Wind Turbine Control Systems: Current Status and Future Developments

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Agenda

- Background and Overview
- Control of Modern Wind Turbines
- Future Developments in Wind Turbine Control

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The Scope

- Discussing dynamic control of wind turbines.
  - Rapid control of the turbine during operation.
  - Not supervisory control (safety systems, fault monitoring, etc).

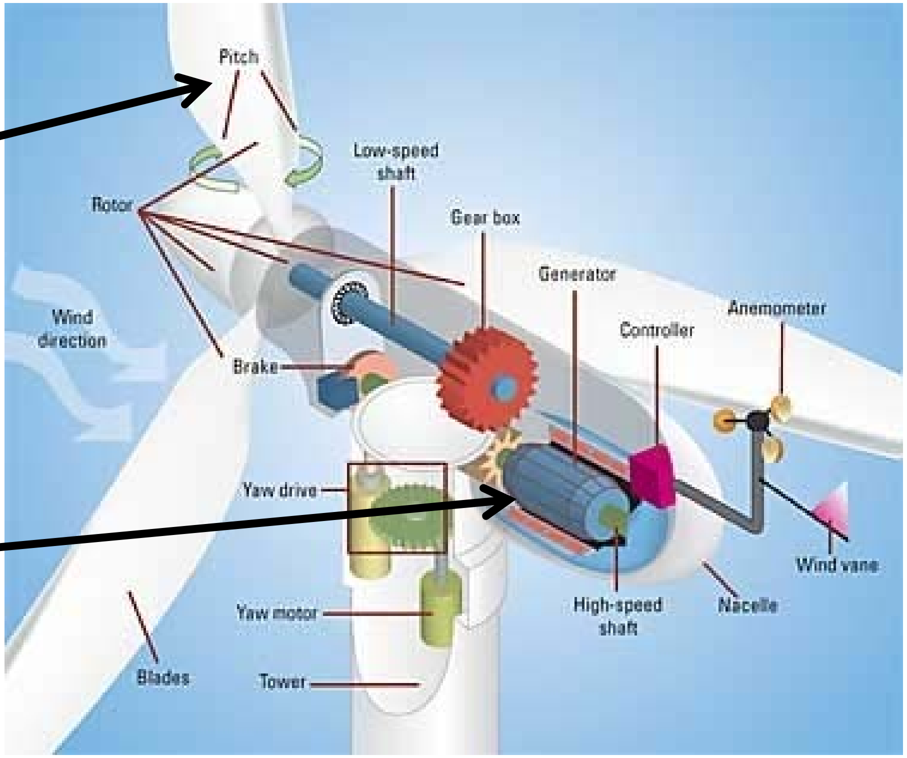
- Primarily focused on modern variable speed, pitch controlled wind turbines.

Control Objectives

- Numerous objectives when controlling a wind turbine:
- Power Regulation
  - Would like to get as much energy out of wind turbine as possible.
- Speed Regulation
  - Noise restrictions limit the tip speeds of wind turbines to ~80 m/s.
- Load Mitigation
  - Ensure that turbine operates safely by limiting the forces.
- Sometimes these objectives conflict.

Control Actuators

- Two major systems for controlling a wind turbine.
- Blade Pitch Control
  - Change orientation of the blades to change the aerodynamic forces.
  - Collective
  - Full span
- Generator Torque Control
  - With a power electronics converter, have control over generator torque.



Wind Turbine Power Production

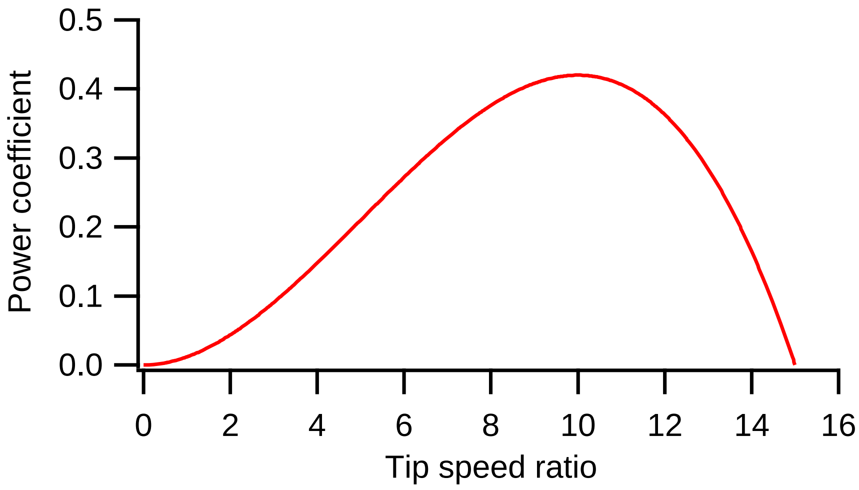
- Two important non-dimensional numbers:

Tip Speed Ratio

$$\lambda = \frac{\Omega R}{U}$$

Power Coefficient

$$C_P = \frac{P}{\frac{1}{2}\rho A U^3}$$



- To maximize power output, want constant optimal tip speed ratio.
  - As wind speed increases, rotor speed increases.

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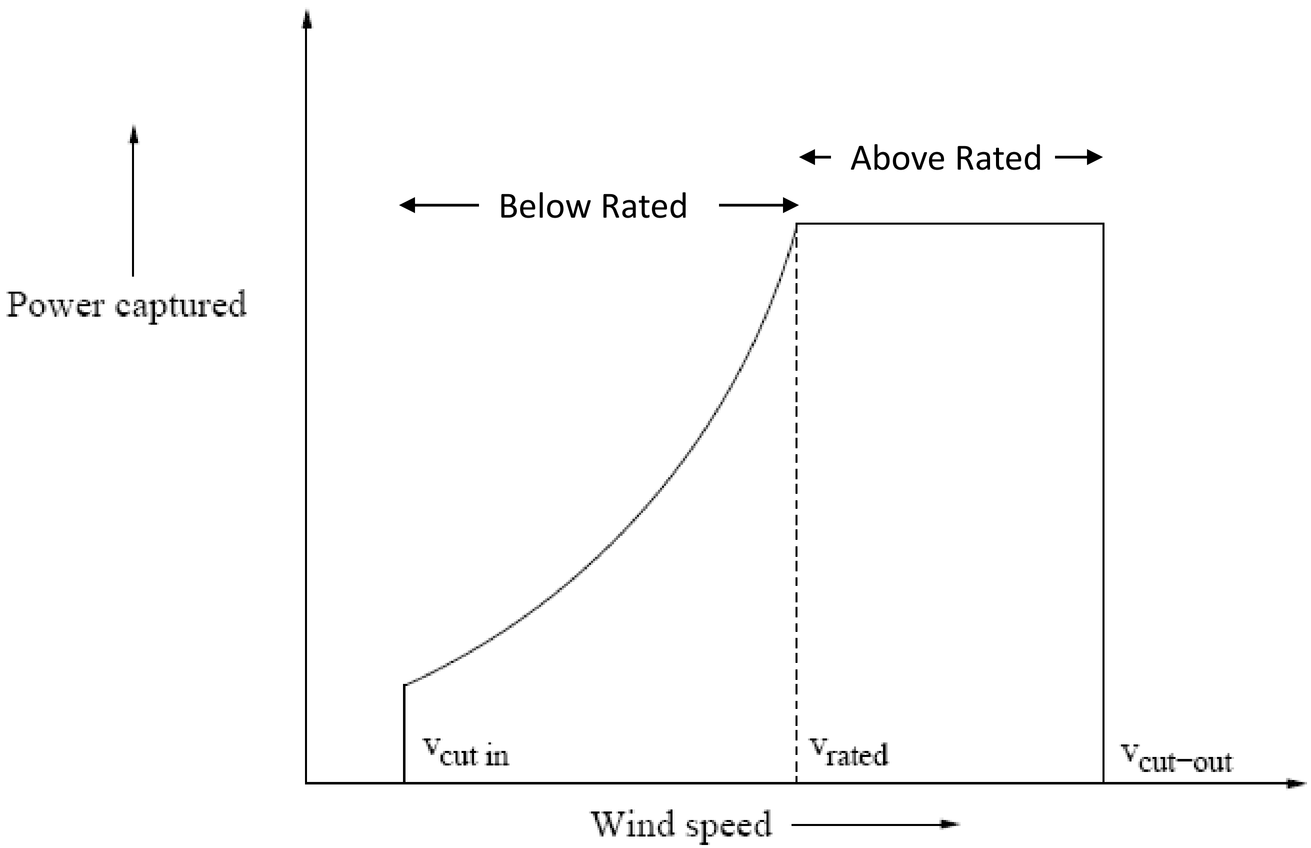
The Power Curve

- Power vs. Wind Speed
- Below Rated: Maximizing power extraction. (Region 2)
- Above rated: Constant power. (Region 3)



Below Rated Operation

- Goal: Maximize power extraction.
- To maximize power output, want optimal power coefficient and so constant tip speed ratio.
- Blade pitch not used. Held constant at one value.
- Use generator torque to control rotor speed for constant tip speed ratio.
- Control law:

$$Q = k\Omega^2$$

- *k* determined for optimal tip speed ratio.
- In practice:
  - Wind speed increases, rotor is spinning too slowly.
  - Aerodynamic torque increases, rotor accelerates.
  - Generator torque increases to capture more power.

Above Rated Operation: Loads and Torque

- Goal in above rated: Constant power output (Limit loads).

$$P = T \cdot U$$

- Generator torque used to produce constant power: $P = Q \cdot \omega$

Control Law: $$Q = \frac{P_{Rated}}{\omega_{Gen} \cdot \eta_{Gen}}$$

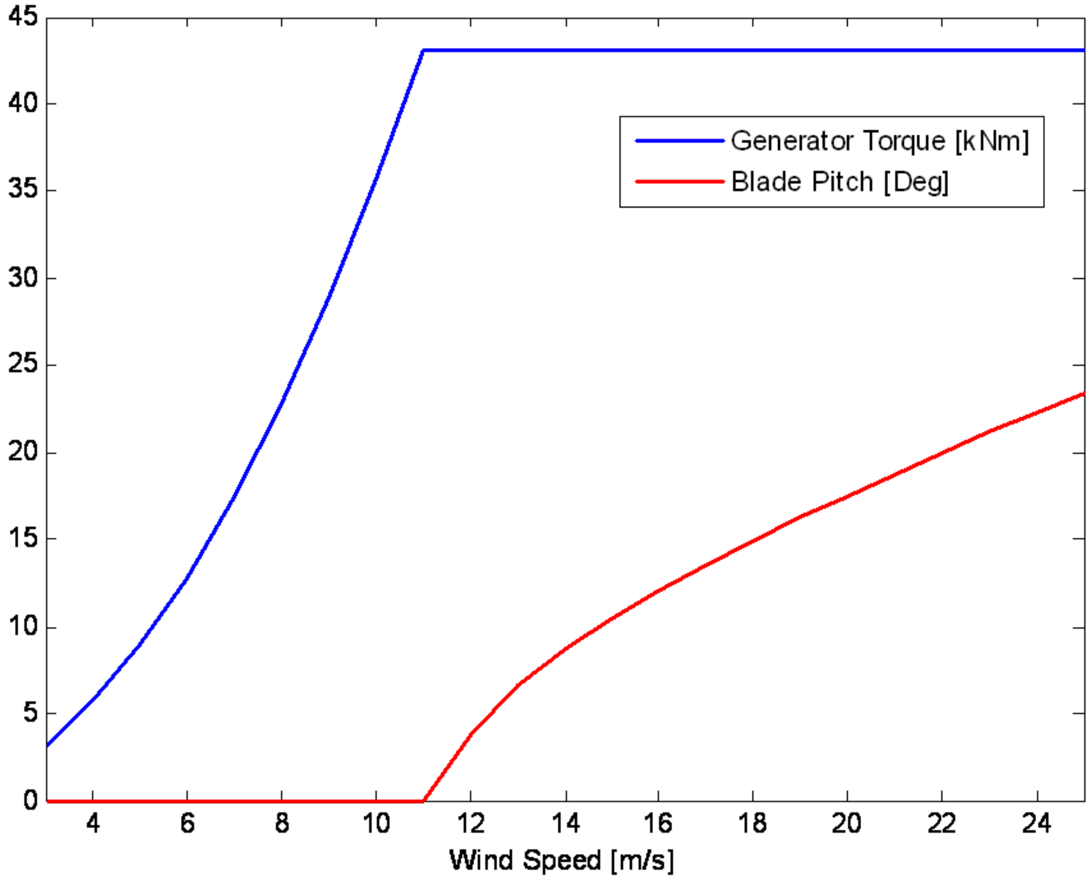
- Responds rapidly to control instantaneous power.

Above Rated Operation: Pitch

- Blade pitch used for constant rotor speed.
- Use to help control average power.
- In practice:
  - "Pitch to Feather": Blades are pitched towards incoming wind as wind speed increases.
    - Angle of attack decreases
    - Forces decrease
    - Sheds power
  - Error signal is: $e = \omega_{Gen} - \omega_{Rated}$
  - PI controllers used to drive *e* to zero.

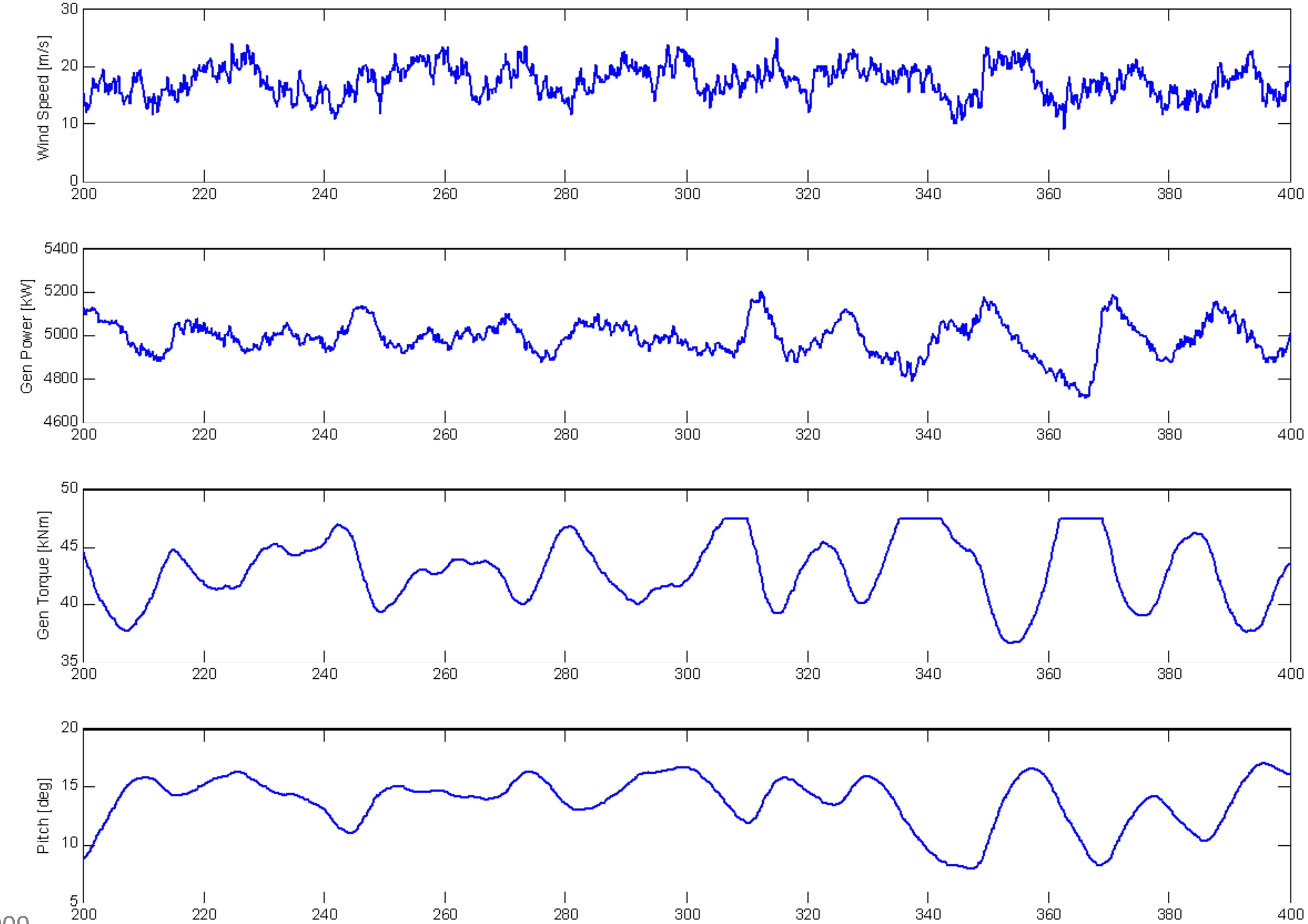
Example Control System Steady State Behavior

- NREL 5 MW reference turbine steady state behavior:



Example Control System Dynamic Behavior

- NREL 5 MW reference turbine dynamic behavior:



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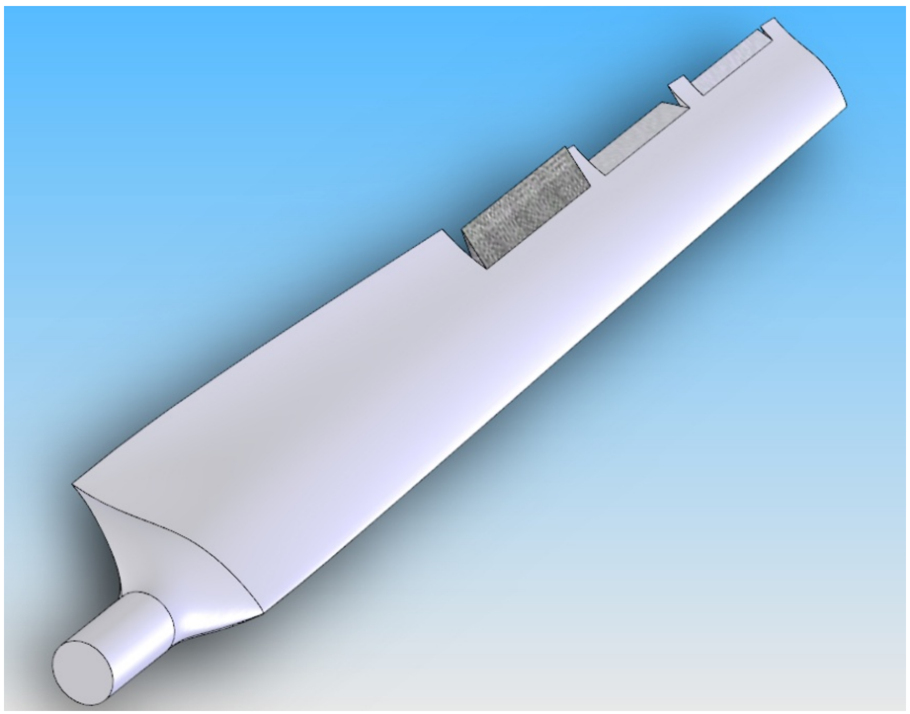
1- Smart Rotor Control of Wind Turbines

Objective of Smart Rotor Control

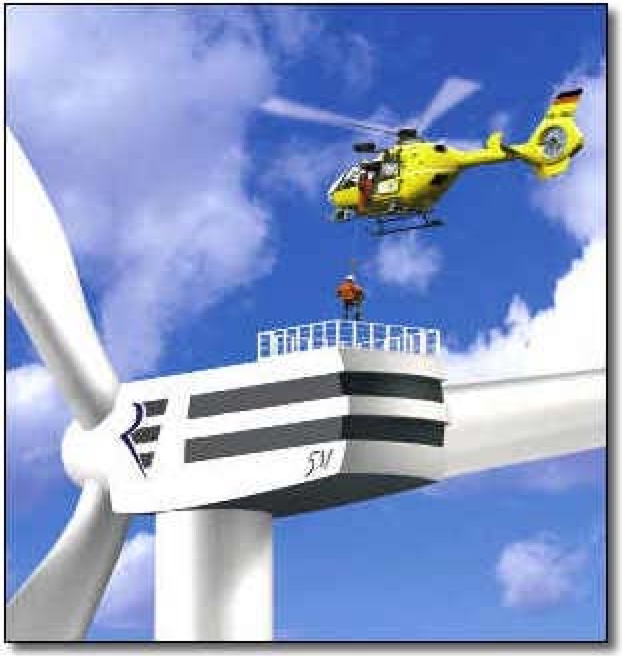
- Objective: Significant reduction of blade loads by applying span-wise-distributed load control devices.

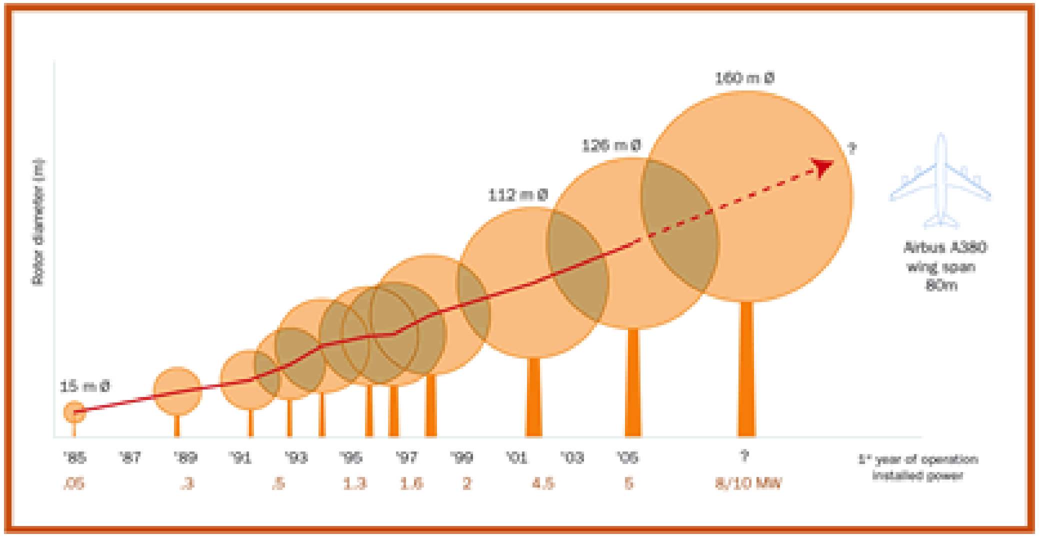


- Faster, local active load control is possible.
- Active feedback control based on local measurements.

Motivation

- Turbines are becoming very large.
  - 5 MW turbine has a 126 m diameter.
- Reduction in blade loads can also reduce the loads in other components:
  - Tower
  - Drive train

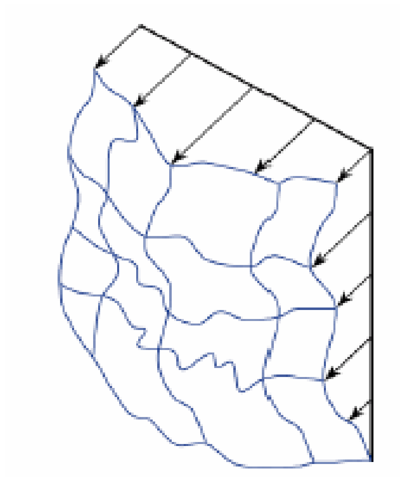




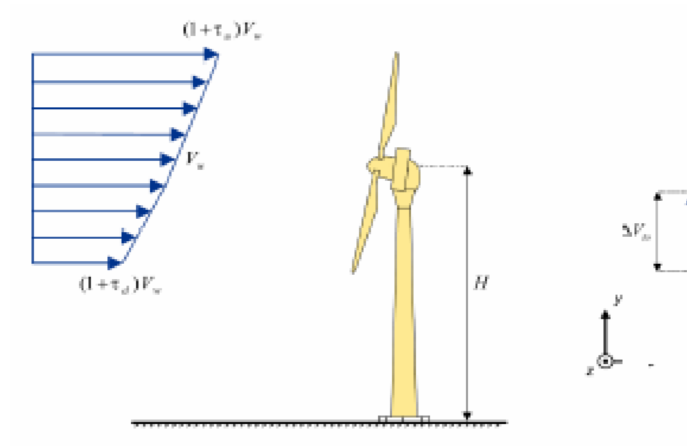
Source: Jos Beurskens, ECN

Sources of Loads

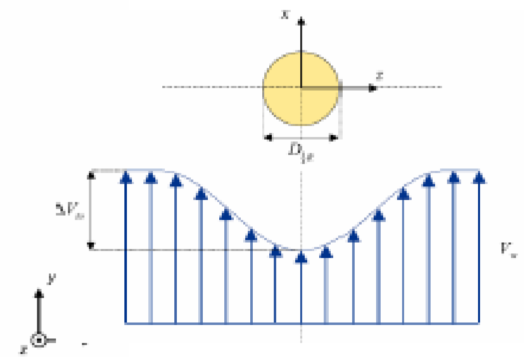
Turbulence



Wind Shear



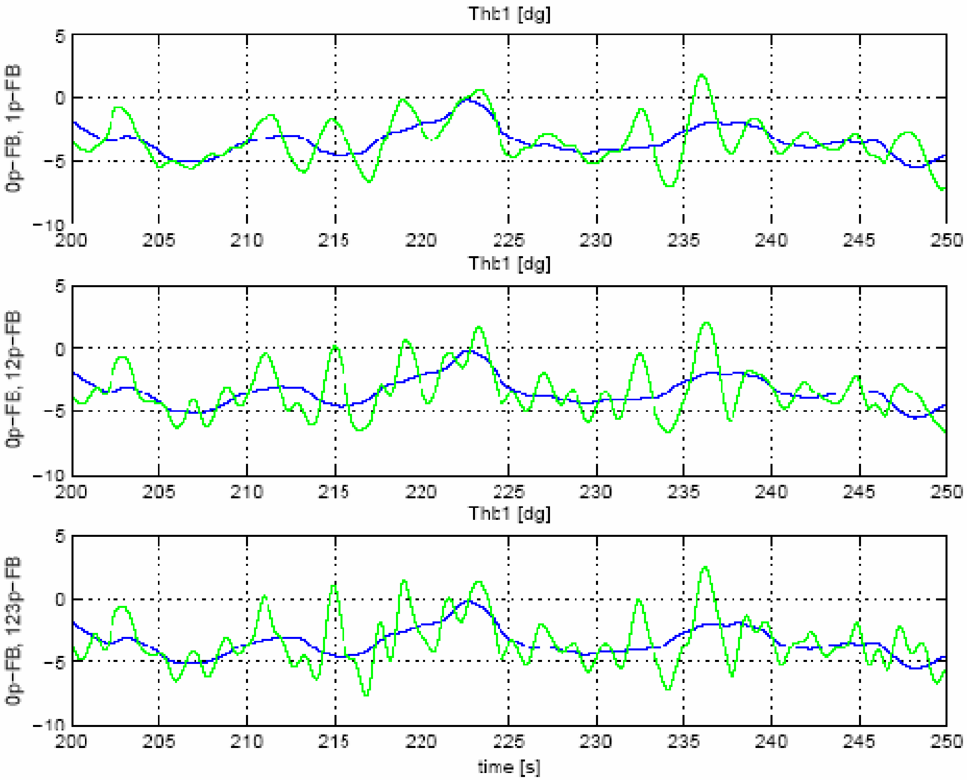
Tower Shadow



- Result is large load on the blades, as well as the drive train and tower.
- Loads especially pronounced at integer multiples of the rotation frequency: 1P, 2P, etc…

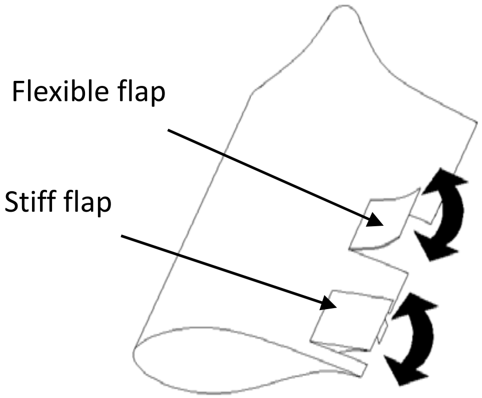
Advanced Current Control Approaches

- Individual pitch control (IPC) can also be used for load reduction.

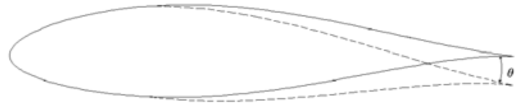


- Problem: Increased demand on the pitch system.

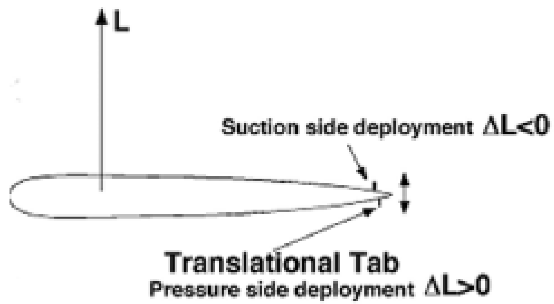
Aerodynamic Load Control Devices



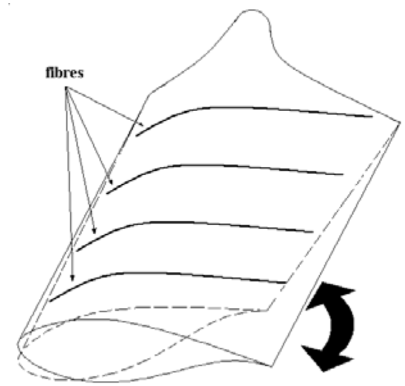
flaps



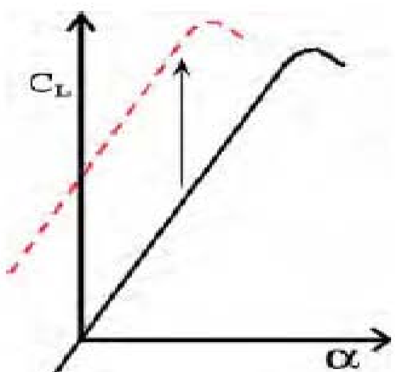
adaptive geometry



microtabs*



active twist



- Shifting of *Cl* curve or change in α

*Van Dam 2001

Example of Successful Smart Rotor Control at Delft

Example Control Approach

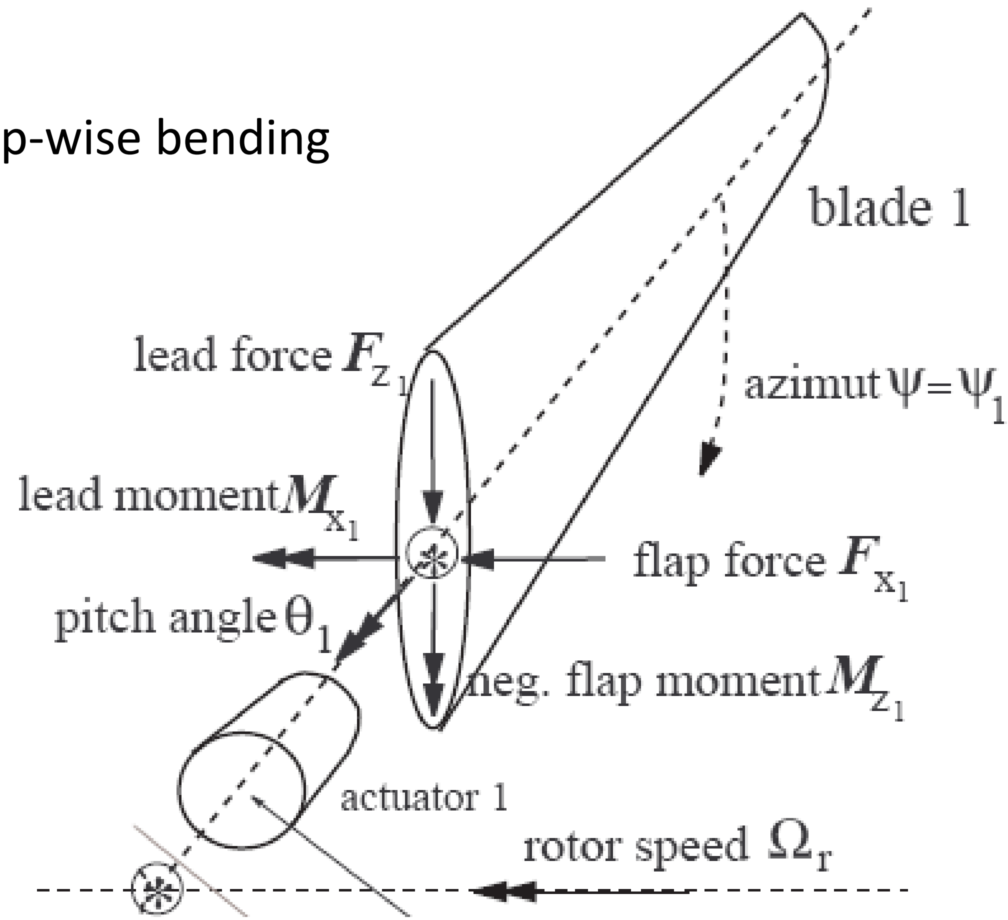
- Trailing edge flap on each blade.

- Objective: Reduce blade root flap-wise bending moment fatigue loads:

$$M_{z1}, M_{z2}, M_{z3}$$

- Utilize flap deflection:

$$\theta_1, \theta_2, \theta_3$$



- Problem: Rotating reference frame.

A Solution: Multi-Blade Transformation

- Map variables in rotating coordinate system into fixed coordinate system.
- Multi-Blade (Coleman) Transformation.

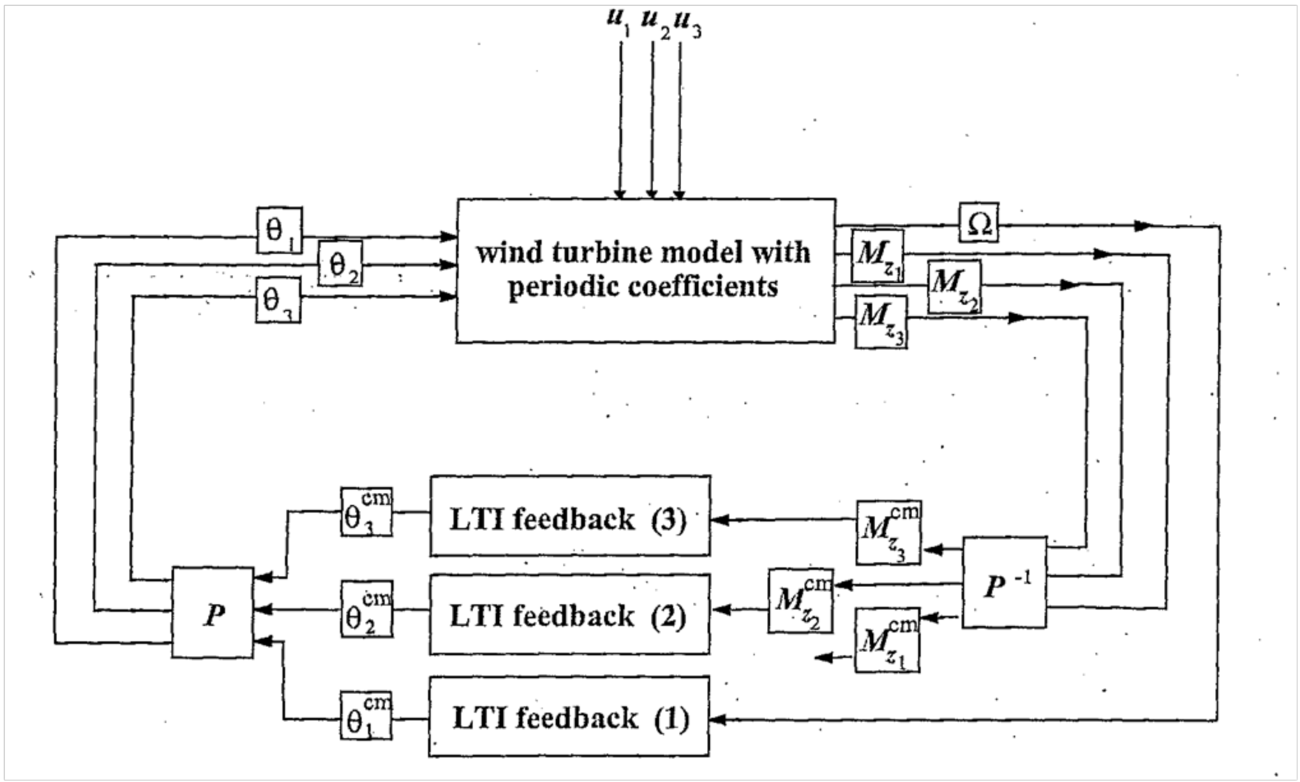
$$\begin{bmatrix}\theta_1(t)\\ \theta_2(t)\\ \theta_3(t)\end{bmatrix} = \begin{pmatrix} 1 & \sin\psi_1(t) & \cos\psi_1(t)\\ 1 & \sin\psi_2(t) & \cos\psi_2(t)\\ 1 & \sin\psi_3(t) & \cos\psi_3(t)\end{pmatrix} \cdot \begin{bmatrix}\theta_1^{cm}(t)\\ \theta_2^{cm}(t)\\ \theta_3^{cm}(t)\end{bmatrix}$$

$$\begin{bmatrix}M_{z_1}^{cm}(t)\\ M_{z2}^{cm}(t)\\ M_{z3}^{cm}(t)\end{bmatrix} = \begin{pmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3}\\ \frac{2}{3}\sin\psi_1(t) & \frac{2}{3}\sin\psi_2(t) & \frac{2}{3}\sin\psi_3(t)\\ \frac{2}{3}\cos\psi_1(t) & \frac{2}{3}\cos\psi_2(t) & \frac{2}{3}\cos\psi_3(t)\end{pmatrix} \cdot \begin{bmatrix}M_{z_1}(t)\\ M_{z_2}(t)\\ M_{z_3}(t)\end{bmatrix}$$

- Variables now mapped into “yaw-wise” and “tilt-wise” axes (independent).
- Time invariant system (LTI).

Feedback Control

1. Measure blade loads.
2. Transform to fixed coordinate system.
3. Two LTI SISO systems for load reduction.
4. Transform back into rotating coordinates.



Summary: Smart Rotor Control

- Simulations show large load reduction potential: ~20% reduction in fatigue loads, some even more.

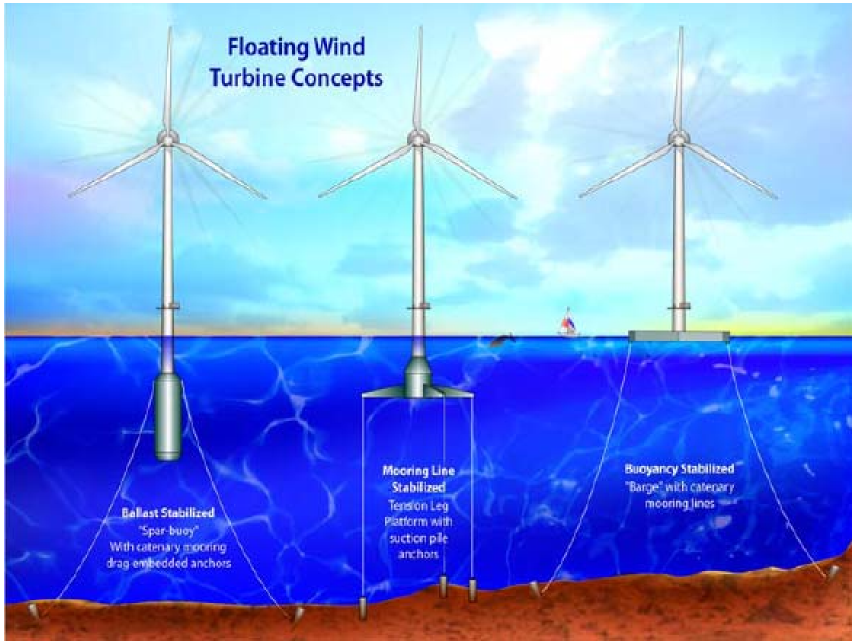
- To exploit full benefit of distributed devices, need distributed sensors for local measurements.
  - Pitot tubes?
  - Accelerometers?

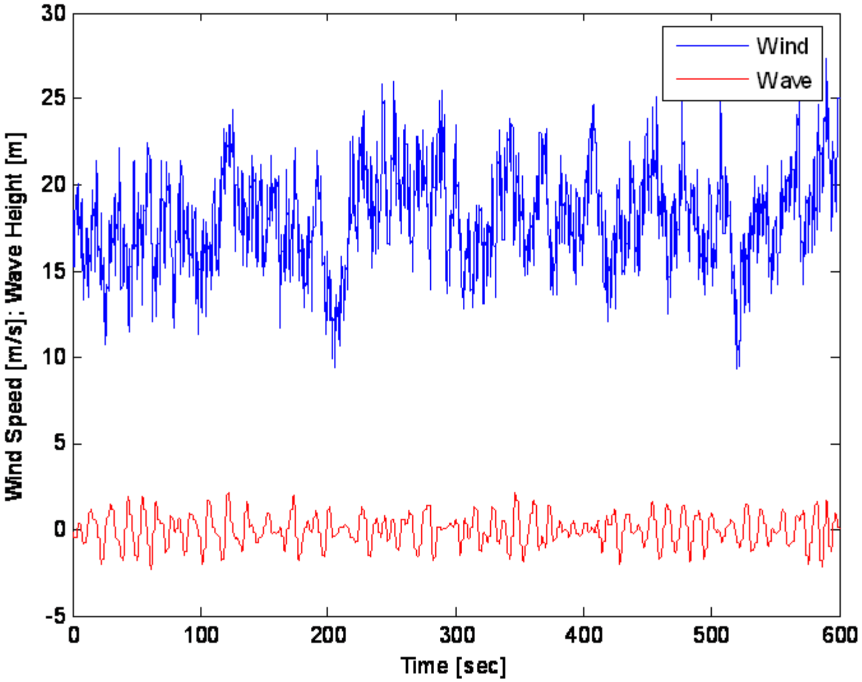
- New and exciting area for control.
  - Challenging control problem and mechanical reliability problem.

Questions?

2 – Control of Floating Wind Turbines

- To be viable, must survive in offshore environment.
- Subjected to wind and wave loads.
- Floating platform leads to motions not present for fixed bottom.
- Bottom line: Imperative that loads and motions on floating turbines are acceptable.

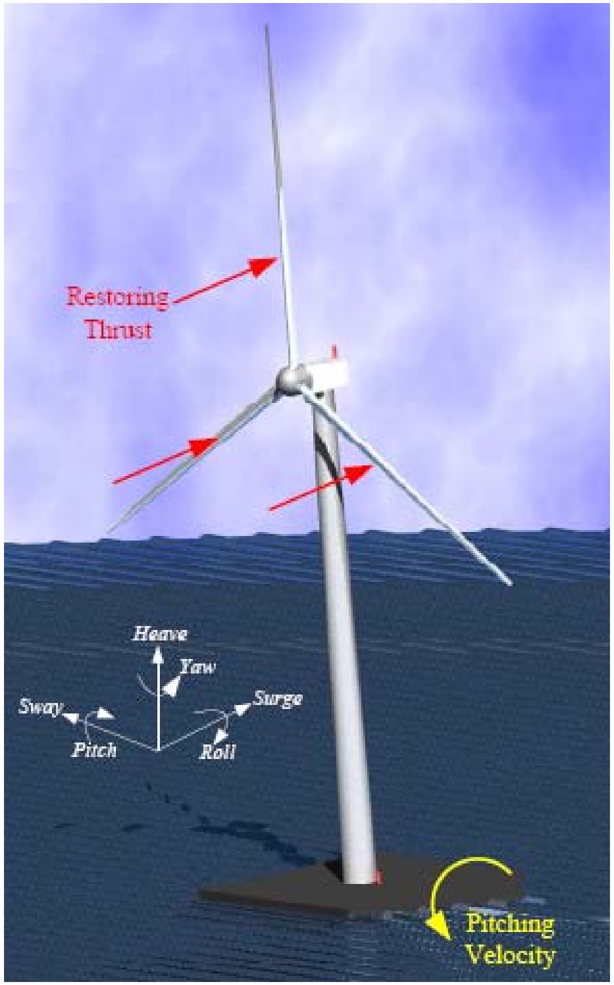




*Butterfield et al., "Engineering Challenges for Floating Offshore Wind Turbines" 2007.

Dynamics and Control

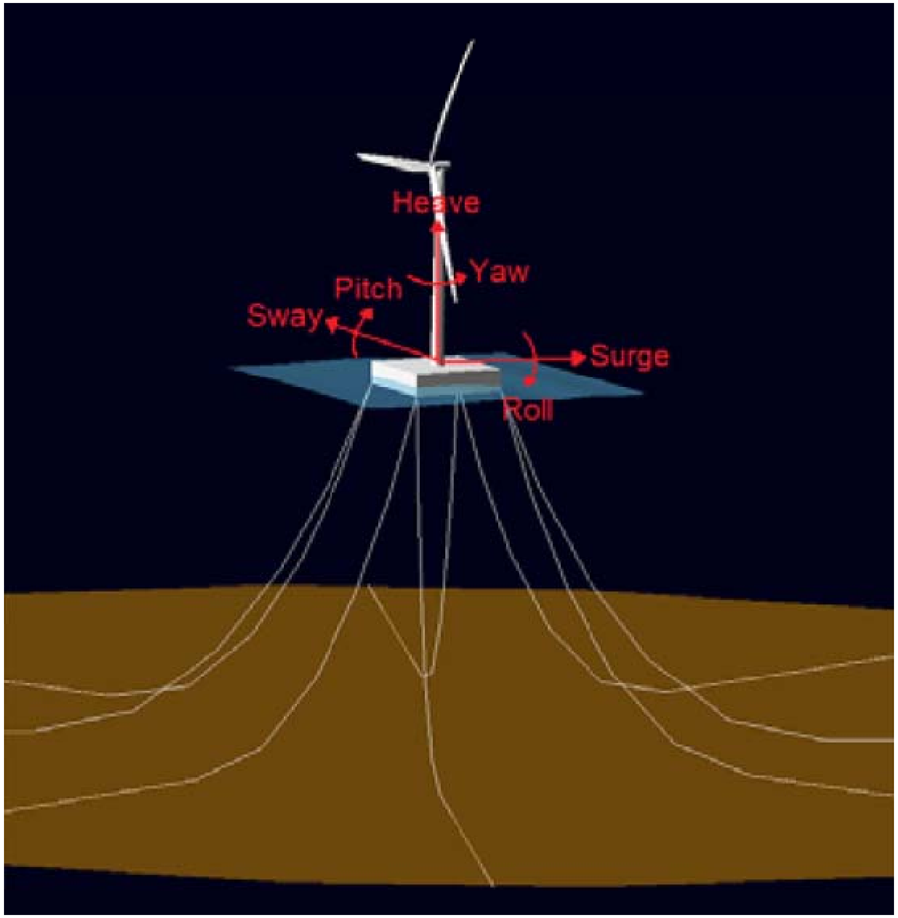
- Motion of platform leads to a more complex dynamic system.
- Conventional Above Rated Pitch Control System:
  - Pitch to feather.
  - Thrust decreases as wind speed increases to produce constant power.
- Conventional Pitch System with a Floating Turbine:
  - Wave motion causes platform to pitch forward
  - Relative wind speed at the rotor increases.
  - Control system pitches blades to feather.
  - Rotor thrust decreases.
  - Platform motion is exacerbated.
- Control system introduces a negative damping term: large motions and loads result.



*Namik et al., "Periodic State Space Control of Floating Wind Turbines" 2009.

Simulation Model

- Wind turbine: NREL 5 MW
  - 3 bladed, upwind, variable speed, pitch controlled.
  - 126 m rotor diameter, 90 m hub height.
- ITI Energy Barge
  - Buoyancy stabilized barge.
  - 40 m x 40 m x 10 m.

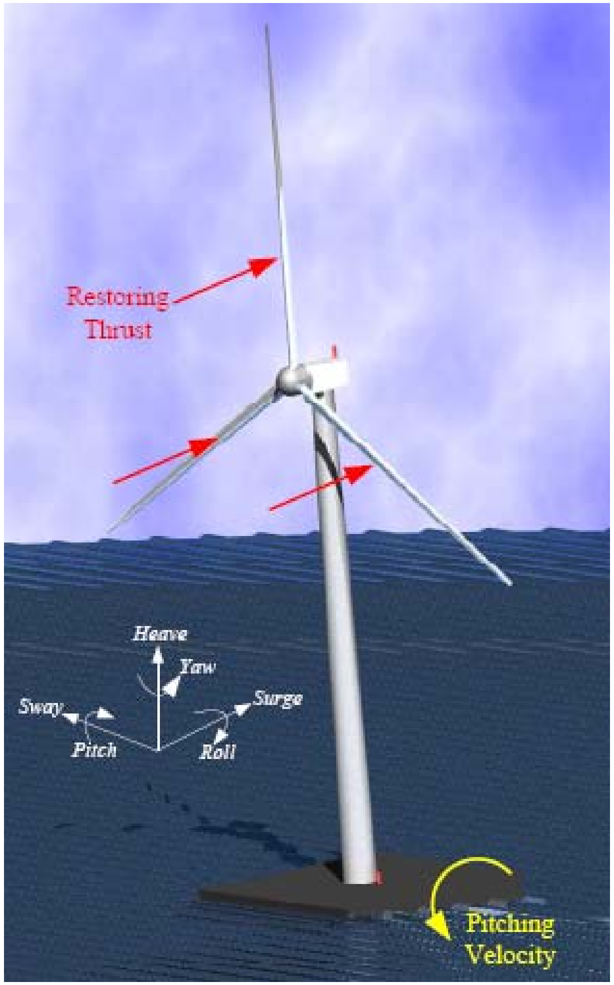


*Jonkman., "Influence of Control on the Pitch Damping of a Floating Wind Turbine" 2007.

Control Approach I: Variable Power Pitch Control

Principle:

- When platform pitches forward, extract more energy from the wind.
  - Increase thrust.
- When platform pitches backward, extract less energy from the wind.
  - Decrease thrust.
- Alter pitch system to increase platform damping.



*Namik et al., "Periodic State Space Control of Floating Wind Turbines" 2009.

VPPC Results

- Metrics compared to the baseline controller with constant generator torque.