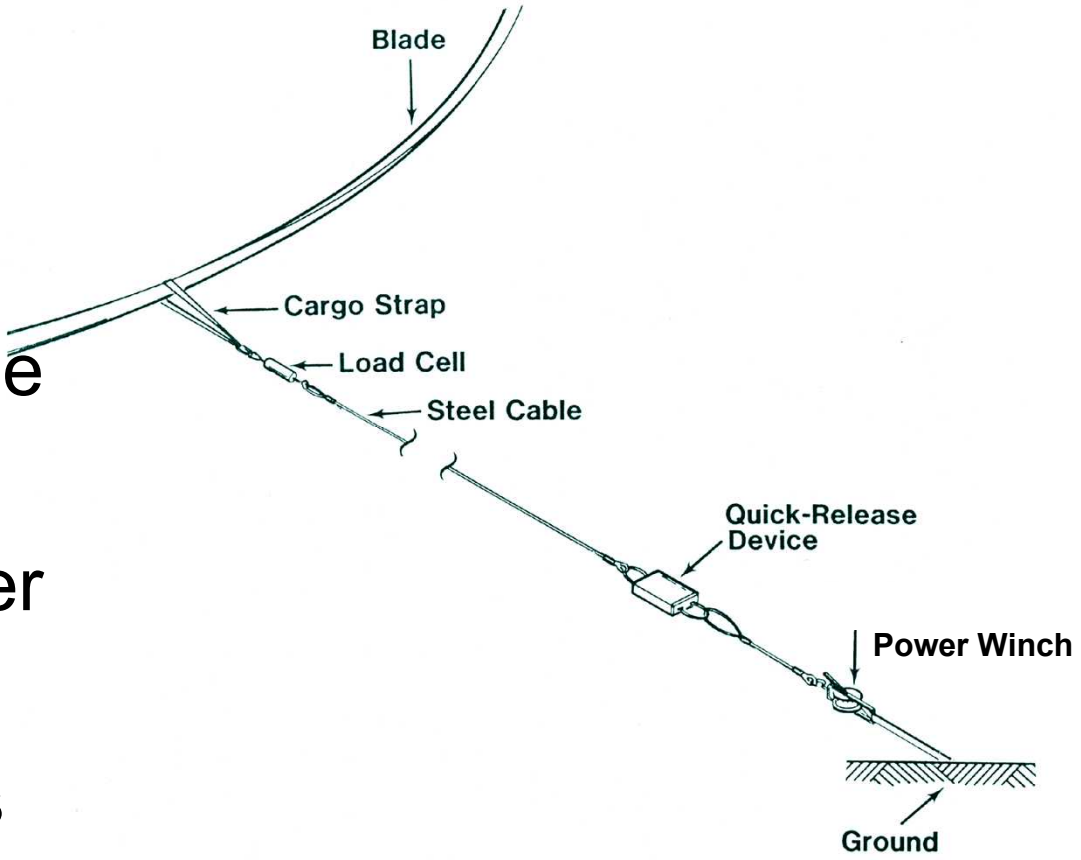
Step Relaxation Device

Step Relaxation

10,000 pounds on blade

30,000 pounds on tower

Release < 0.1 seconds



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E'OLE Wind Turbine

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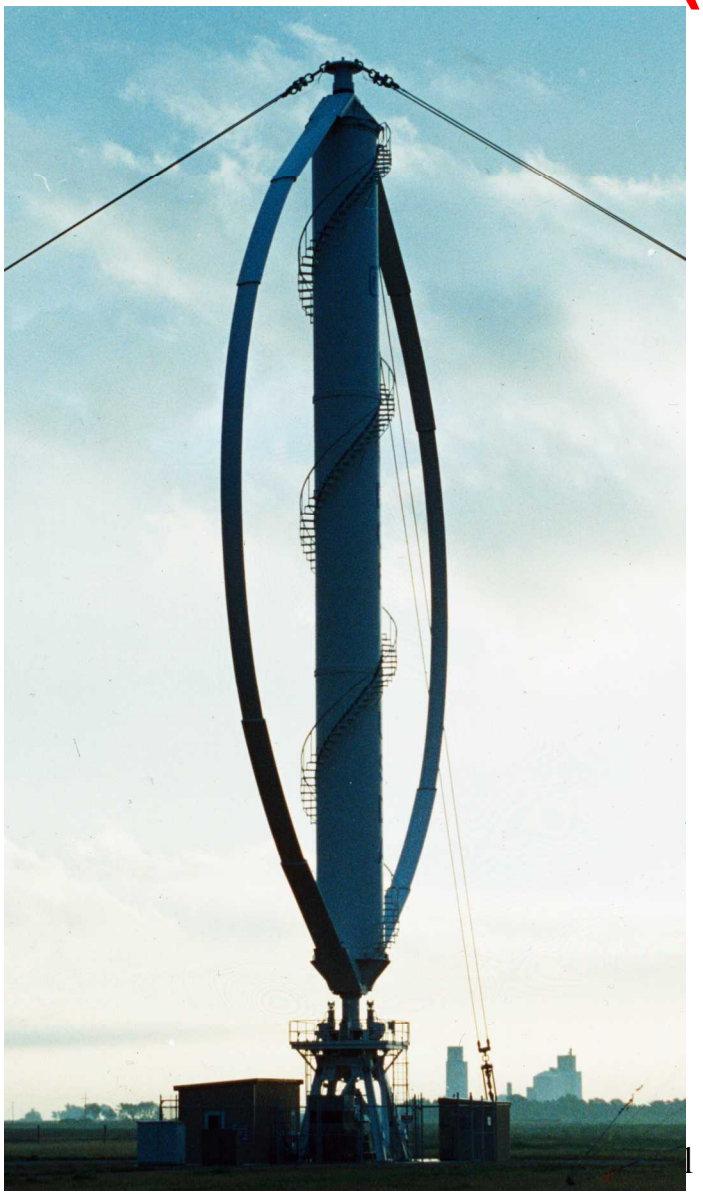
Modal Frequencies From Step Relaxation, Wind Excitation Tests, And From Finite Element Predictions

MODE SHAPE DESCRIPTION	STEP RELAXATION (Hz)	WIND EXCITATION (Hz) NExT / OMA	FINITE ELEMENT MODEL (Hz)
FIRST TOWER OUT-OF-PLANE	0.63	0.63	0.63
FIRST TOWER IN-PLANE	0.74	0.73	0.75
SECOND TOWER OUT-OF-PLANE	0.93	0.94	0.92
BLADE FLATWISE ANTI-SYMMETRIC	1.30	1.30	1.27
BLADE FLATWISE SYMMETRIC	1.32	1.34	1.29
SECOND TOWER IN-PLANE	1.38	1.39	1.42
BLADES BENDING OUT-OF-PLANE	1.55	1.55	1.61
THIRD TOWER OUT-OF-PLANE	1.79	---	1.76
ROTOR TWIST (DUMBBELL)	1.93	1.94	1.96
SECOND FLATWISE SYMMETRIC	2.24	2.25	2.20
SECOND BLADE OUT-OF-PLANE	2.33	2.33	2.34
SECOND BLADE ANTI-SYMMETRIC	2.40	2.39	2.38

Great Success for OMA Natural Excitation

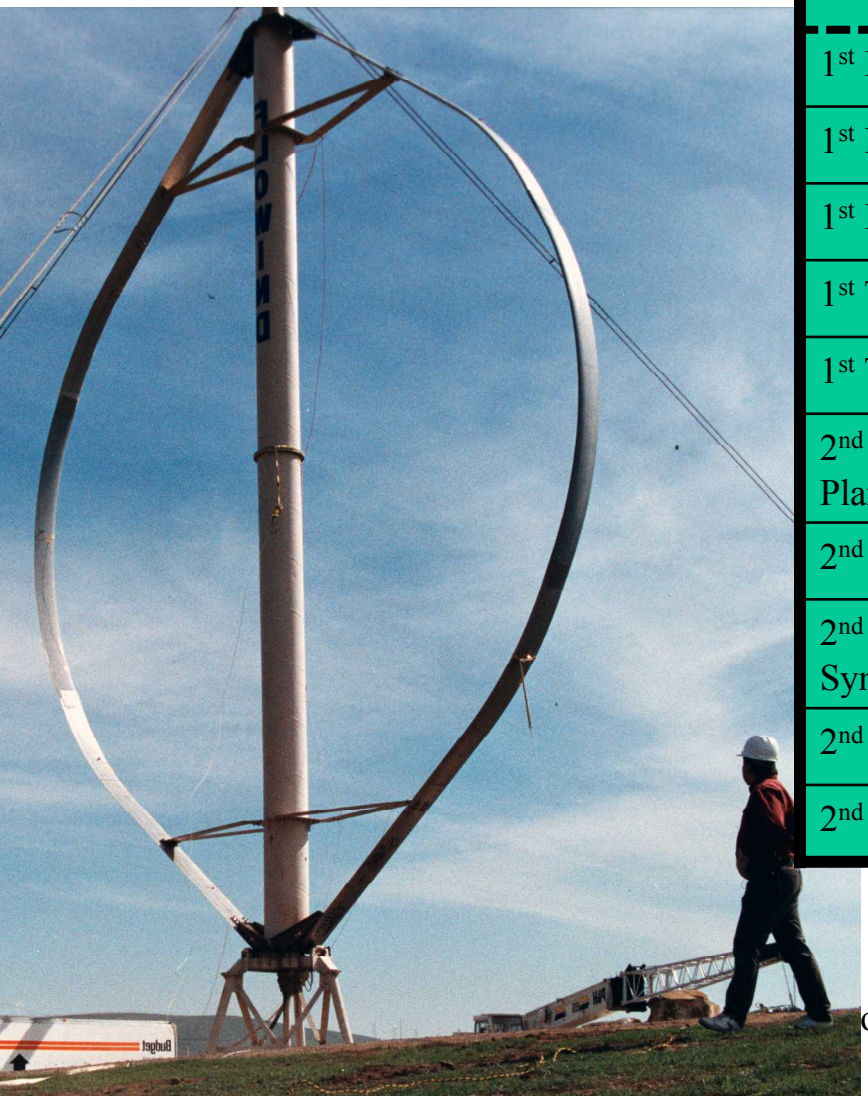
- Used OMA on all future turbines testing
- E'OLE test published '88 IMAC and M.A. journal
- Formalized approach in '92 IMAC & Oct.95 journal
- Called this NExT: Natural vs. Operational
  - 1. Acquire response data -- long time histories
  - 2. Calculate auto & cross- correlation functions
    - Showed that correlation fcns sum of decaying sinusoids
    - Reference dofs
  - 3. Time domain modal id algorithm to estimate
    - Poly-Reference and ERA
  - 4. Extract mode shapes

34-Meter VAWT, Parked (1992 IMAC)



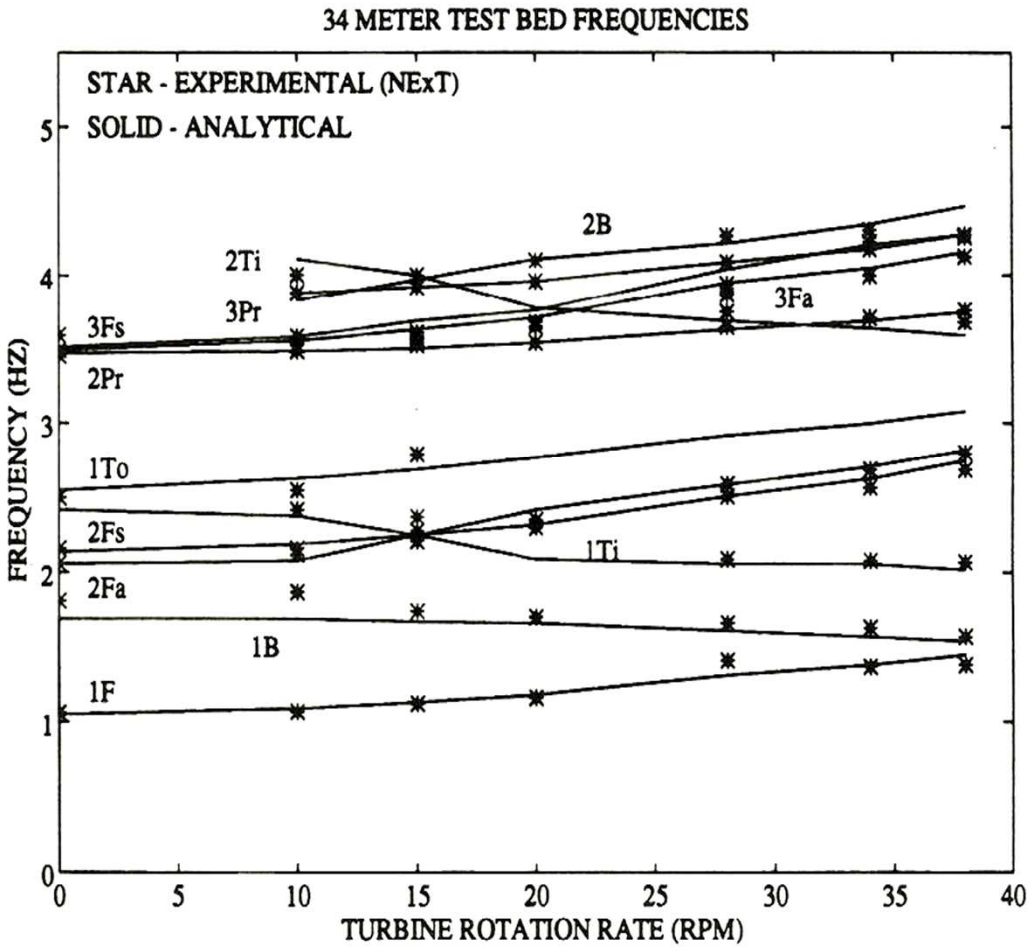
Mode Shape Description	Frequency (Hz)		Damping (%)	
	Simulated	NExT	Simulated	NExT
1st Flatwise Antisymm	1.27	1.31	0.2	0.4
1st Flatwise Symm	1.35	1.32	0.2	0.3
1st Blade Edgewise	1.59	1.59	0.3	0.3
1st Tower In-Plane	2.02	2.01	0.3	0.4
2nd Flatwise Symmetric	2.43	2.44	0.4	0.5
2nd Flatwise Antisymm	2.50	2.50	0.4	0.4
1st Tower Out-of-Plane	2.80	2.80	0.3	0.5
2nd Rotor Twist	3.39	3.39	0.5	0.6
2nd Tower In-Plane	3.46	3.45	0.5	0.4
3rd Flatwise Antisymm	3.65	3.63	0.5	0.4
3rd Flatwise Symmetric	3.73	3.73	0.6	0.4
2nd Blade Edgewise	3.88	3.87	0.5	0.3

FloWind 19-Meter, Parked

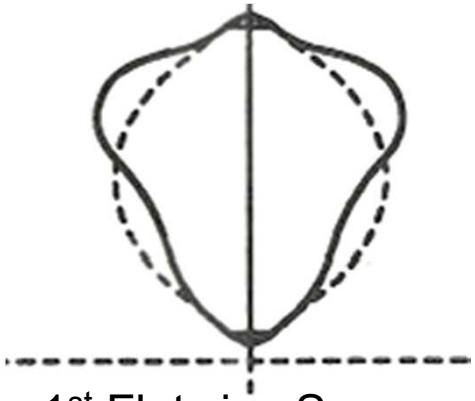


Mode Shape Description	Frequency (Hz)		Damping (%)	
	Step Relax	NExT	Step Relax	NExT
1st Rotor Twist	2.37	2.38	0.2	0.1
1st Flatwise Antisymm	2.48	2.49	0.2	1.3
1st Flatwise Symmetric	2.51	2.51	0.1	1.4
1st Tower Out-of-Plane	2.72	2.76	0.4	0.4
1st Tower In-Plane	3.11	3.15	0.4	0.4
2nd Tower Out-of-Plane	4.53	4.53	0.1	0.1
2nd Flatwise Antisymm	5.30	5.31	0.3	0.8
2nd Flatwise Symmetric	5.64	5.65	0.1	0.6
2nd Rotor Twist	6.59	6.62	0.1	0.1
2nd Tower In-Plane	6.64	6.71	0.3	0.6

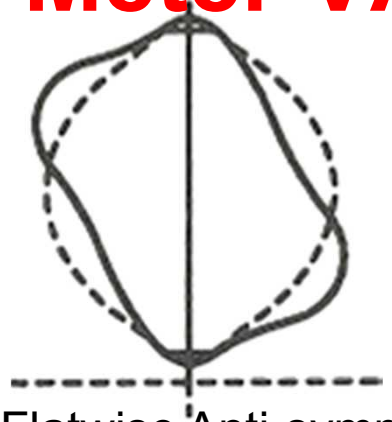
Rotating 34-Meter VAWT



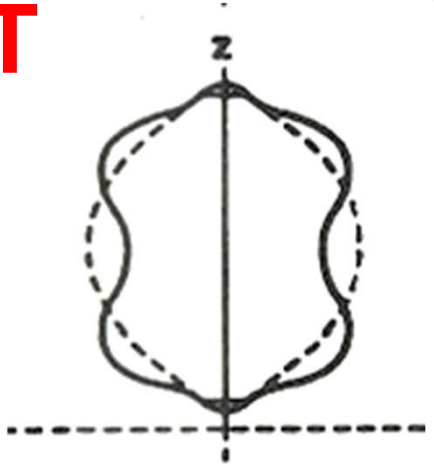
Damping for Rotating 34-Meter VAWT



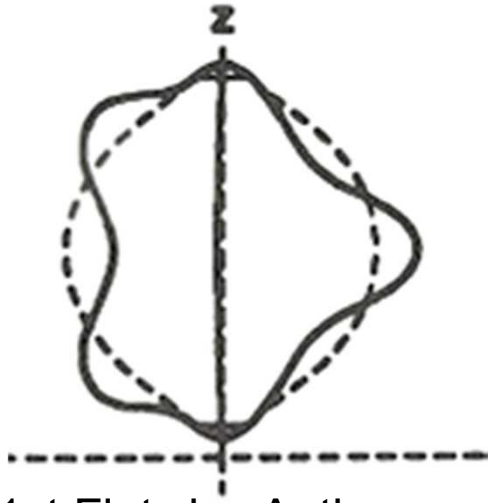
1st Flatwise Symm



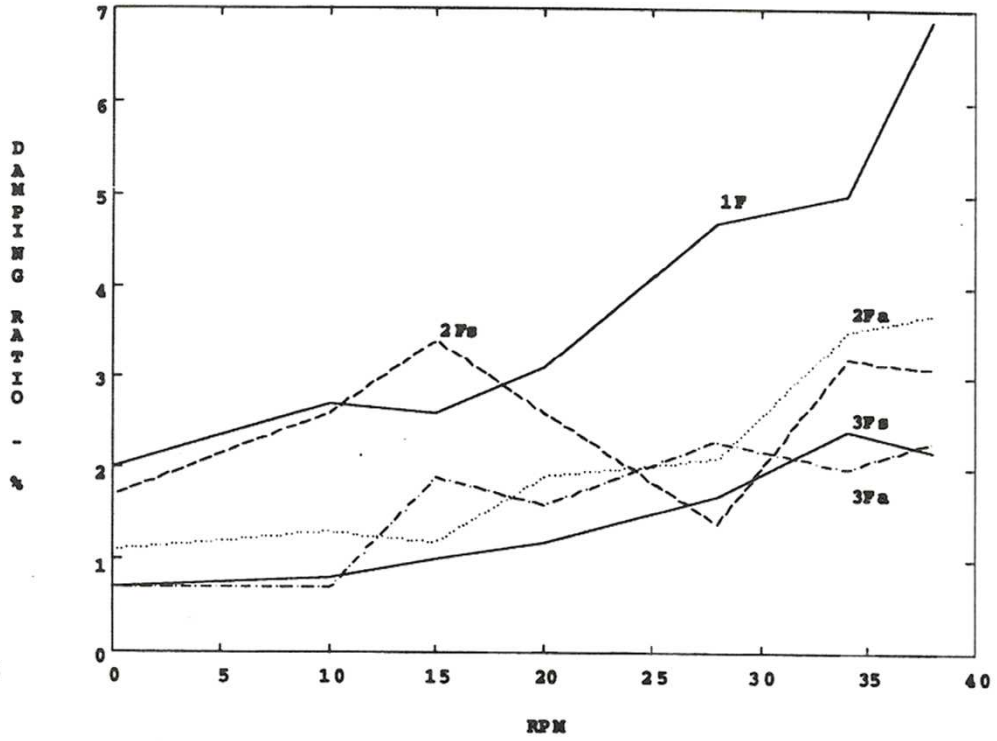
1st Flatwise Anti-symm



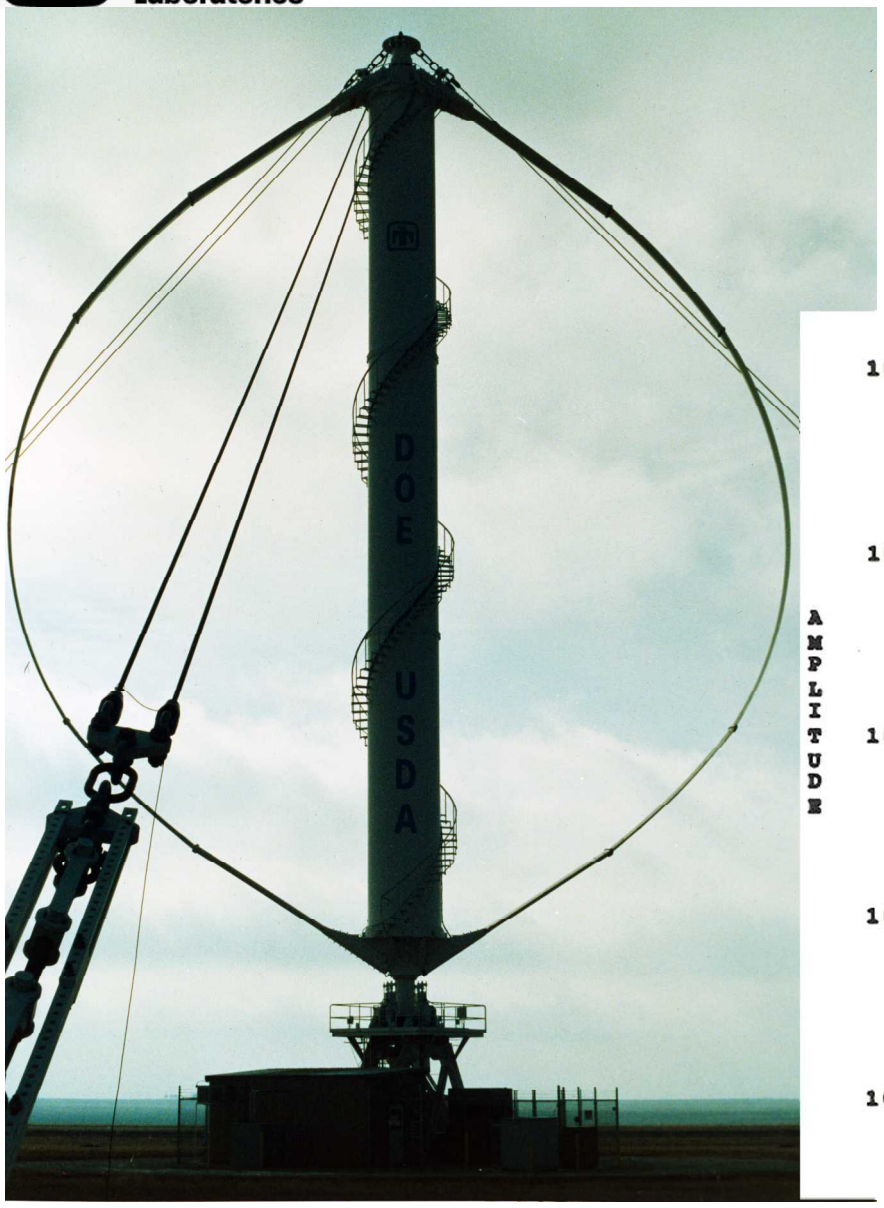
2nd Flatwise Symm

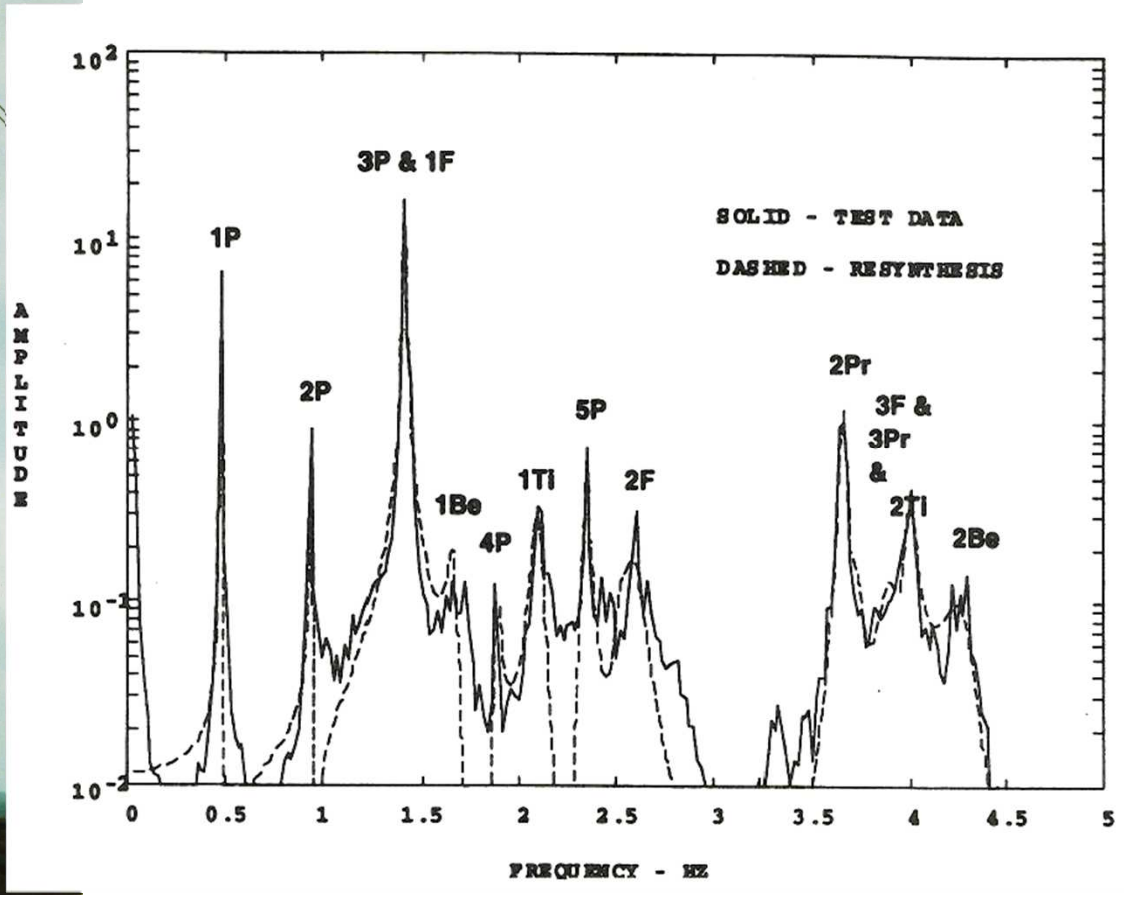


1st Flatwise Anti-symm

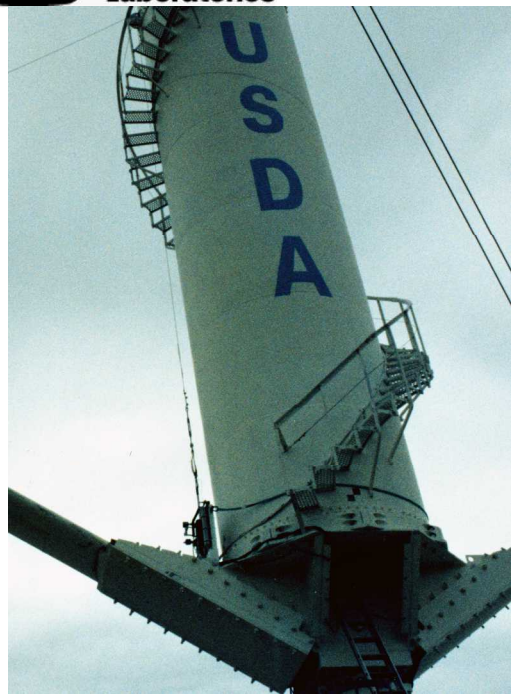


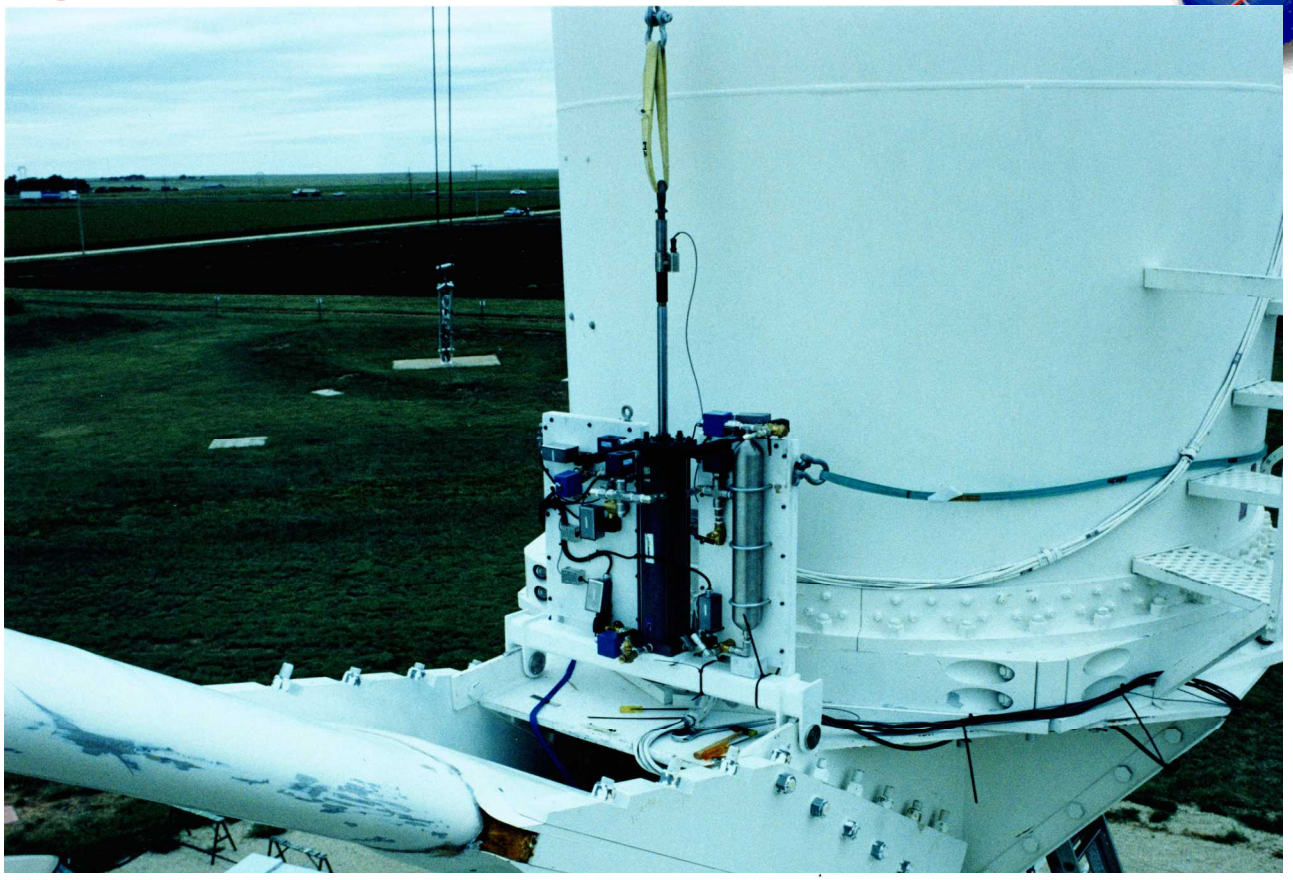
Validation of NExT on 34-Meter

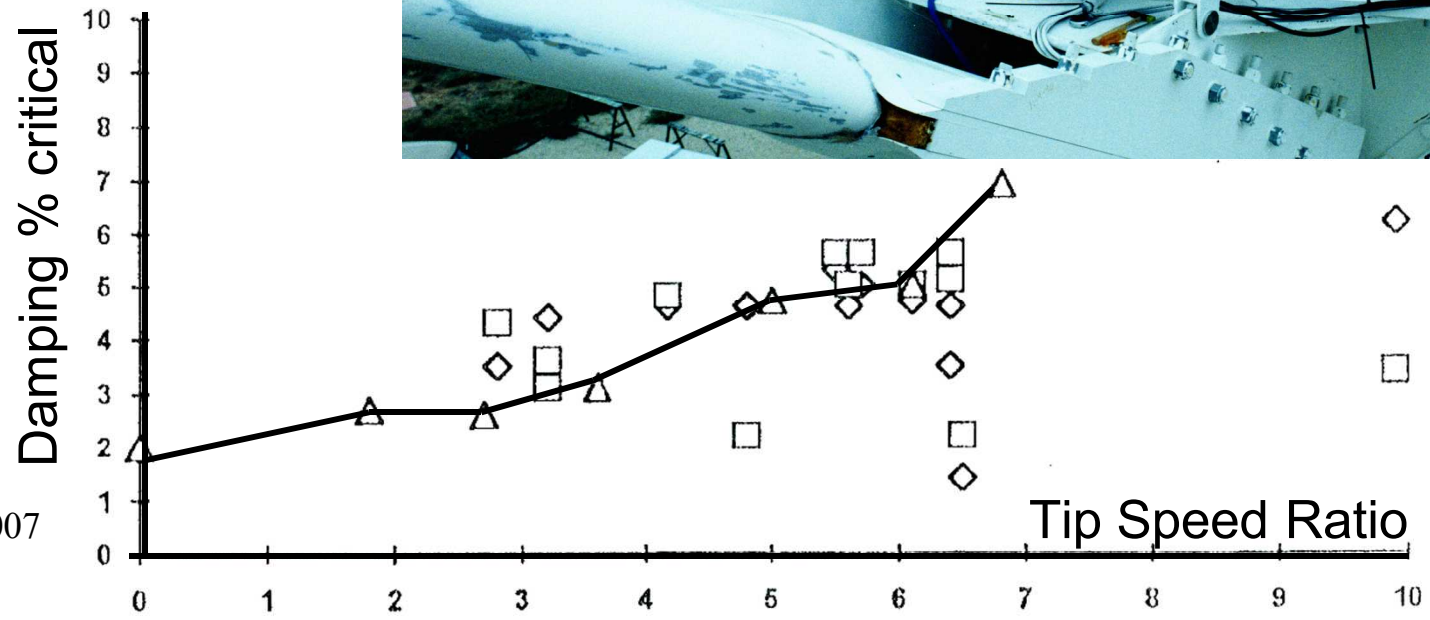




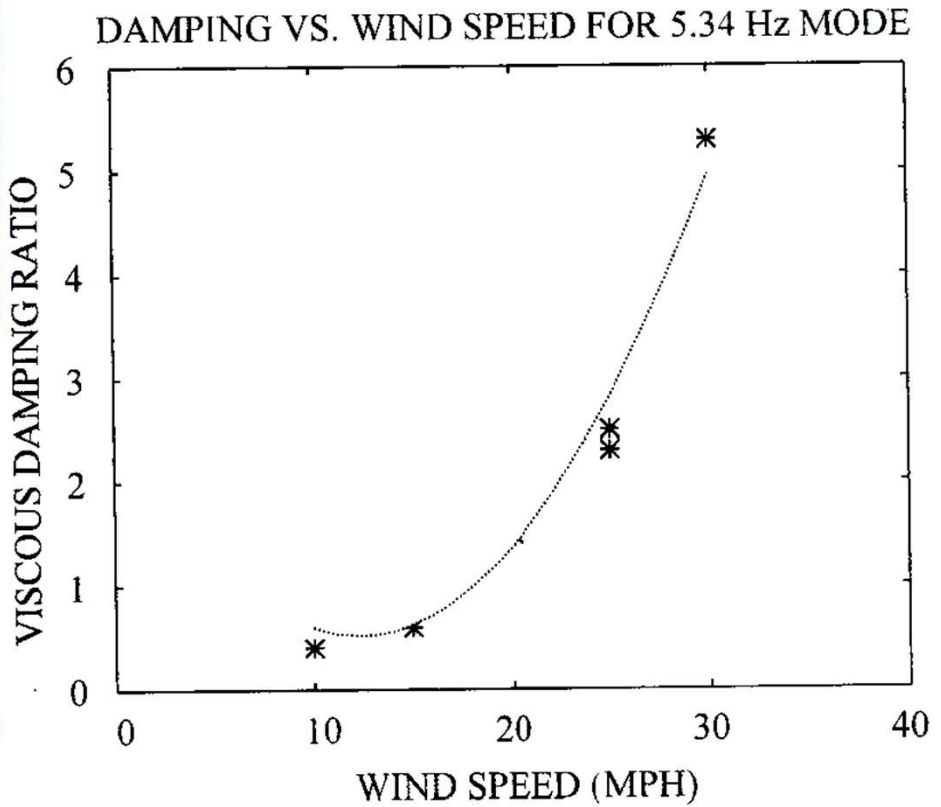
Damping vs. Tip Speed for 34-Meter





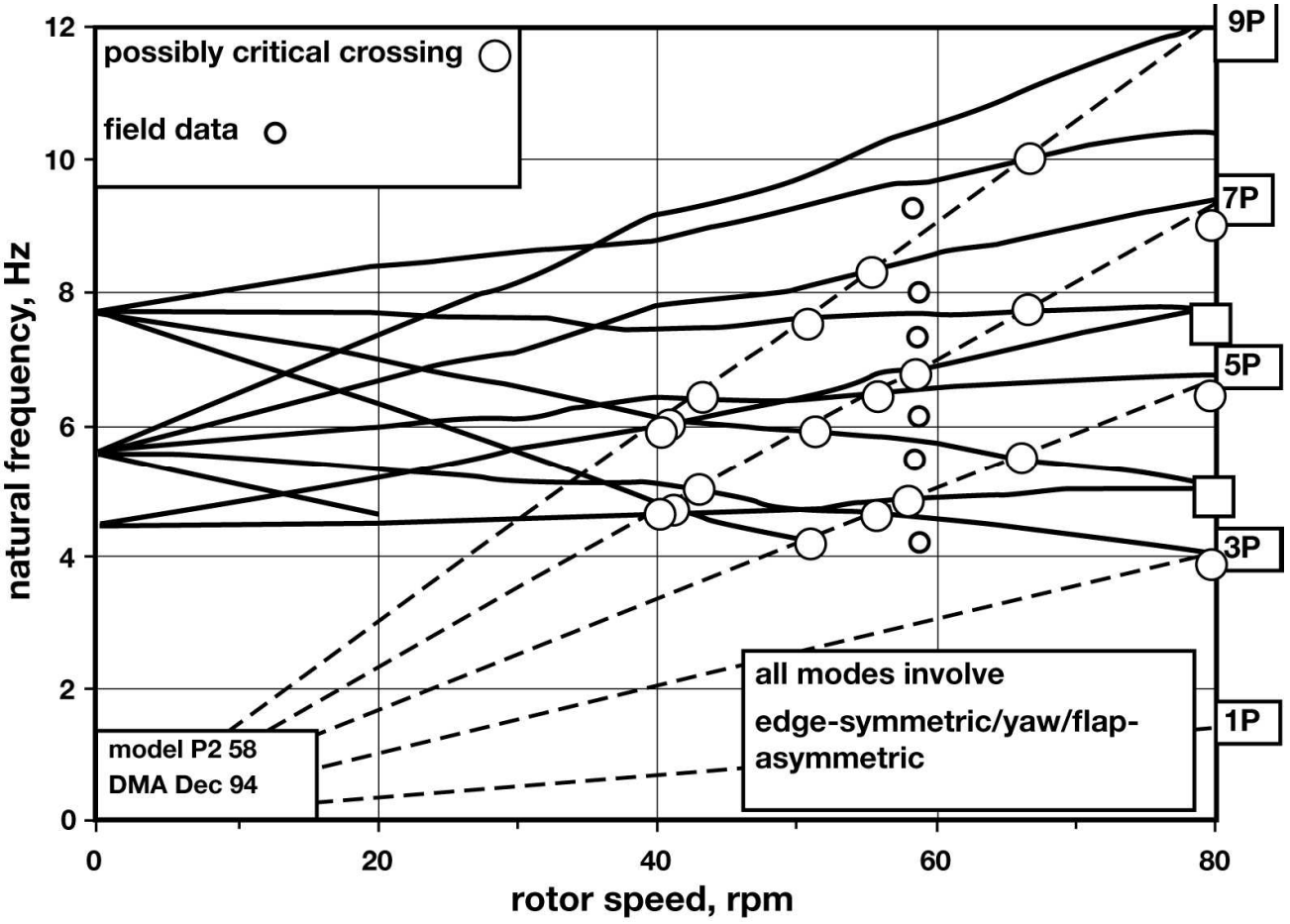


1995 → Transition to HAWT's



Controlled-Yaw HAWT

Free-Yaw AWT-26 Turbine



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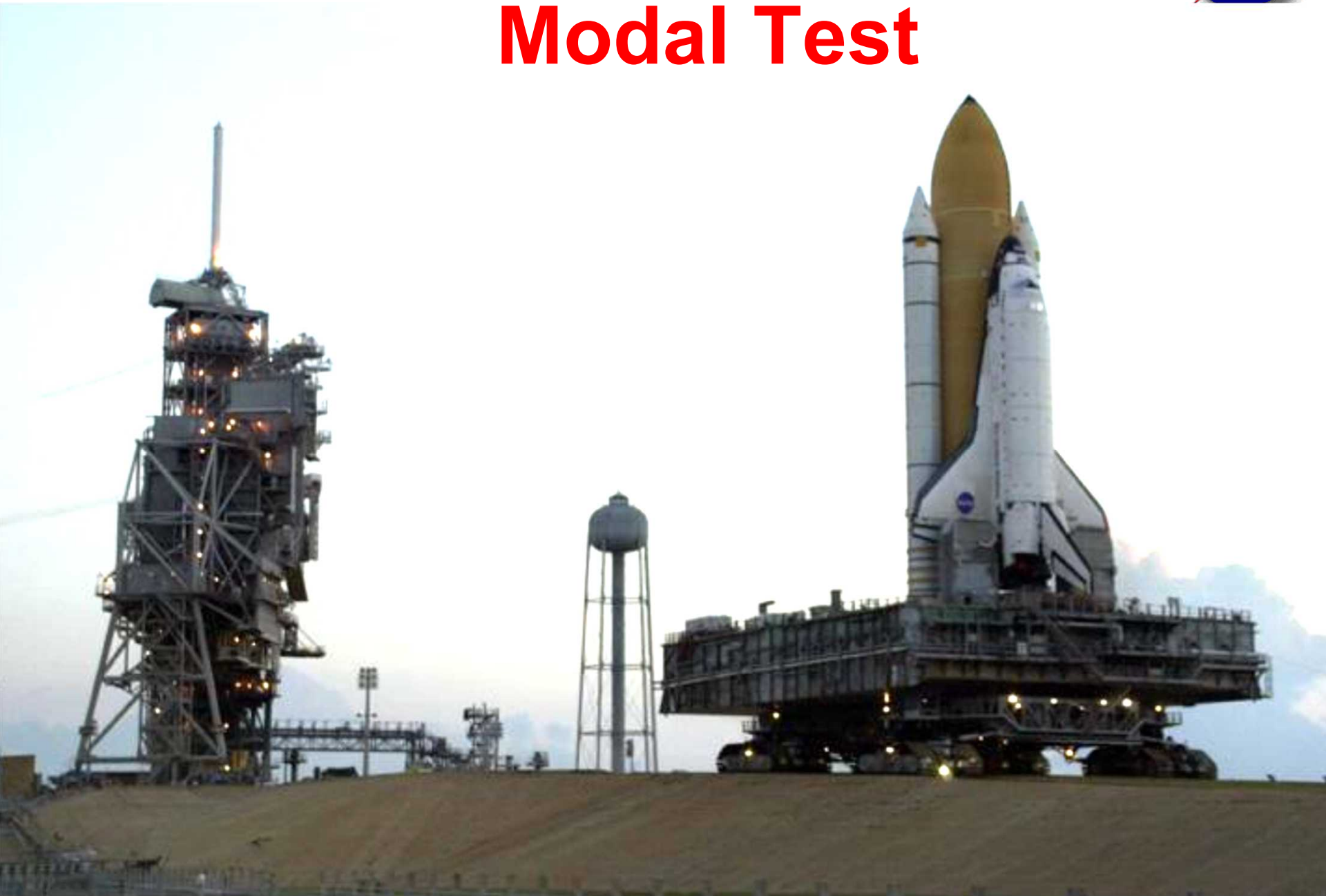
Natural Excitation Modal Test



Operational Modal Test