Floating Wind Turbines

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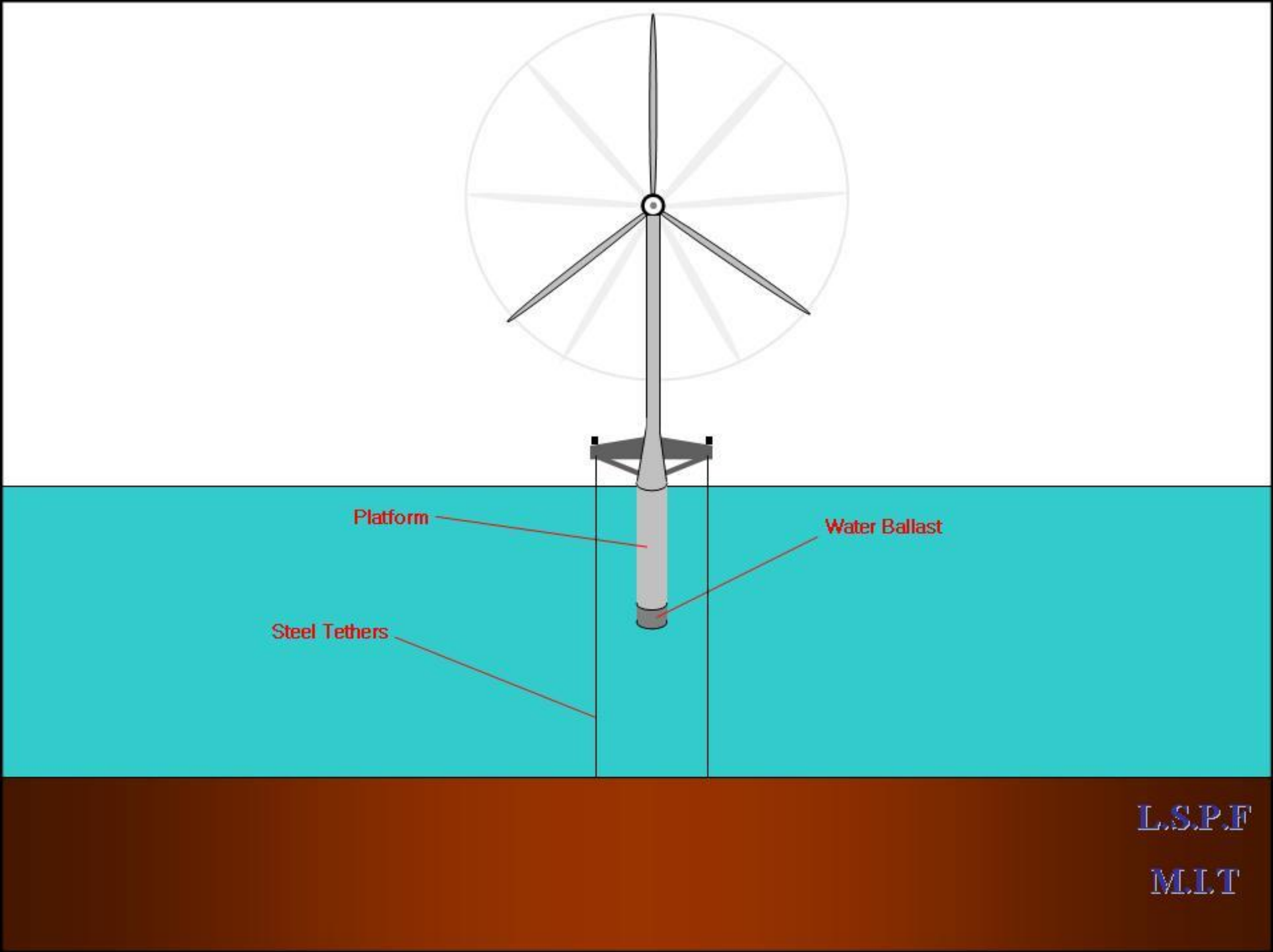
Floating Wind Turbines

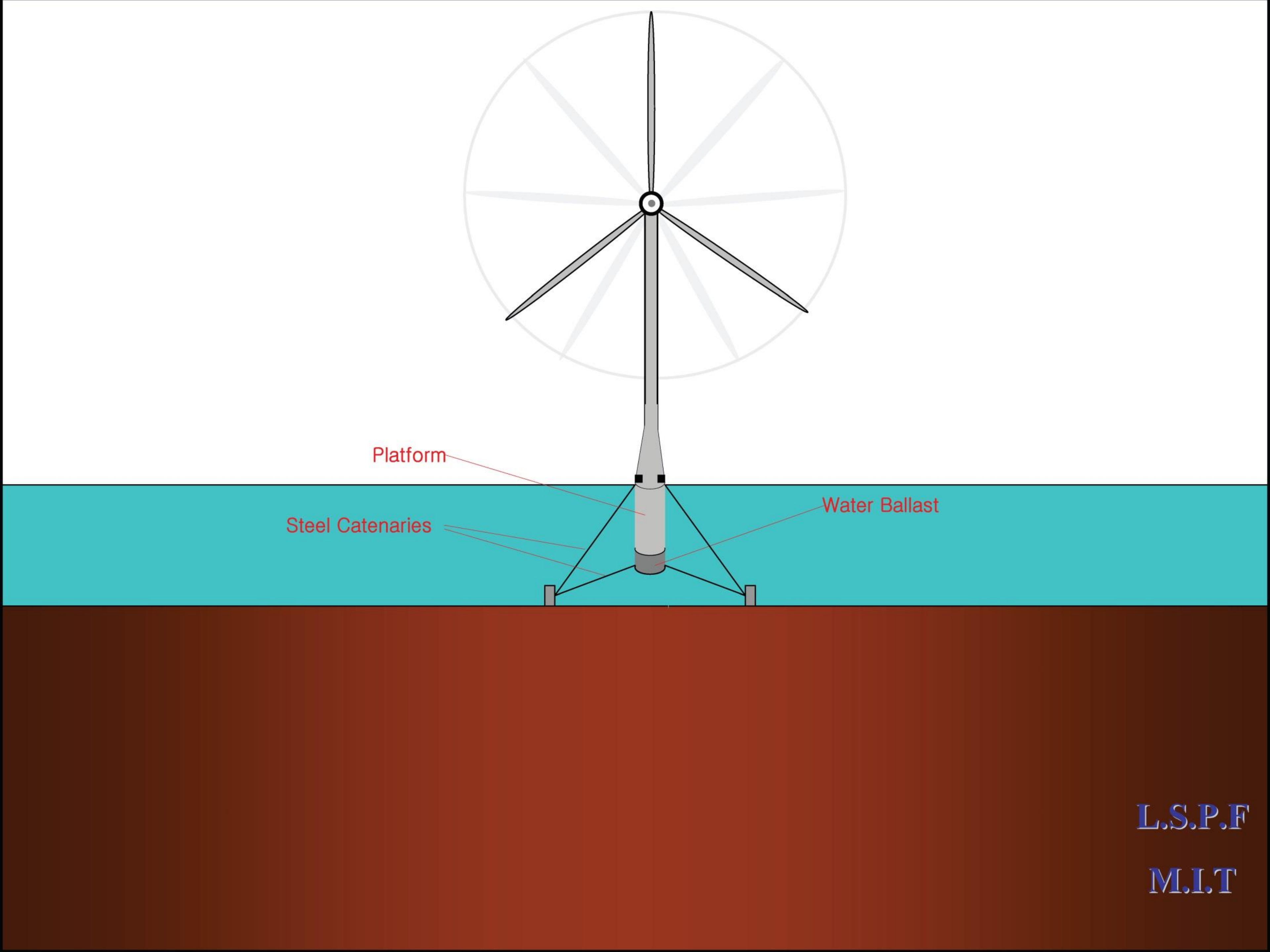
- Vast Offshore Sites Available for Wind Resource Development
- Offshore Siting Mitigates Visual, Noise and Flicker Impact
- Coastal Assembly – Low Cost Float-out Operation
- Floater Cost Lower than Turbine Cost per Marginal MW
- Fault Tolerant Efficient Operation using Turbine Controls
- Larger Turbines on Fewer Floaters – Low O&M Costs per MW

Floating Wind Turbine Prototypes

Hydrodynamics

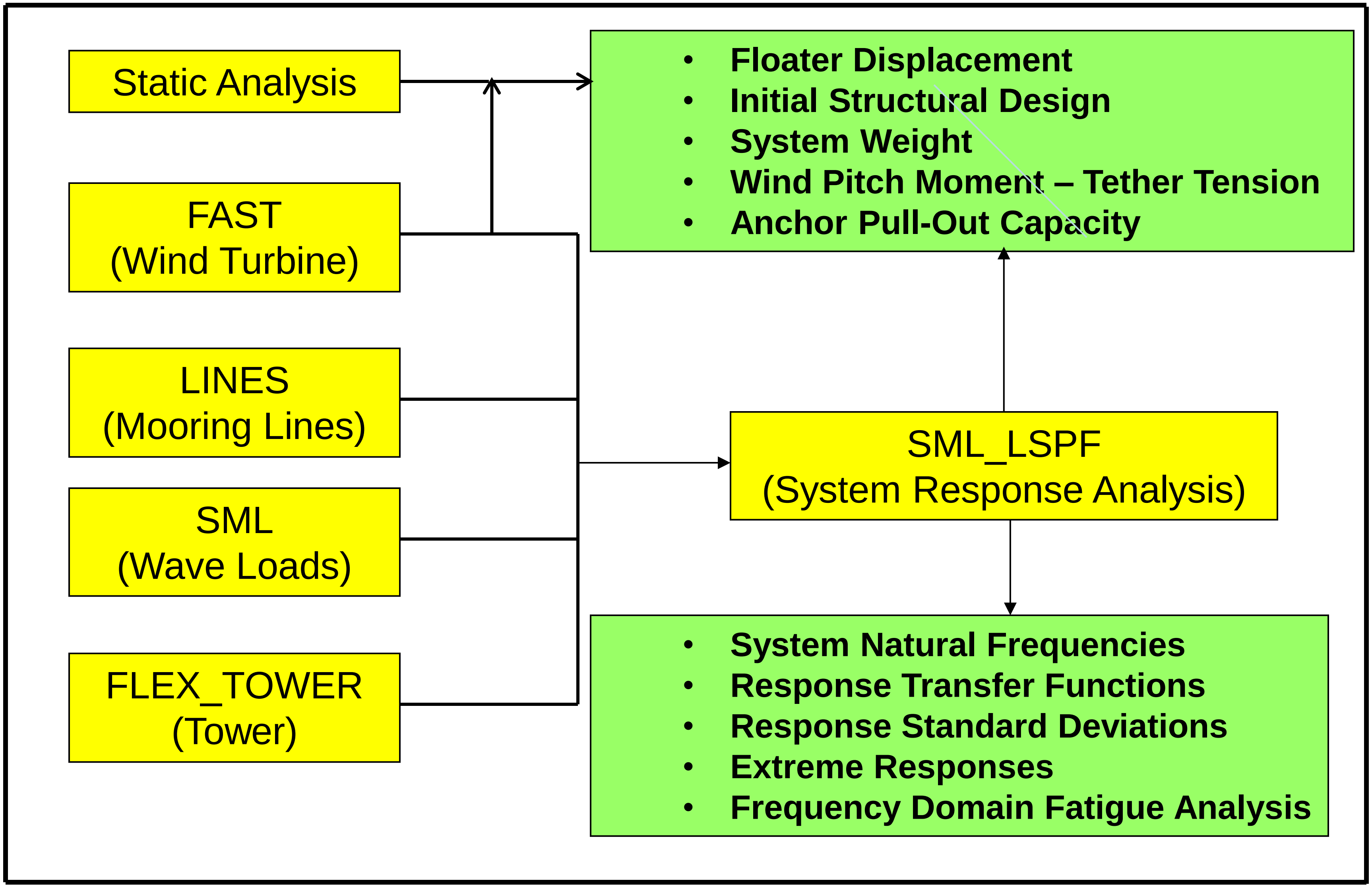
- Frequency Domain Preliminary Design Analysis
- State-Space Formulation of Free Surface Hydrodynamics
- Generalized Morison Equation with Memory Effects
- Fluid Impulse Theory for Nonlinear Loads
- Ringing Loads
- Efficient Computation – Nonlinear Statistics

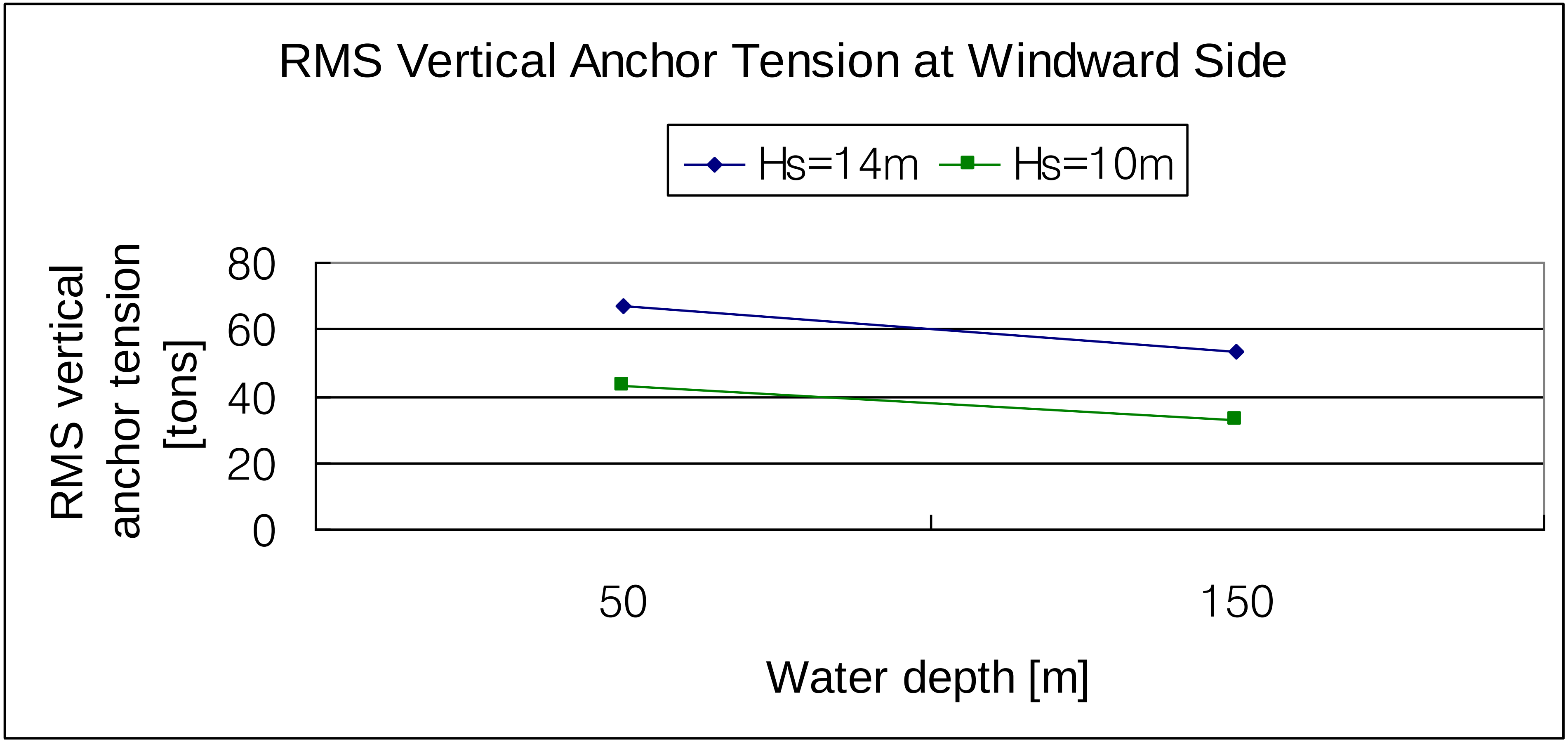

Platform
Water Ballast
Steel Tethers
L.S.P.F
M.I.T



Platform
Steel Catenaries
Water Ballast
L.S.P.F
M.I.T

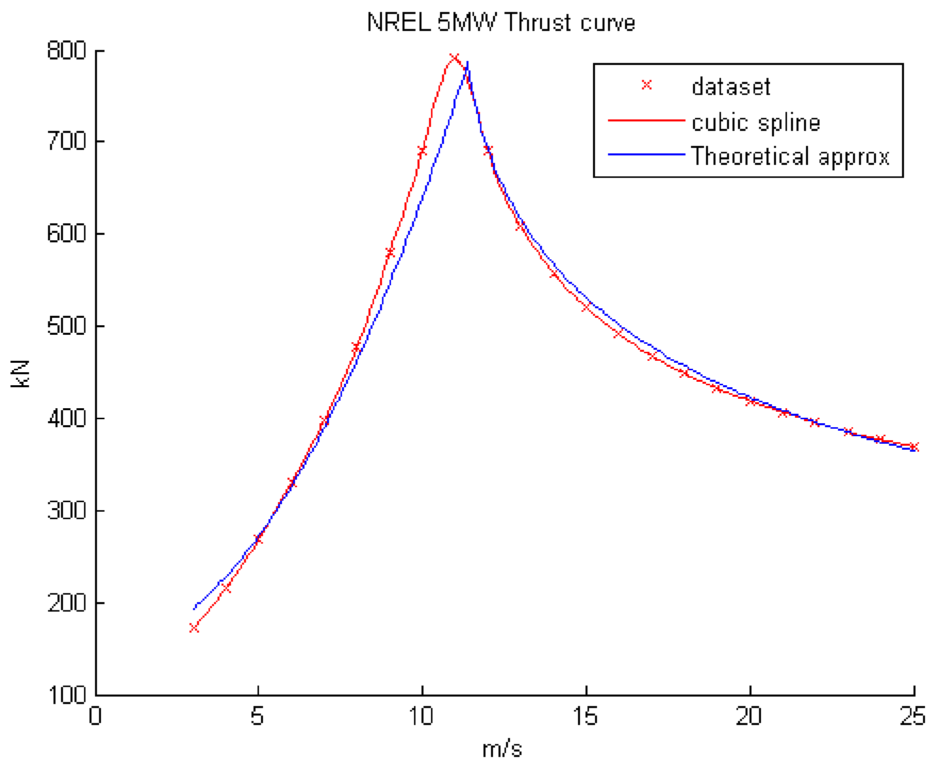
Dynamic Analysis of Floating Wind Turbines





3 MW TLP Floating Wind Turbine

Wind Turbine and Floater Damping



$$B_{TURBINE}(U) = \frac{dT}{dU}; \quad B_{BUOY} = \frac{1}{2}\rho C_d S \sqrt{\frac{8}{\pi}}\sigma_V;$$

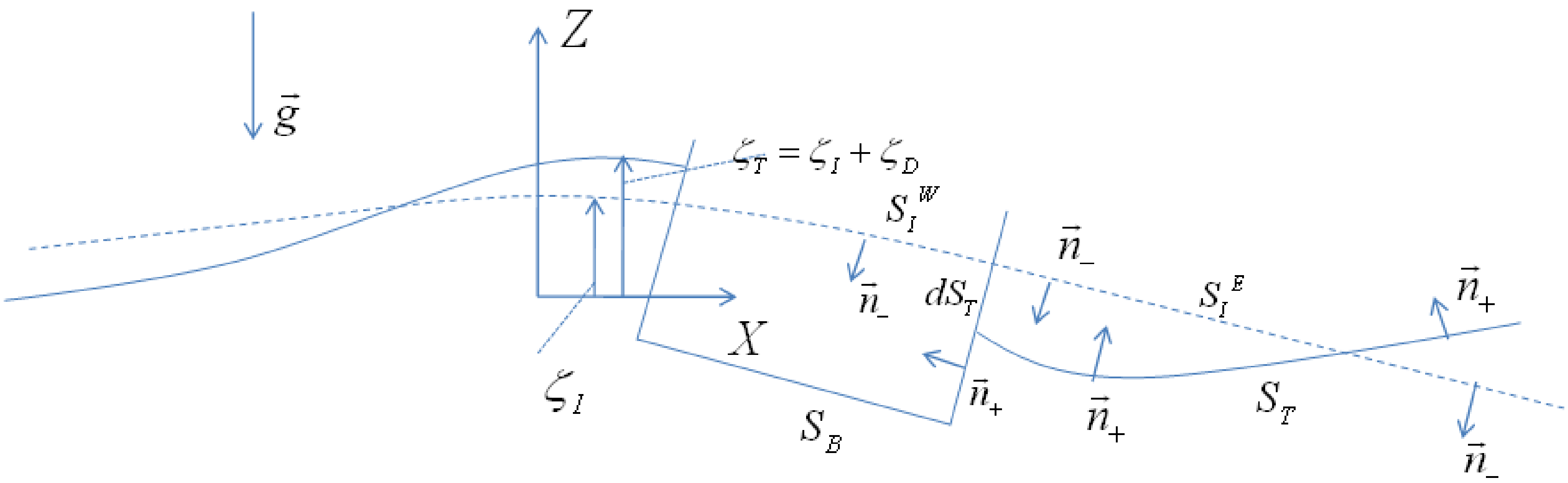
Damping Ratio=0.23 at U=10 m/s; Hs=6m
Damping Ratio=0.15 at U=15 m/s; Hs=6m

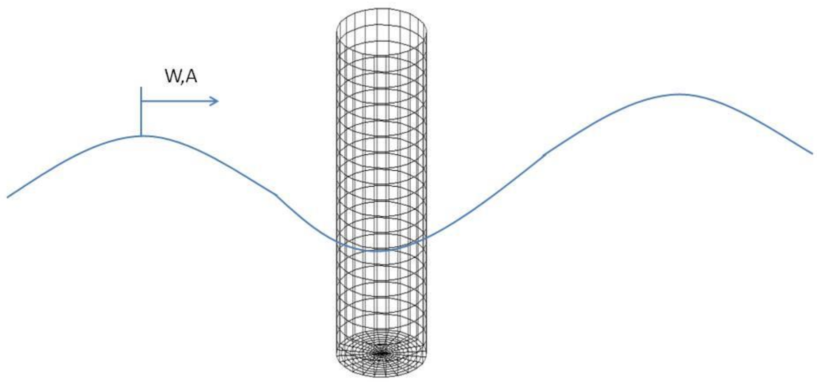
Nielsen et. al. (OMAE, 2006), Jonkman (Wind Energy, 2008)

Wave Energy Extraction Potential – NREL 5MW

NREL – 5 MW – TLP platform					
Buoy characteristics					
		Draft	30 m	Draft	15 m
		Radius	4.75 m	Radius	6.72 m
Depth	**Conditions**	**Additional Power** (+% of turbine power at that wind speed)			
50 m	Sig. Wave H. [**m**]	**6**	**10**	**6**	**10**
	Mean Period [**s**]	**11.6**	**13.6**	**11.6**	**13.6**
	Wind **6** m/s	+3.13%	+8.94%	+4.92%	+13.5%
	Wind **8** m/s	+2.47%	+6.73%	+3.89%	+10.2%
	Wind **10** m/s	+2.29%	+5.59%	+3.58%	+8.33%
100 m	Sig. Wave H. [**m**]	**6**	**10**	**6**	**10**
	Mean Period [**s**]	**11.6**	**13.6**	**11.6**	**13.6**
	Wind **6** m/s	+2.3%	+6.46%	+3.55%	+9.5%
	Wind **8** m/s	+1.74%	+4.83%	+2.69%	+7.11%
	Wind **10** m/s	+1.51%	+4.06%	+2.34%	+5.98%

Nonlinear Time Domain Loads





Cylinder Diameter: d
Wave Amplitude: A
Wavenumber: k

Nonlinear Fluid Impulse Hydrodynamic Force

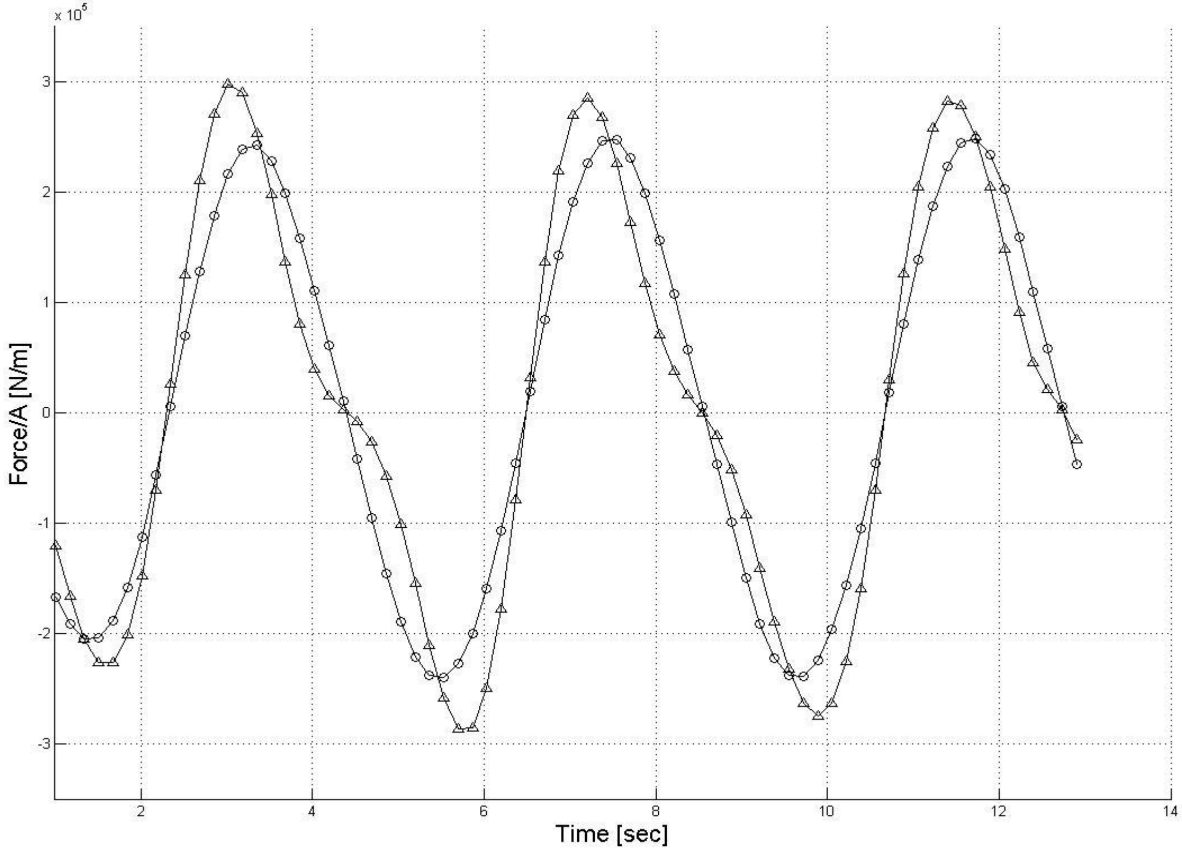
$$\vec{F}(t) = \vec{F}_1(t) + \vec{F}_2(t)$$

$$\vec{F}_1(t) = \underbrace{-\rho g \int_{S_B^W(t)+S_I^W(t)} Z\,\vec{n}\,ds}_{\text{Buoyancy force}} \underbrace{-\rho \frac{d}{dt} \int_{S_B^W(t)+S_I^W(t)} \varphi_I\,\vec{n}\,ds}_{\text{Froude-Krylov Impulse Force}} \underbrace{-\rho \frac{d}{dt} \int_{S_B^W(t)} \varphi_D\,\vec{n}\,ds}_{\text{Radiation and Diffraction Body Impulse Force}}$$

$$\left.\begin{aligned}\vec{F}_2(t) = &-\rho \frac{d}{dt} \int_{S^E{}_I(t)} \varphi_D \vec{n}\,ds - \rho g \vec{k} \int_{S^E{}_I(t)} \zeta_D\,ds \\ &-\rho \frac{d}{dt} \iint_{\upsilon(t)} \left(\nabla \varphi_I + \nabla \varphi_D\right) \mathrm{sgn}\left(\zeta_D\right) d\upsilon\end{aligned}\right\}$$

Radiation and Diffraction
Free Surface Impulse Force
Slow Drift, Springing and
Ringing Loads

Sclavounos (Journal of Fluid Mechanics, 2012)



Nonlinear Surge exciting force in an ambient wave with kA=0.4 and kd=0.9. Triangles: Bernoulli Force; Circles: Body Impulse Force F_1.

Controls

- State-Space Model of Floating Wind Turbine Dynamics
- Unsteady Linear Quadratic Controller – Conjugate Control
- Energy Yield Enhancement by Blade Pitch and Torque Control
- Forecasting of Wave Elevation and Exciting Forces
- Load Mitigation and Damping at Above Rated Wind Speeds
- Energy Yield Increase by LIDAR Forecasting of Wind Speed

State-Space Model of Floater and Wind Turbine Dynamics

- Surge Equation of Motion in the Time-Domain:

$$\left[M + A_\infty\right]\ddot{\xi}(t) + \int_0^t K\left(t-\tau\right)\cdot\dot{\xi}(\tau)\,d\tau + B_V\dot{\xi} + C\xi(t) = X\left(t\right) + F_T(t,\vec{u})$$

$$K\left(s\right) = \frac{p_r s^r + p_{r-1}s^{r-1} + \cdots + p_0}{s^n + q_{n-1}s^{n-1} + \cdots + q_0}$$

- Equation of Motion of Rotor and Generator:

$$I\,\frac{d\Omega}{dt} = T_{Aero}(t,\vec{u}) - \eta T_{Gen}(\Omega); \quad \eta = \Omega_{Gen}\,/\,\Omega; \quad I = I_{Rotor} + \eta^2 I_{Gen}$$

- State-Space Model of System:

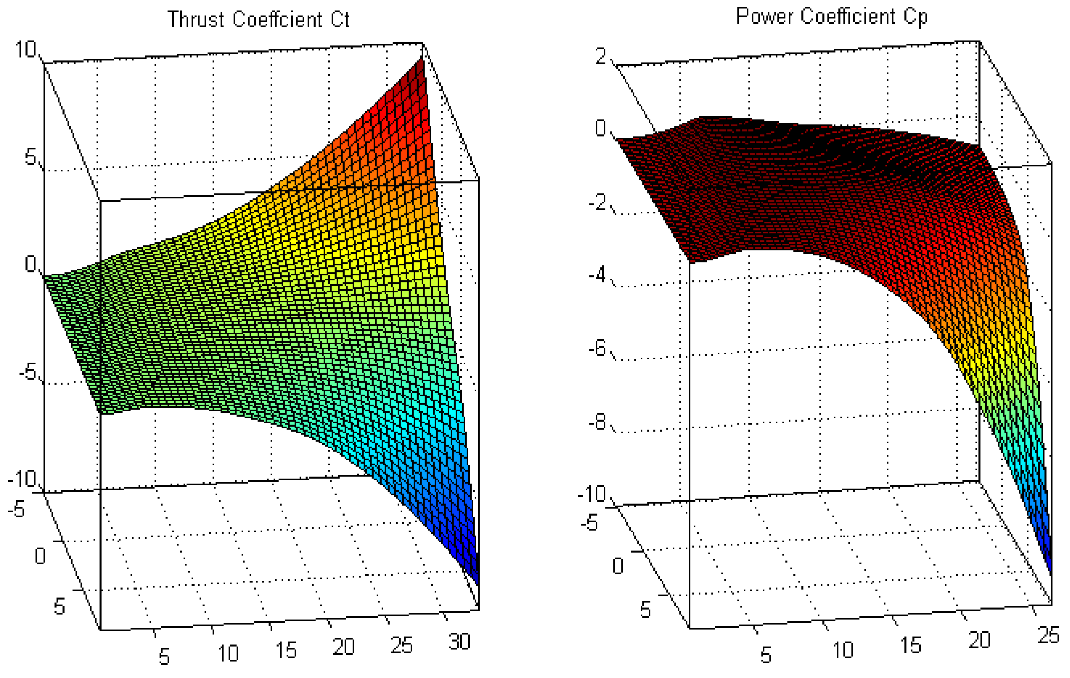
$$\dot{\vec{x}} = [A]\vec{x} + \vec{X} + [B_W]\vec{u}$$

Taghipour, Perez, Moan (Ocean Engineering, 2008)

Aerodynamic Model

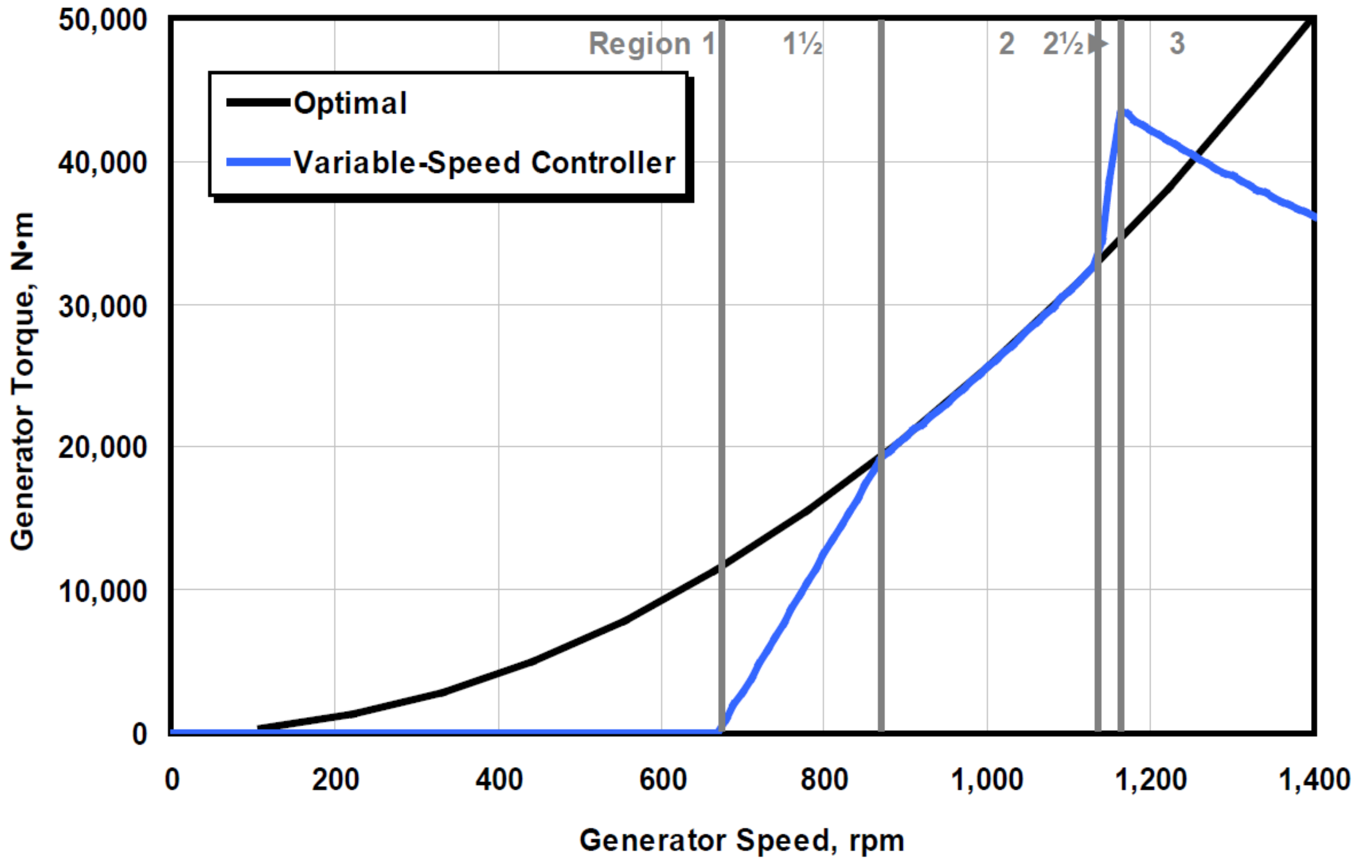
$$T_{Aero} = \frac{P}{\Omega} = \frac{1}{2}\rho_A S_R C_P\left(\lambda,\theta\right)\cdot\frac{\left(V_\infty - \dot{\xi}\right)^3}{\Omega};$$

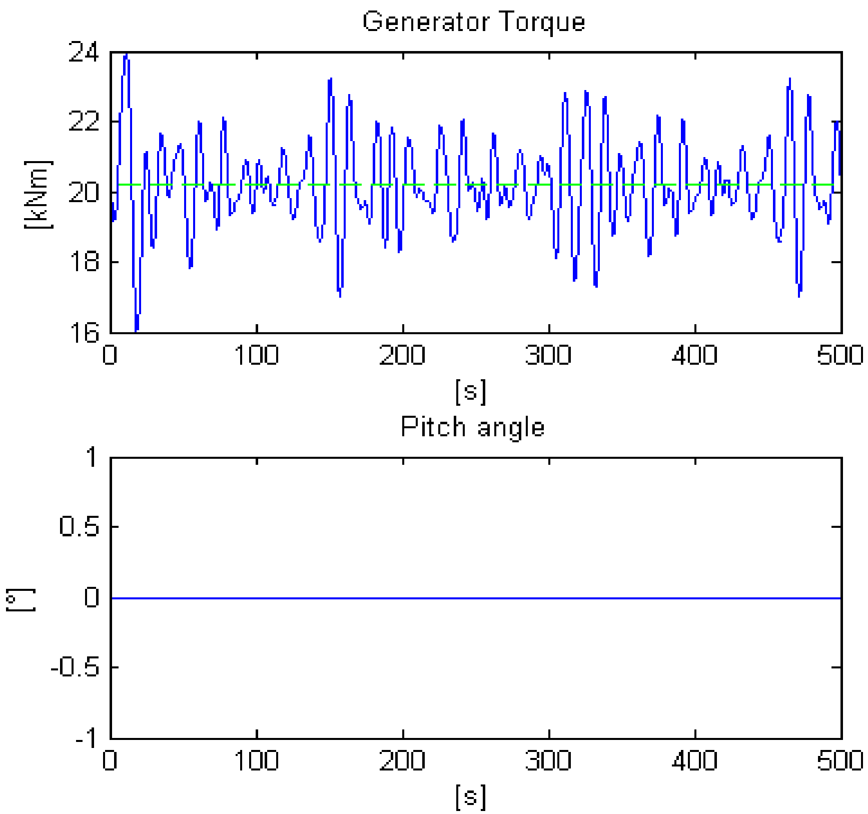
$$F_T = \frac{1}{2}\rho_A S_R C_T\left(\lambda,\theta\right)\cdot\left(V_\infty - \dot{\xi}\right)^2$$



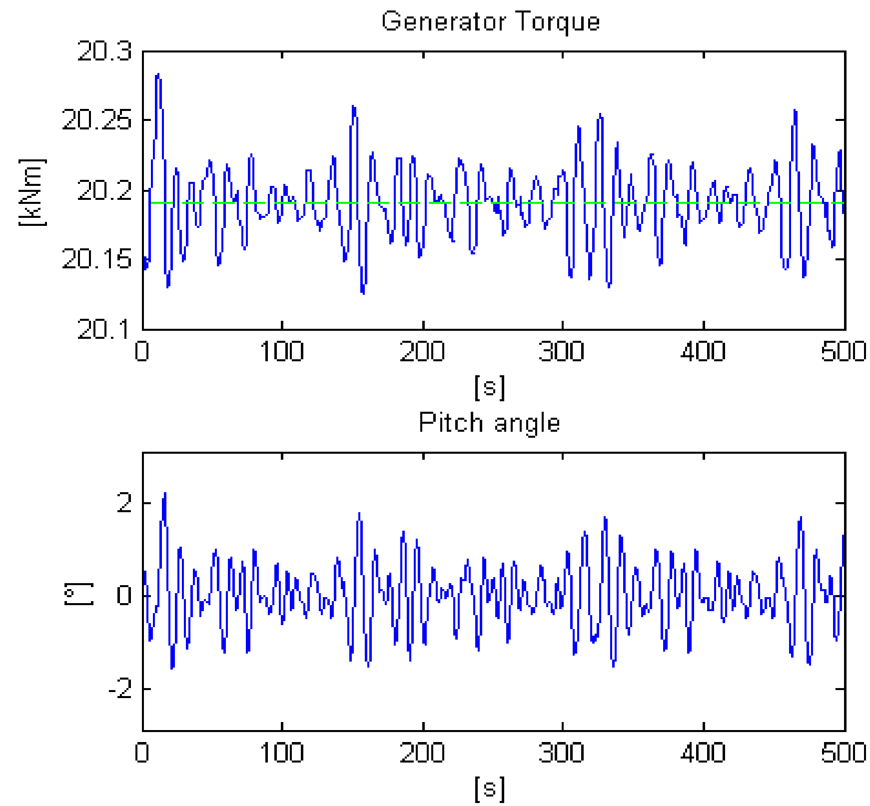
Ct and Cp Surfaces of NREL 5 MW Turbine

NREL Torque Controller

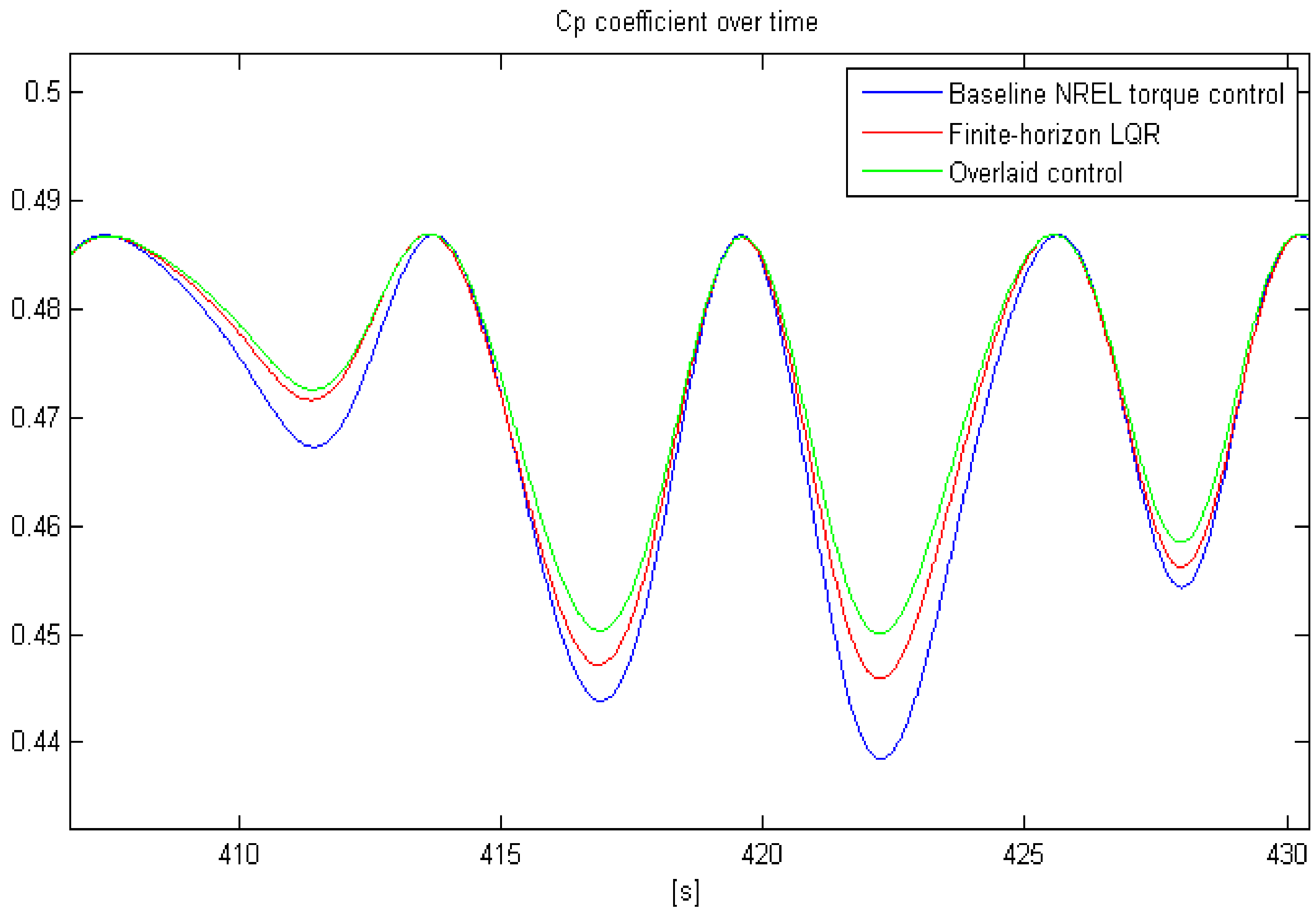




NREL torque controller



Finite-horizon LQR control



Power Coefficient comparison

Comparison of Target to Conjugate Control Energy Yield Increase

H_s	6 m			10 m		
V_∞	6 m/s	8 m/s	10 m/s	6 m/s	8 m/s	10 m/s
Target	+2.3%	+1.74%	+1.51%	+6.46%	+4.83%	+4.06%
Unsteady LQR	+2.952%	+1.595%	+1.261%	+8.306%	+4.889%	+3.927%

Conclusions

- Nonlinear Loads for Bottom Mounted and Floating Turbines
- Unsteady Conjugate Control of Floating Wind Turbines
- Wind Farm Energy Yield Optimization
- Energy Yield Enhancement via LIDAR Wind Speed Forecasts
- Load Mitigation of Floating Wind Turbines
- Optimal Control of Wave Energy Converters