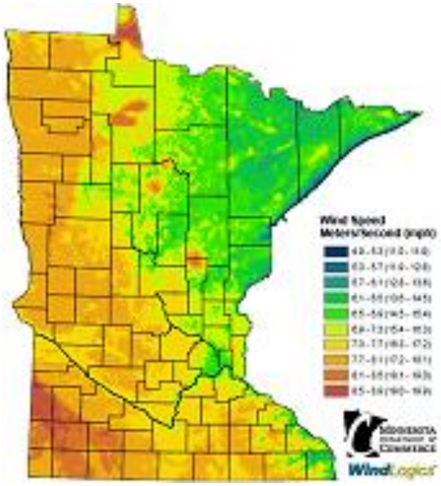
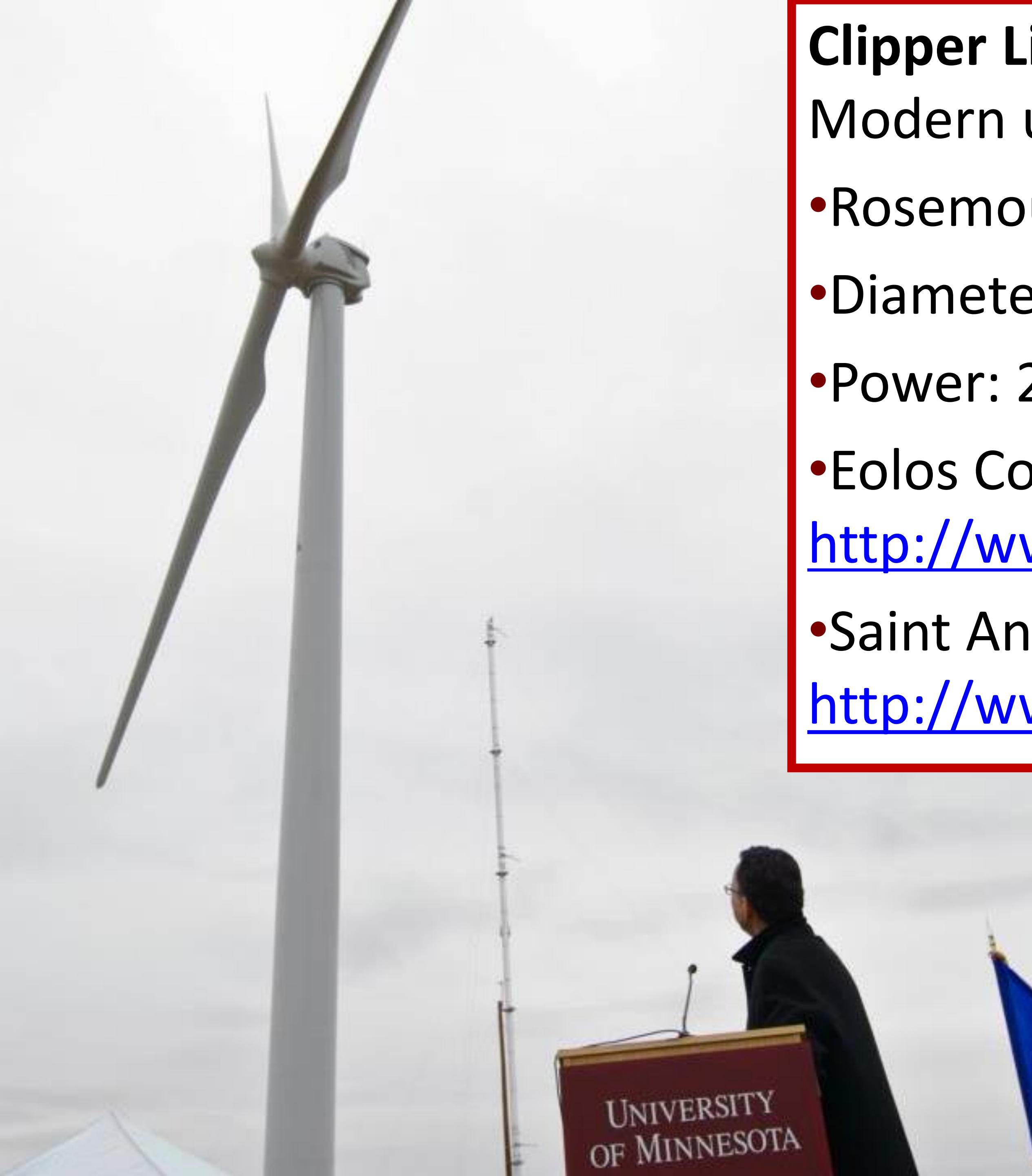
# Control-Oriented Modeling for Wind Farms

Peter Seiler
Aerospace Engineering & Mechanics
University of Minnesota

Students: Jen Annoni, Kevin Howard, Shu Wang
Collaborators: Michele Guala, Fotis Sotiropoulos, Xiaolei Yang








**Clipper Liberty, 2012**:
Modern utility-scale turbine.

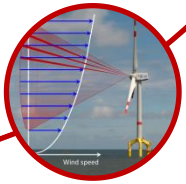
- Rosemount, MN.
- Diameter: 96m
- Power: 2.5MW
- Eolos Consortium: http://www.eolos.umn.edu/
- Saint Anthony Falls Lab: http://www.safl.umn.edu/

# Trends in Wind Energy

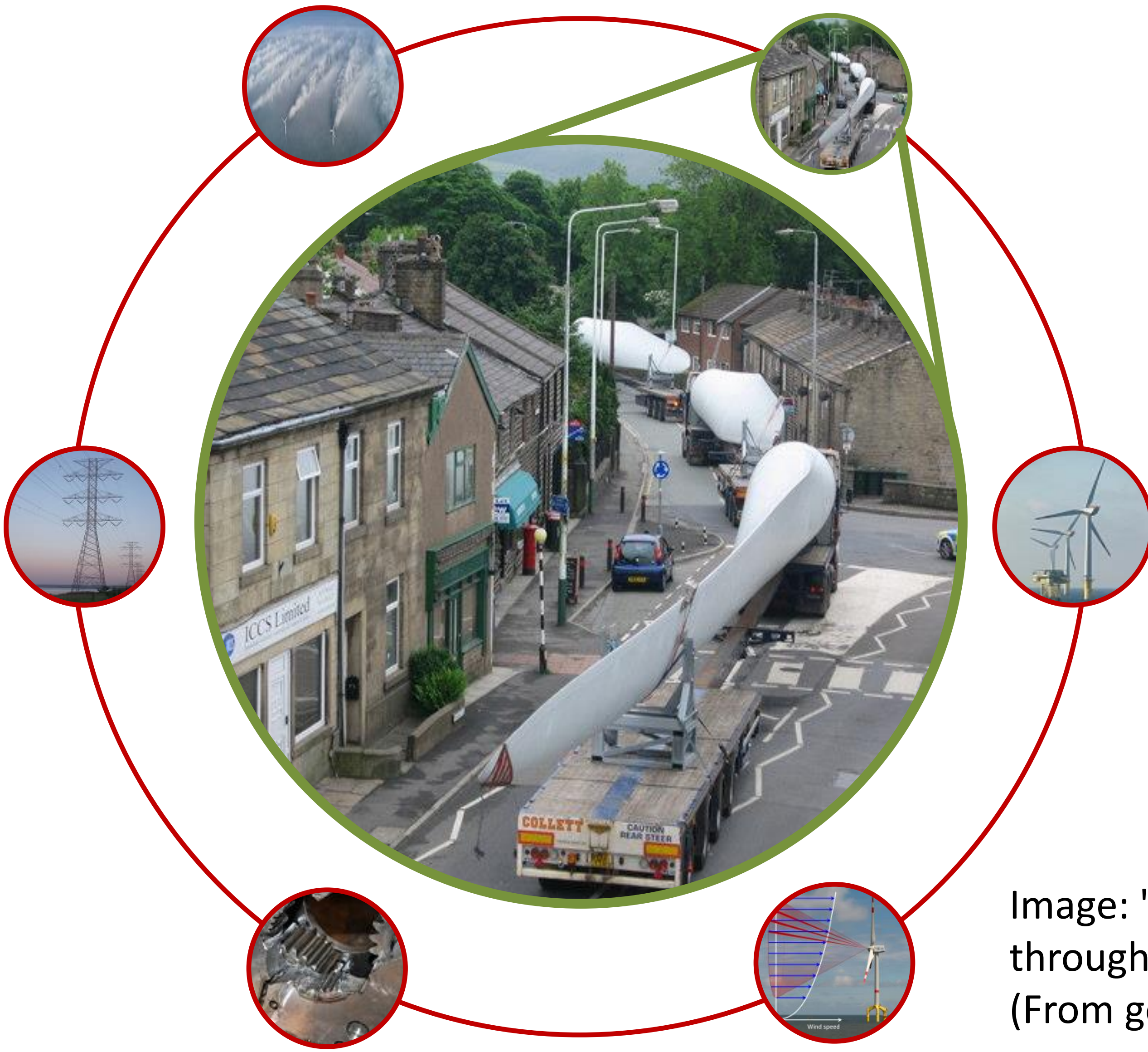

**Key Issues:**

1. Structural Design
2. Available Wind Resources
3. Improved Efficiency
4. Installation & Maintenance Costs
5. Grid Integration
6. Turbine/Turbine Interactions



# Trends in Wind Energy




**1. Structural Design**

- Larger turbines
- New materials for tower / blades
- Aeroacoustics
- Passive Films
- Transportation

**Refs:** Cotrell, Stehly, Tangler, Moriarty

Image: "Turbine Blade Convoy Passing through Edenfield" by Paul Anderson (From geograph.org.uk.)

# Trends in Wind Energy

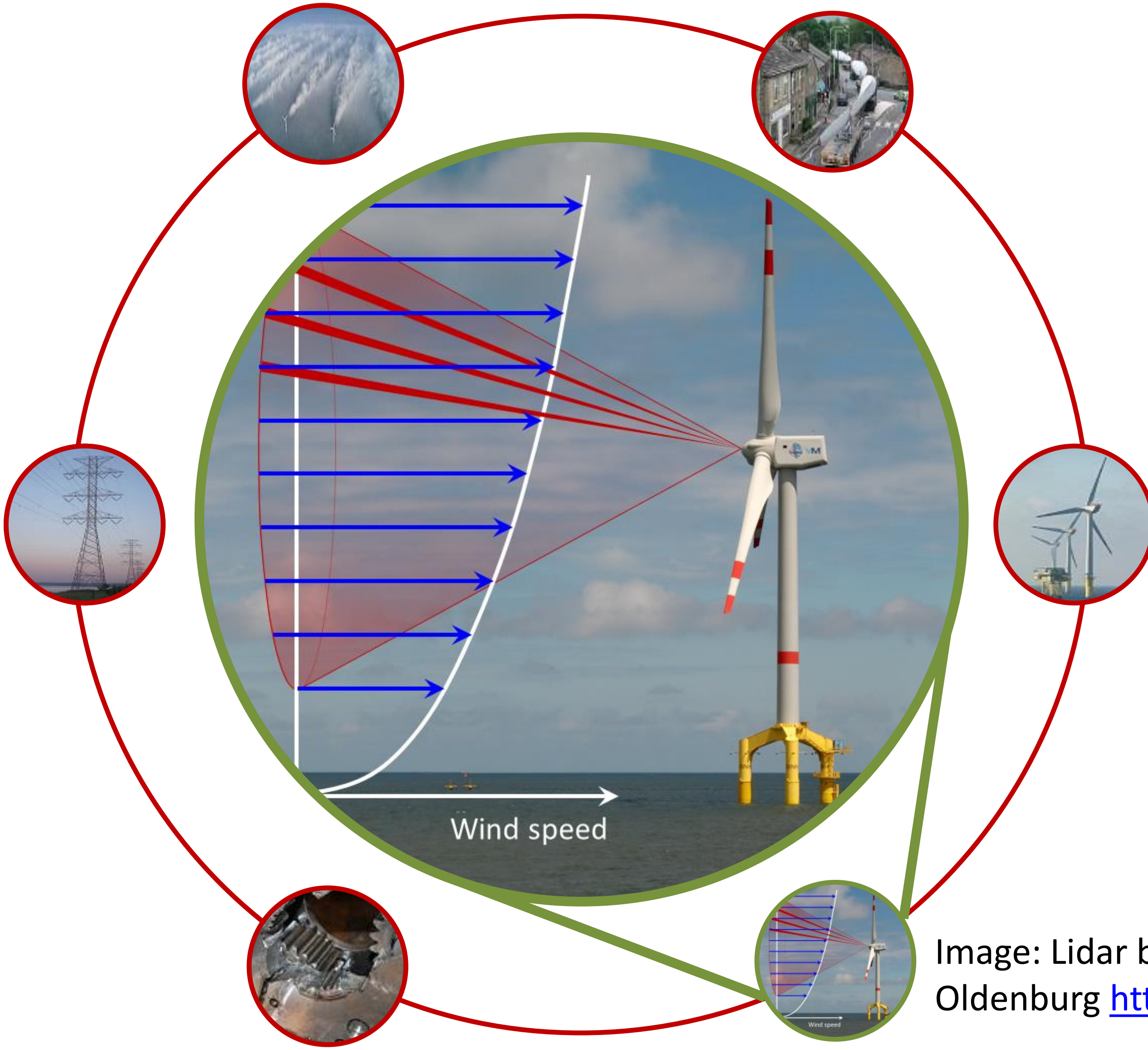
## 2. Available Wind Resources

- Off-shore
- Vertical axis
- Airborne (Kites)
- Inter-annual variability
- Environmental impacts

**Refs:** Rotea, Dabiri, Goldstein, Archer

Image: "Alpha Ventus Windmills" by SteKrueBe (From Wikipedia “Offshore Wind Power”)

# Trends in Wind Energy



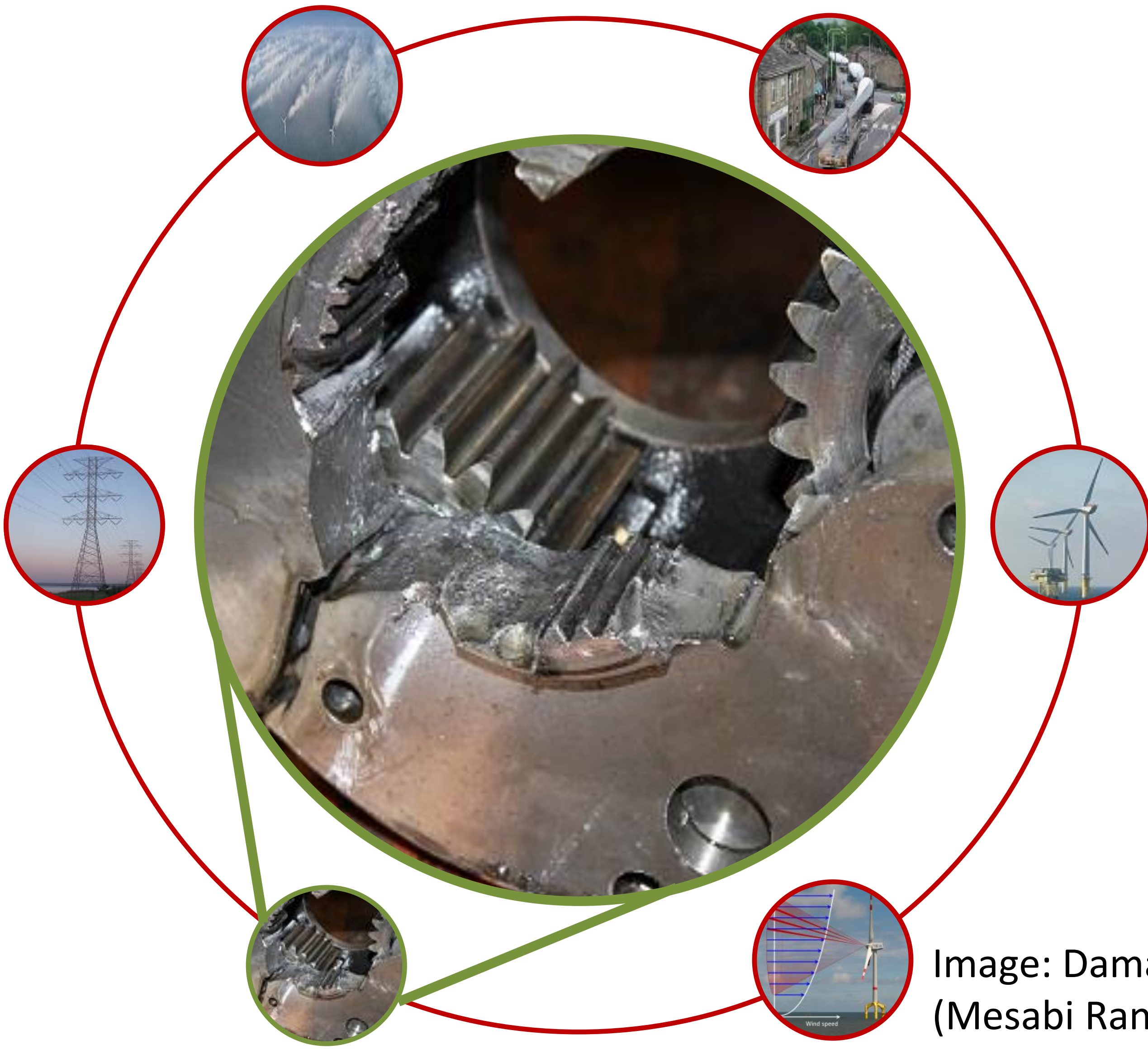

**3. Improved Efficiency**

- Advanced controls
- New sensors (Lidar)
- Novel actuators (microflaps)

**Refs:** Schlipf, Johnson, Pao, Balas, Fingersh, Wang, Harris, Hand, Houtzager

Image: Lidar by Dr. Rainer Reuter, University of Oldenburg http://las.physik.uni-oldenburg.de/

# Trends in Wind Energy



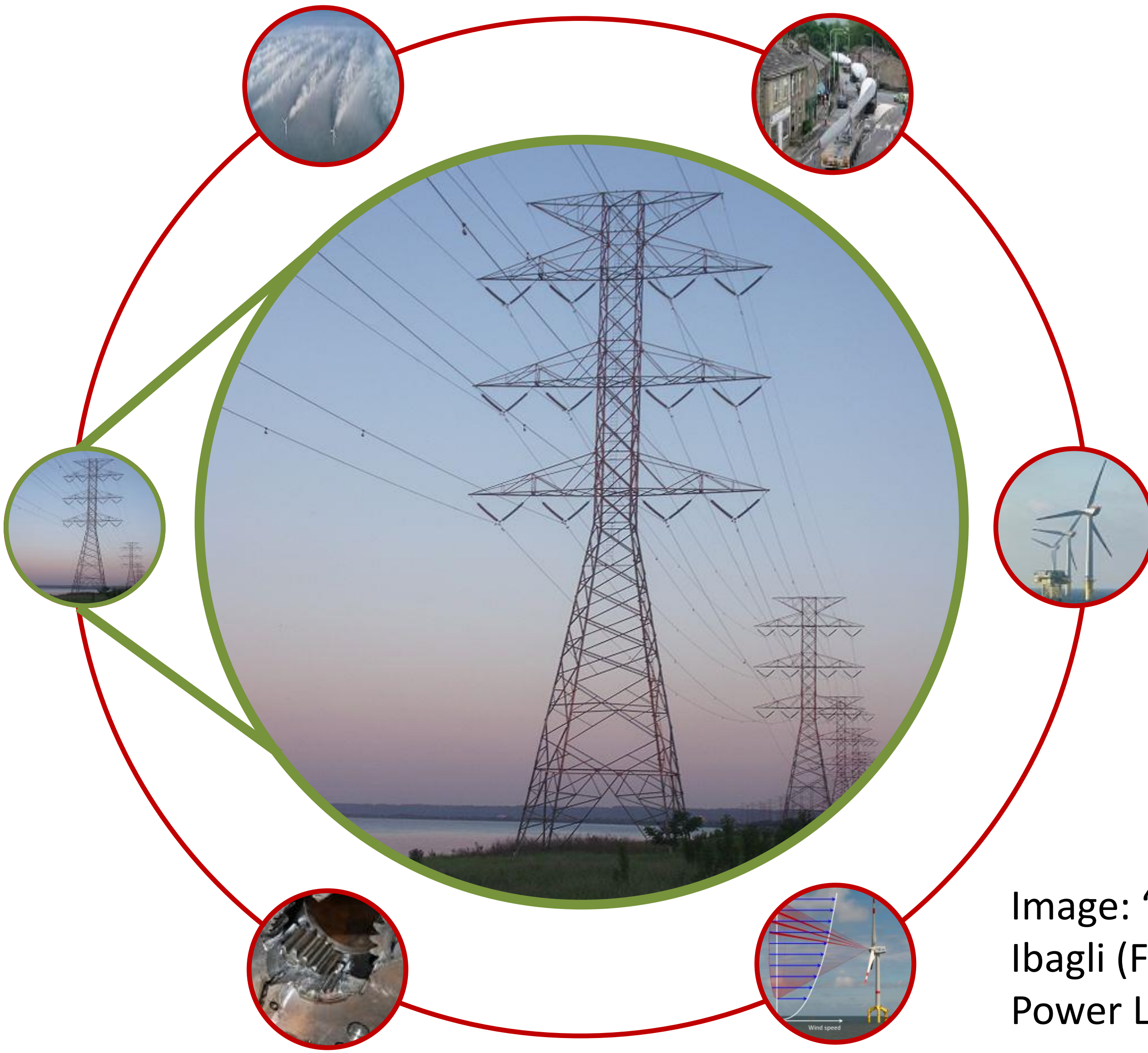
**4. Installation & Maintenance Costs**

- Health Monitoring & Prognostics
- Fault Detection & Isolation
- Fault Tolerant Control

**Refs:** FDI/FTC Competitions, Ozdemir, Lim, Seiler, Rezaei, Johnson, Odgaard

Image: Damaged gear teeth, by Dan Janisch (Mesabi Range Wind Technology Program).

# Trends in Wind Energy



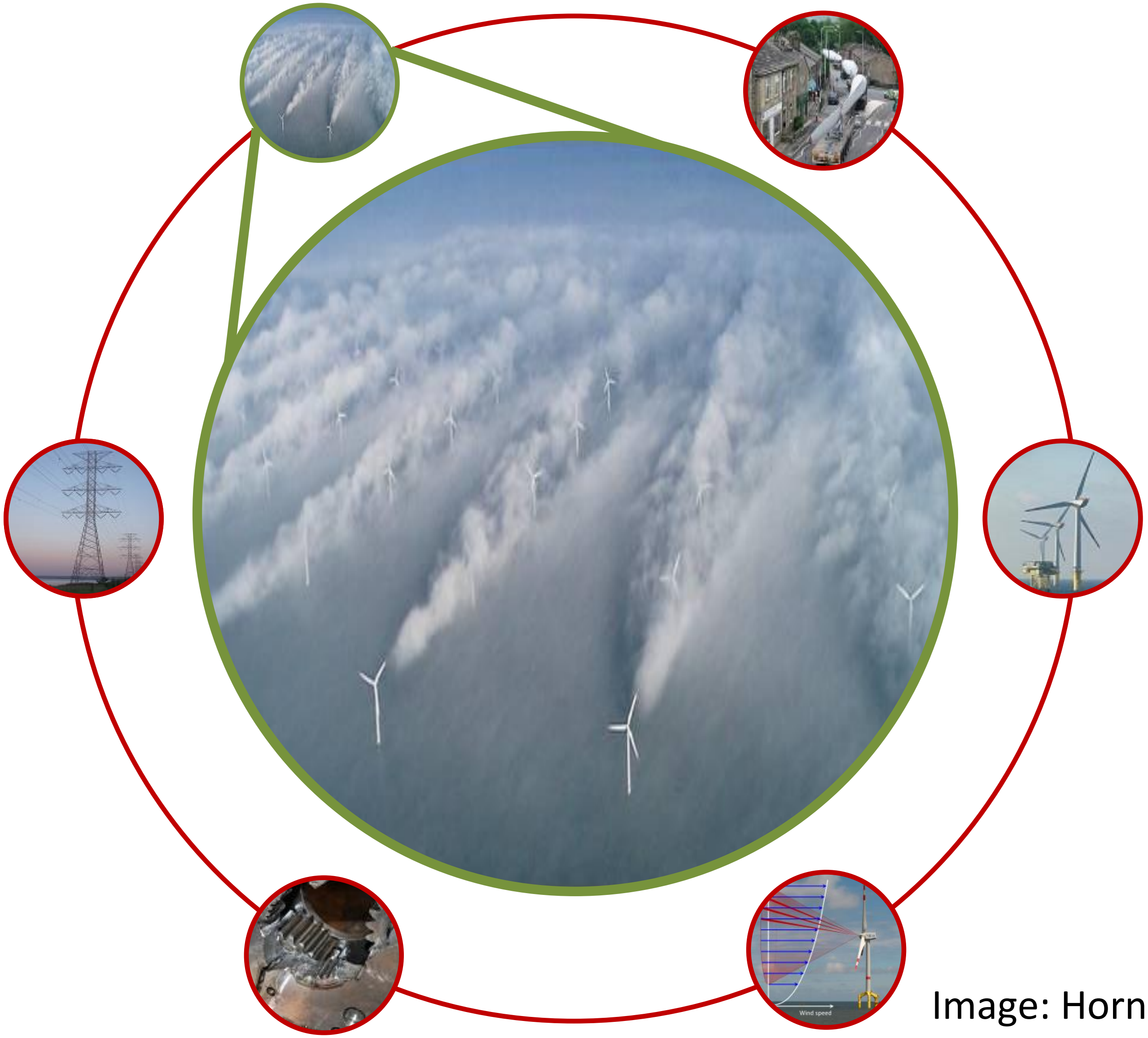
**5. Grid Integration**

- Active Power Control
- Emulated Inertia
- Ancillary Services

**Refs:** Aho, Pao, Johnson, Fleming, Wright, Wang, Buckspan, Jeong

Image: “Hamilton Beach Pylon" by Ibagli (From Wikipedia “Overhead Power Line”)

# Trends in Wind Energy



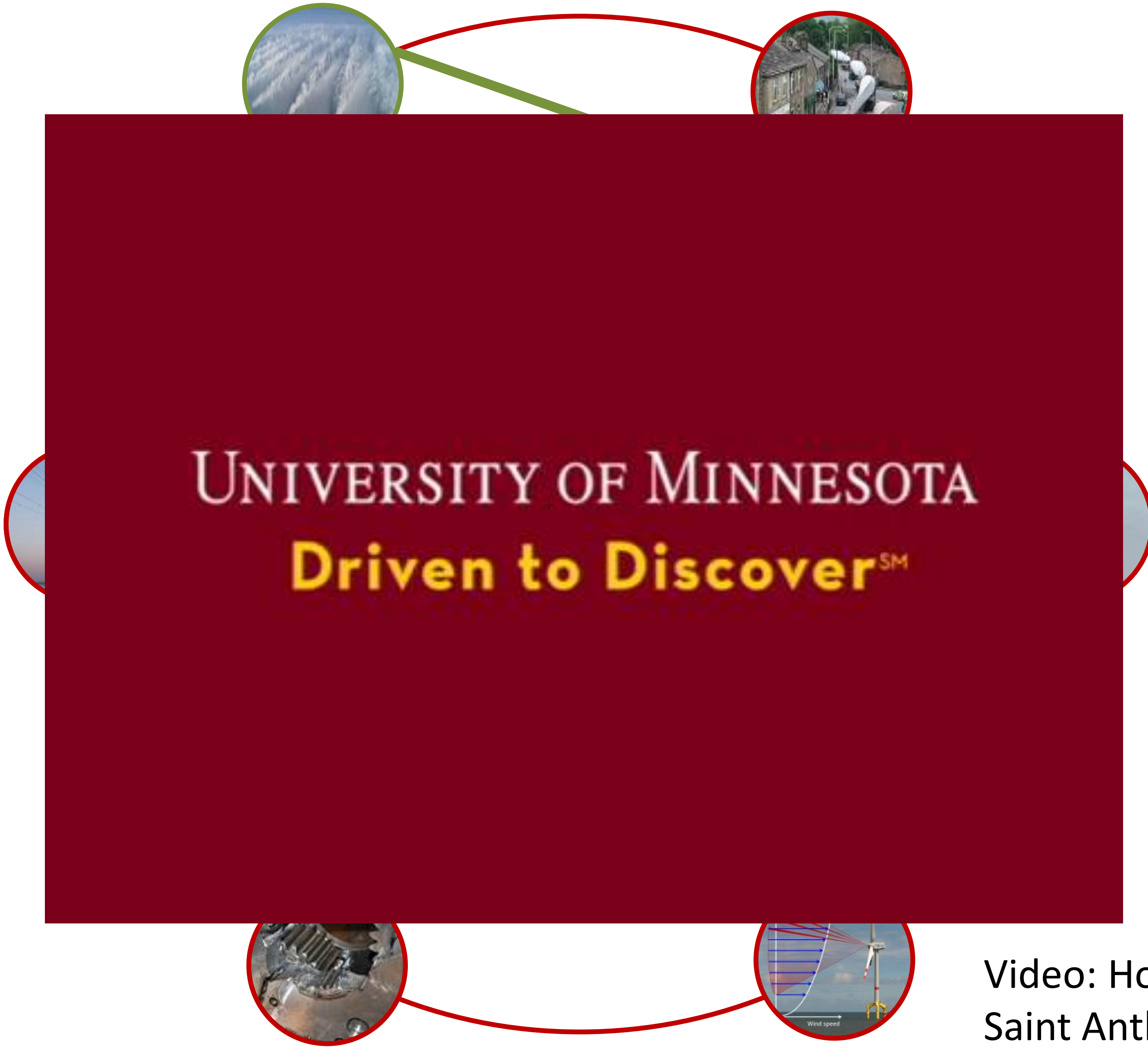
## 6. Turbine/Turbine Interactions

- Maximize power
- Reduce structural loads
- High Fidelity Simulations

**Refs:** Johnson, Fleming, Gebraad, Seiler, Annoni, Howard, Guala, Yang, Sotiropoulos

Image: Horns Rev 1, by Christian Steiness

# Trends in Wind Energy




## 6. Turbine/Turbine Interactions

- Maximize power
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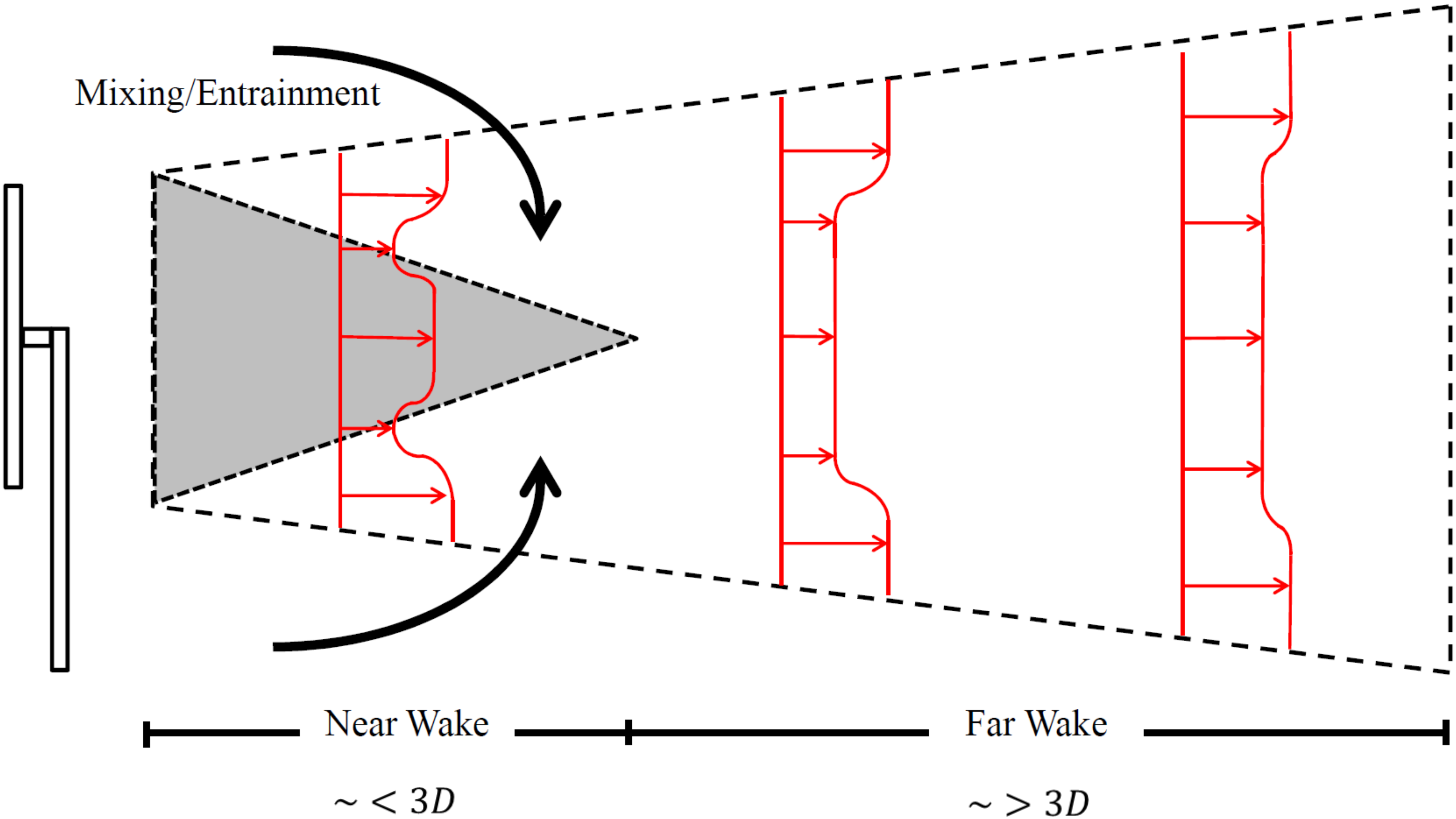
**Refs:** Johnson, Fleming, Gebraad, Seiler, Annoni, Howard, Guala, Yang, Sotiropoulos

Video: Hong, et al., Nature Comm., 2014
Saint Anthony Falls Laboratory

# Near Wake vs. Far Wake



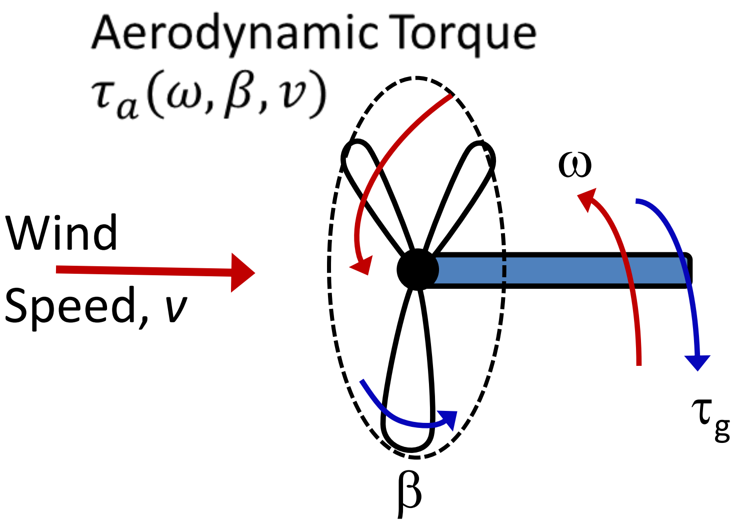
# Outline

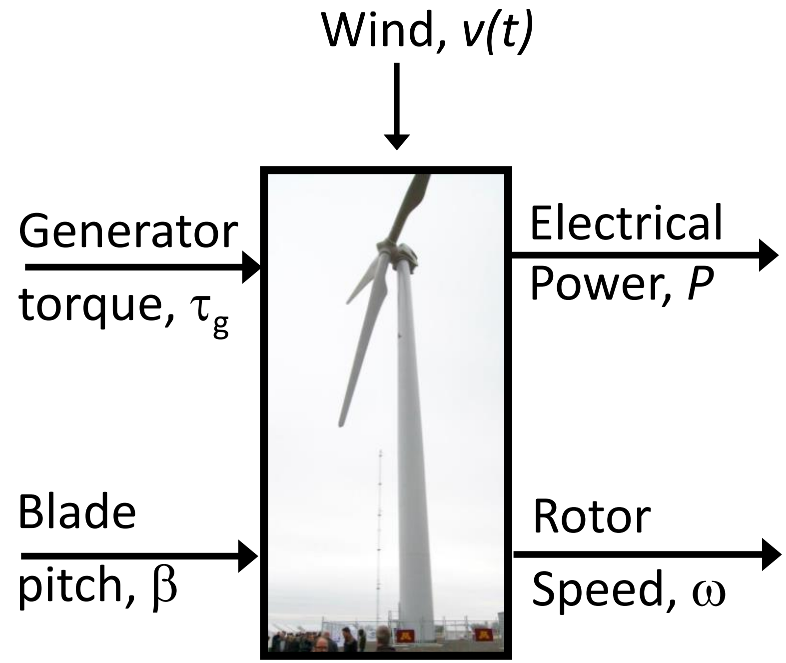
- **Goal:** Construct control-oriented models for wind farms
  - Models need to be low-order but of sufficient fidelity.
  - Use models to design coordinated wind farm controllers

- Individual turbine control
- Coordinated wind farm control
- Wind farm modeling
  - Experimental (black-box) models
  - First-principles, reduced order models
- Conclusions

# Individual Turbine Control

# Modern Utility-Scale Wind Turbines



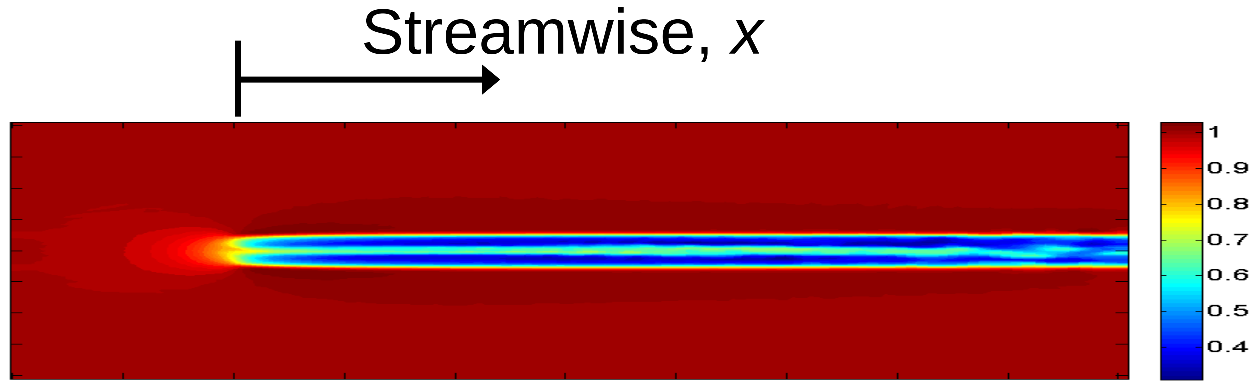

Objectives for Individual Turbine Control:

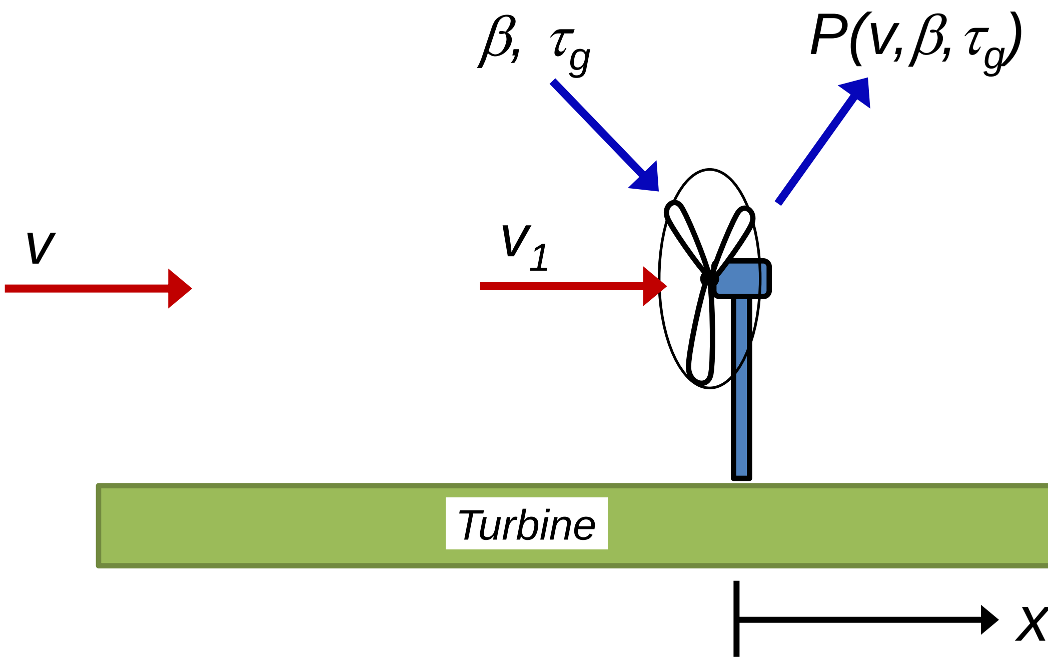
1. Maximize power at low wind speeds.
2. Reduce loads at high wind speeds.

Ref: Johnson, Pao, Balas, Fingersh, IEEE CSM, 2006

# Actuator Line Turbine Model

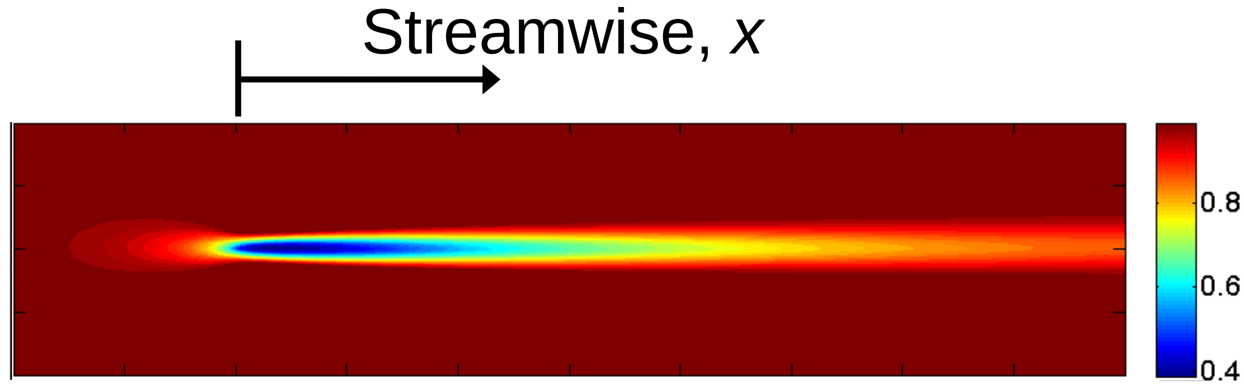
*Actuator Line Results:*
Yang, et. al. The virtual wind simulator (VWiS)

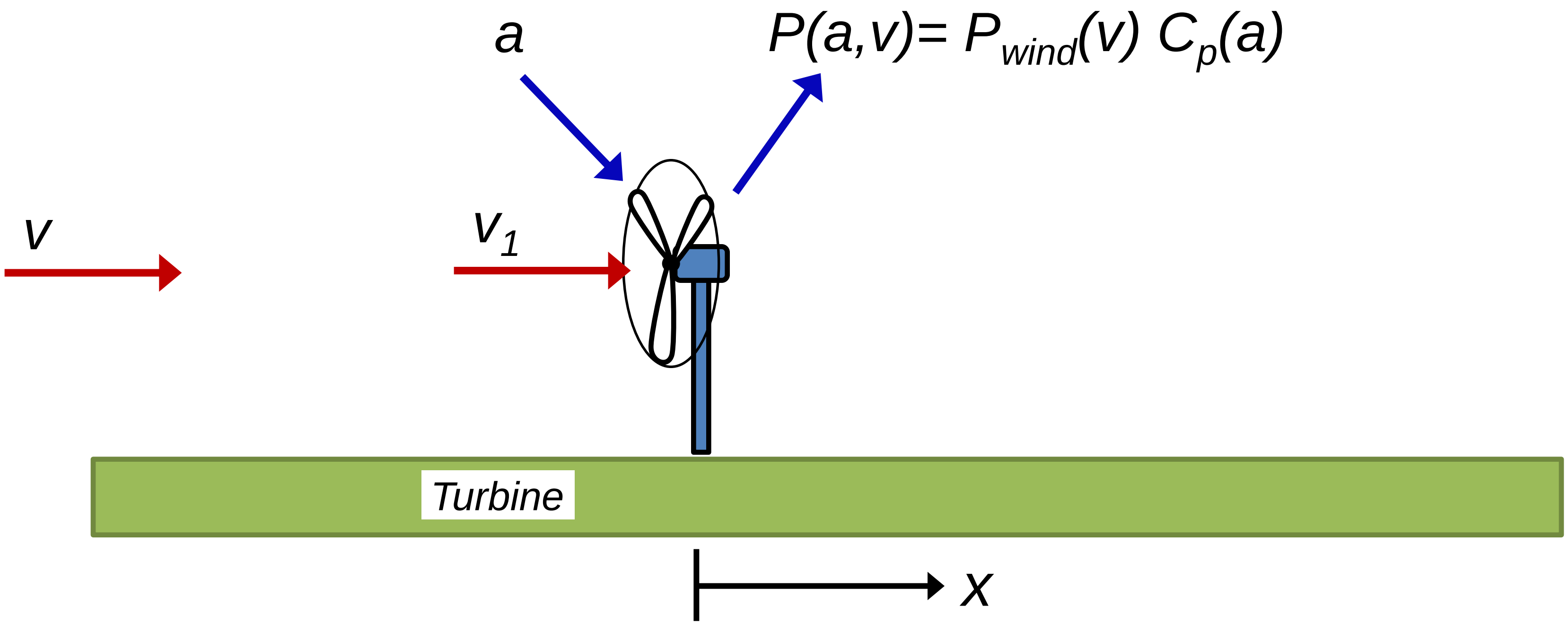


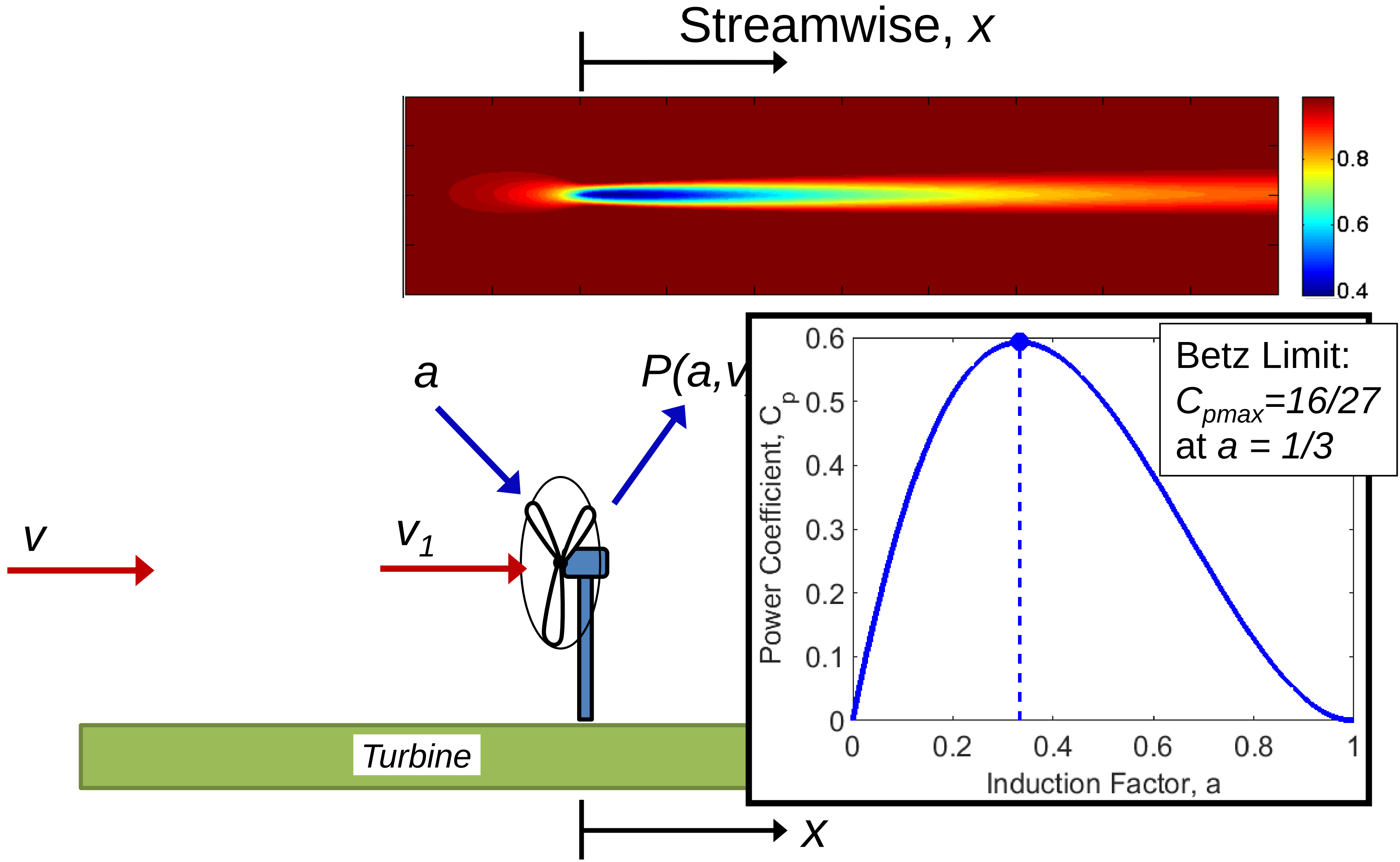

Induction Factor
$a := 1 - v_1/v$

# Actuator Disk Turbine Model

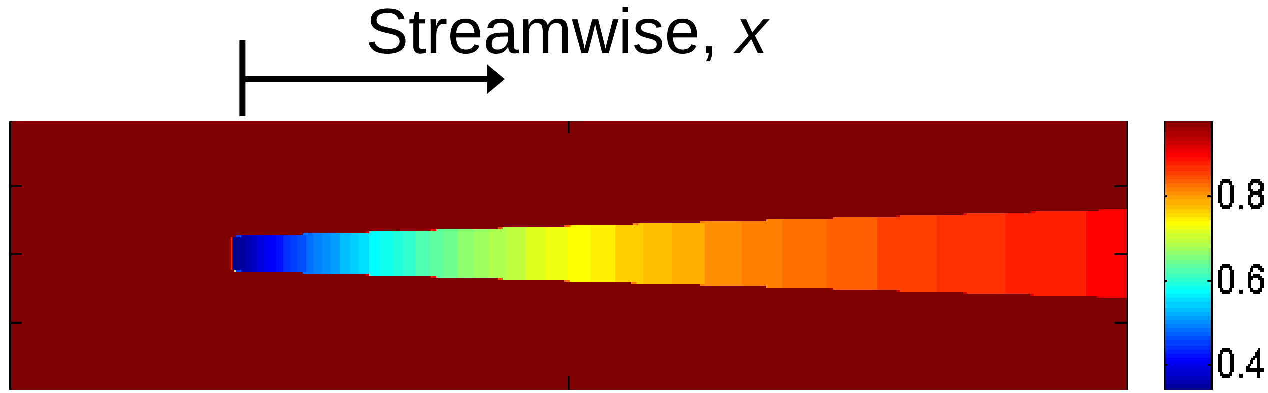


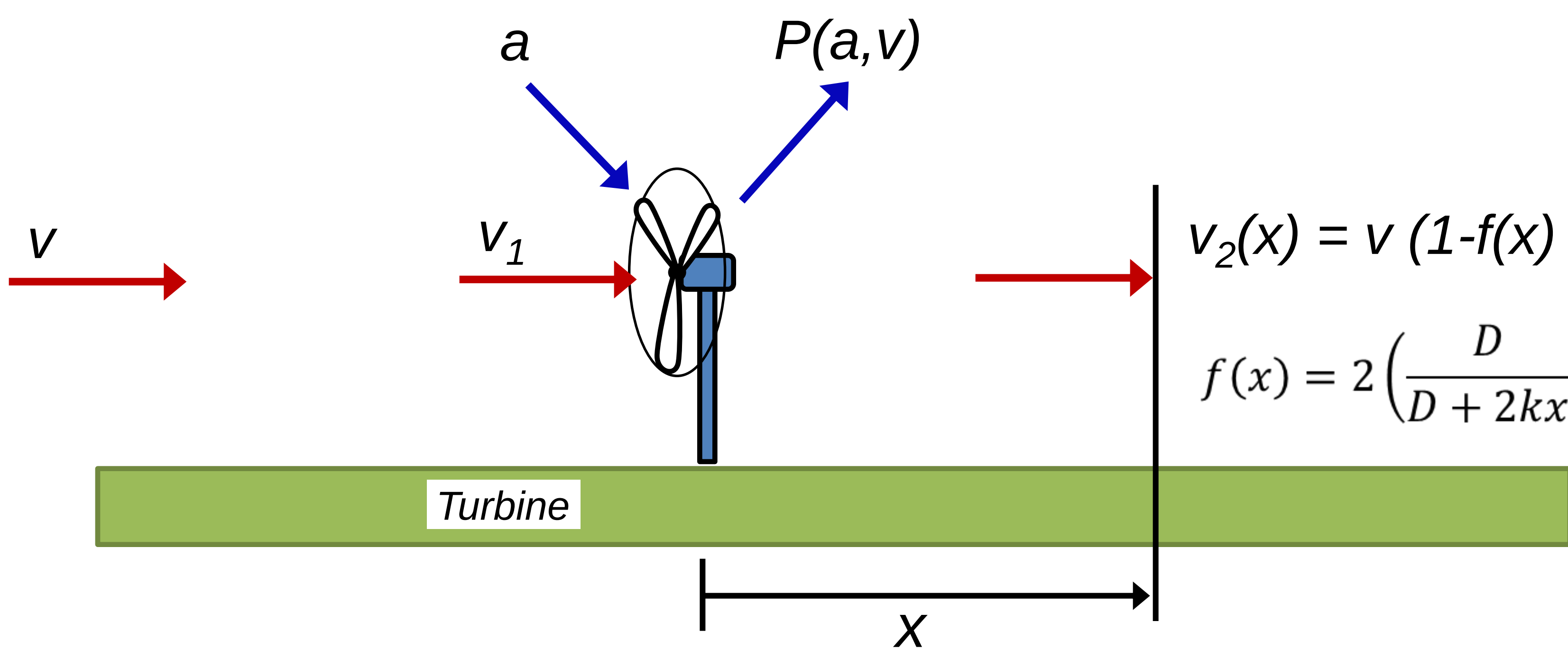



# Actuator Disk Turbine Model



# Park Model (Jensen, 1983)



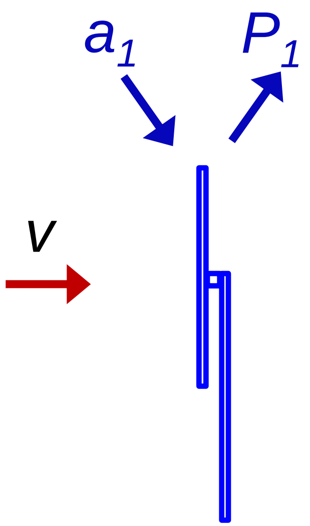




$$v_2(x) = v\,(1 - f(x)\,a)$$

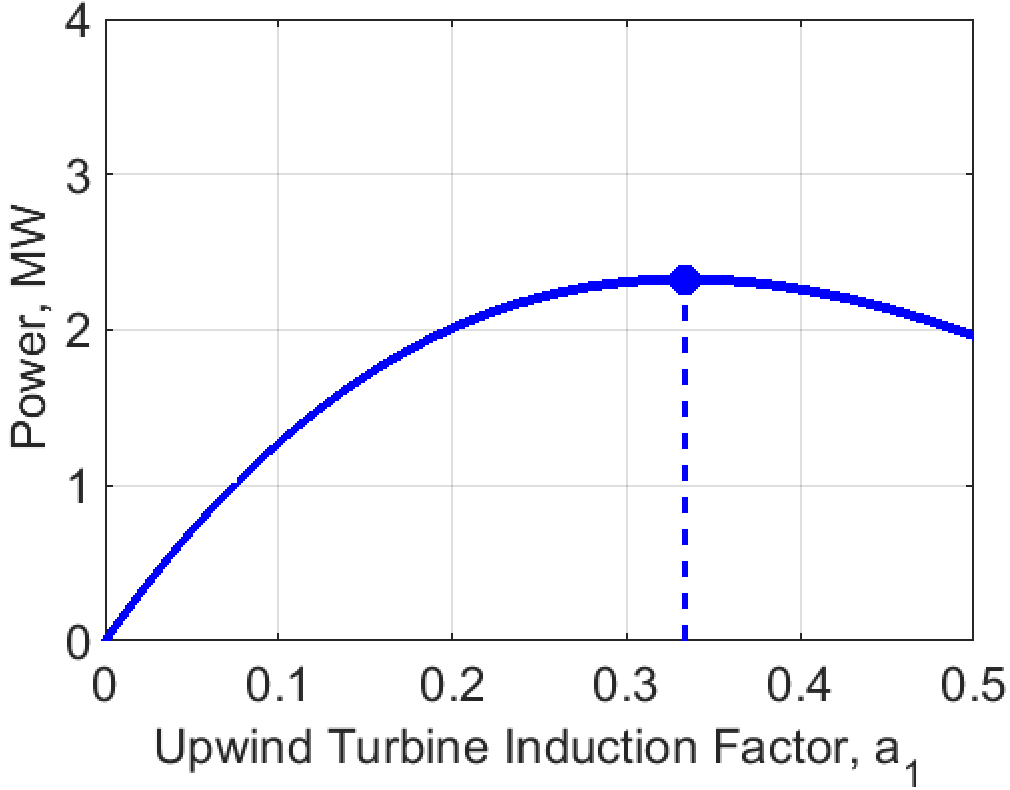
$$f(x) = 2\left(\frac{D}{D + 2kx}\right)^2$$

# Coordinated Wind Farm Control

# Coordinated Control: Two Turbines




**Optimal:** $a_1 = 1/3$

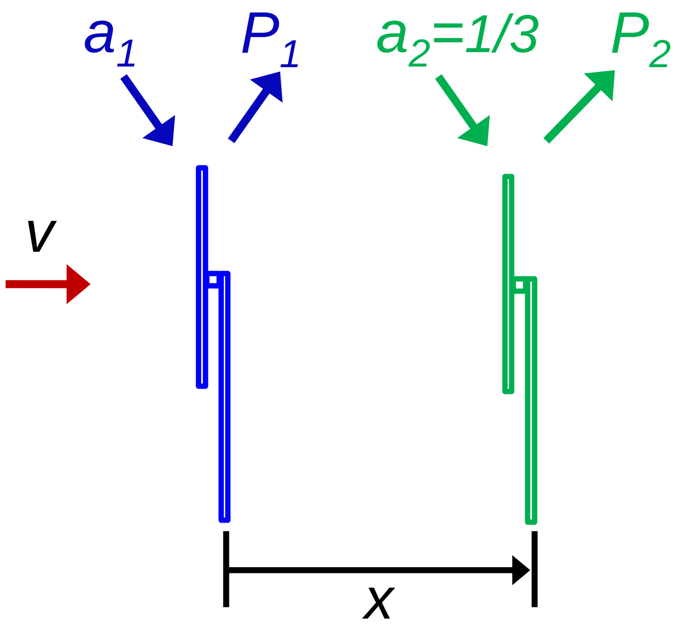


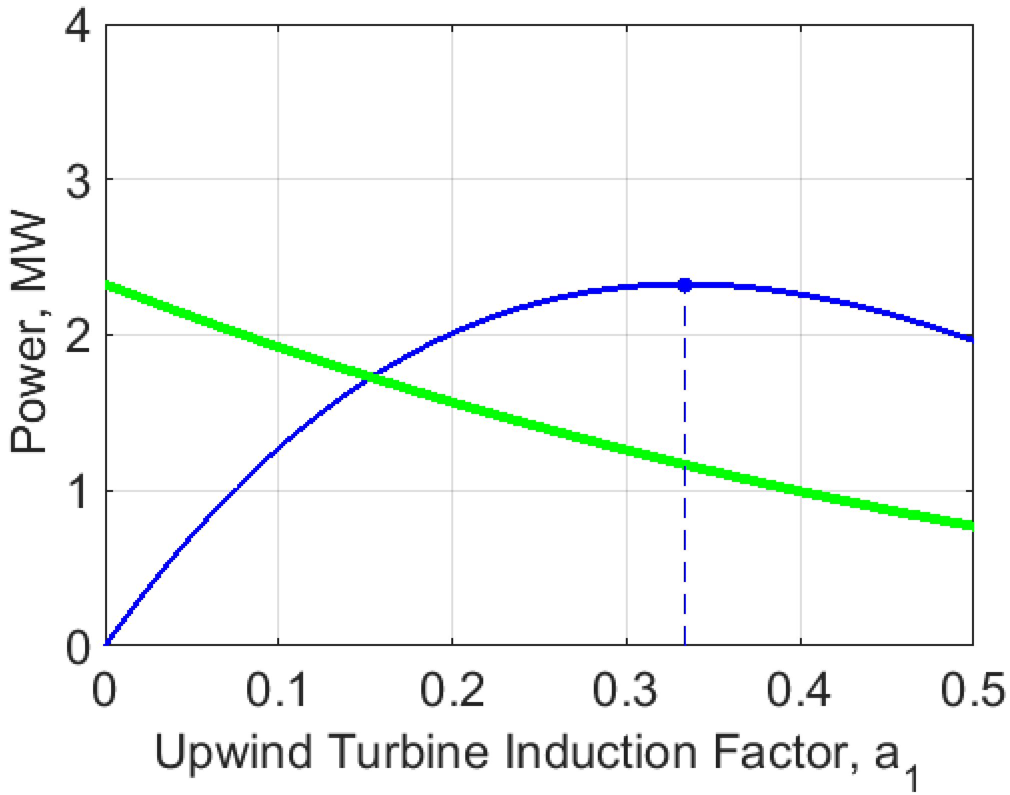

Parameters:

- Rotor Diam=100m
- v=10m/s
- Park and Betz model used

Ref: Johnson & Thomas (2009 ACC)

# Coordinated Control: Two Turbines



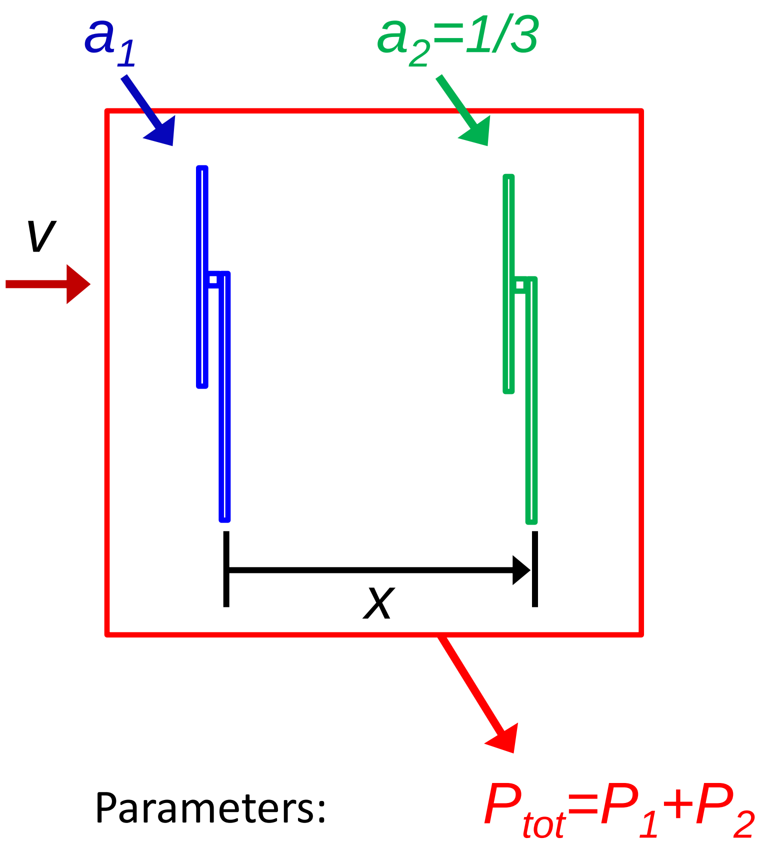




Parameters:

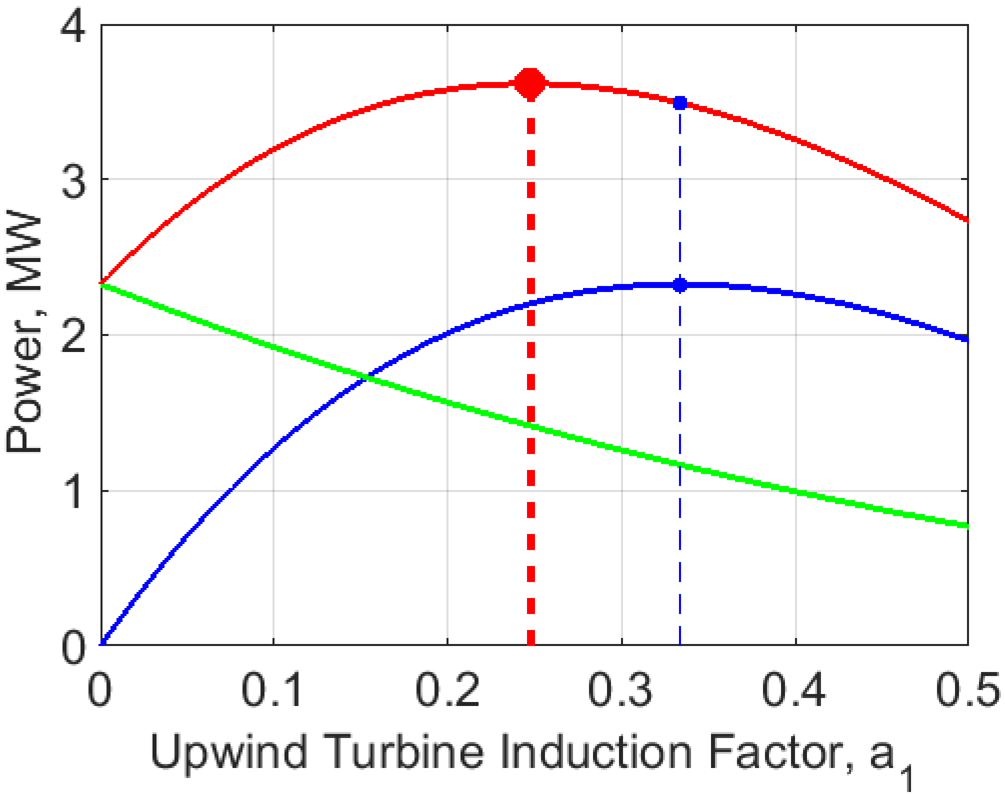
- Rotor Diam=100m
- v=10m/s
- k=0.1
- x=4D

Ref: Johnson & Thomas (2009 ACC)

# Coordinated Control: Two Turbines




**Optimal**: $a_1 = 0.25$, 3.5% ↑ Power

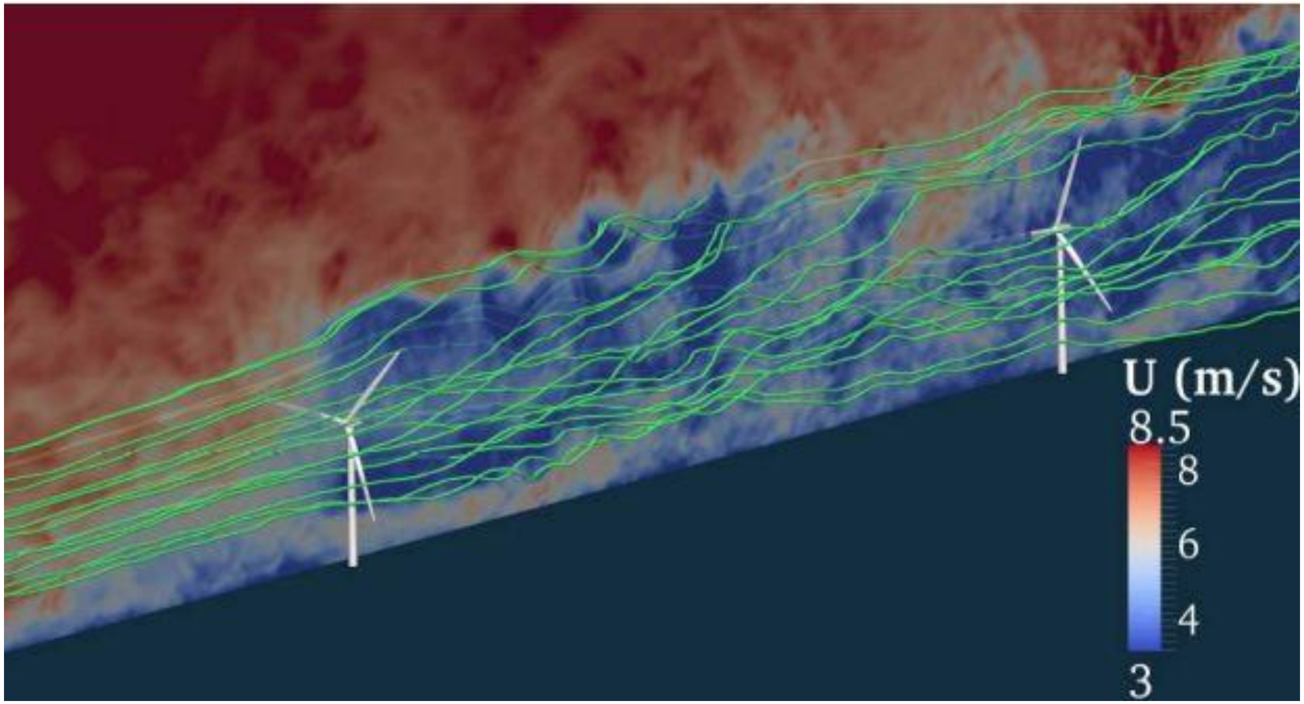



Parameters:
- D=100m
- v=10m/s
- k=0.1
- x=4D

Ref: Johnson & Thomas (2009 ACC)

# Need for Improved Wake Modeling

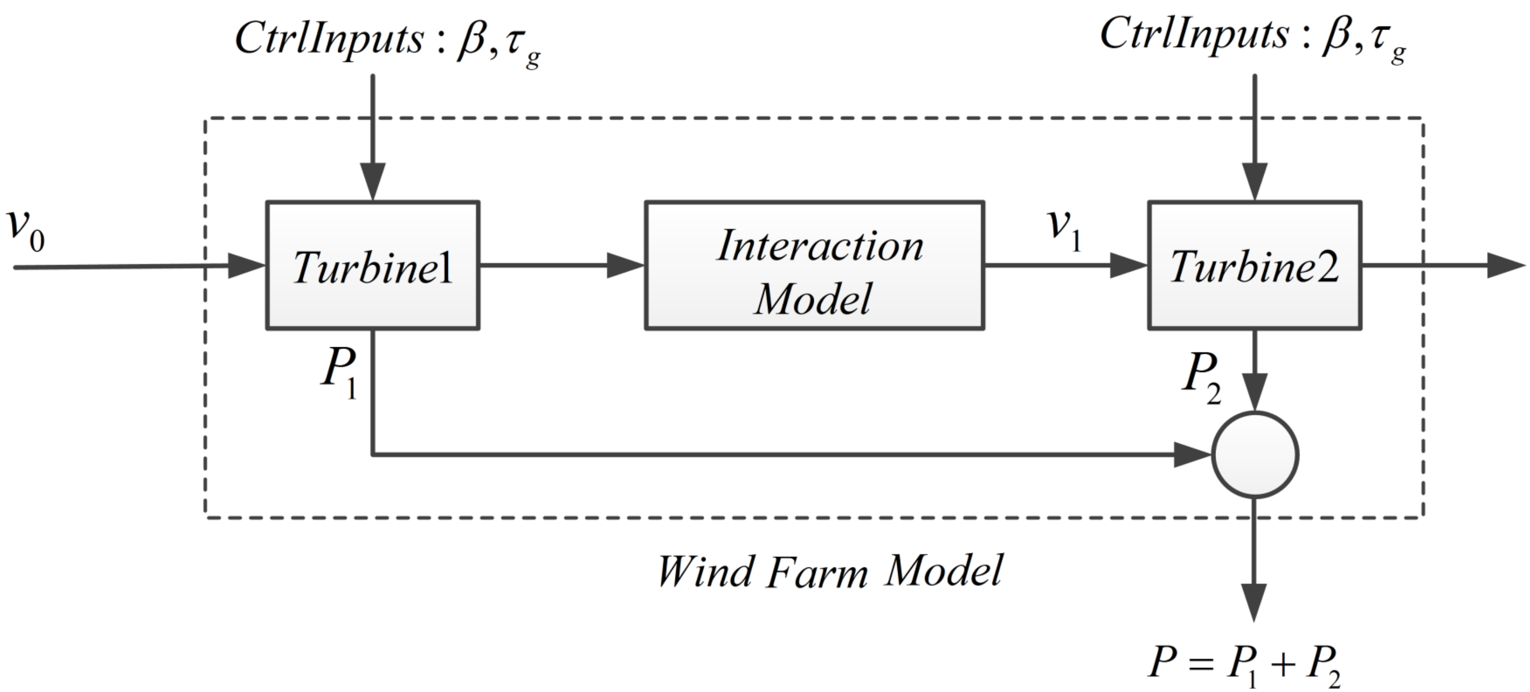
- **Issue:** High fidelity simulations show no increased power.
  - ~-10% compared to the +3.5% gain with the Park model
  - Ref: Annoni, Gebraad, Scholbrock, Fleming, van Wingerden, "Analysis of axial-induction-based wind plant control using engineering and high-order wind plant models." Submitted 2014




*Simulator for Wind Farm Applications (SOWFA) Churchfield and Lee*
*http://wind.nrel.gov/designcodes/simulators/SOWFA*

# Need for Improved Wake Modeling

- **Summary:** Park model neglects important spatio-temporal dynamics that are relevant for control.



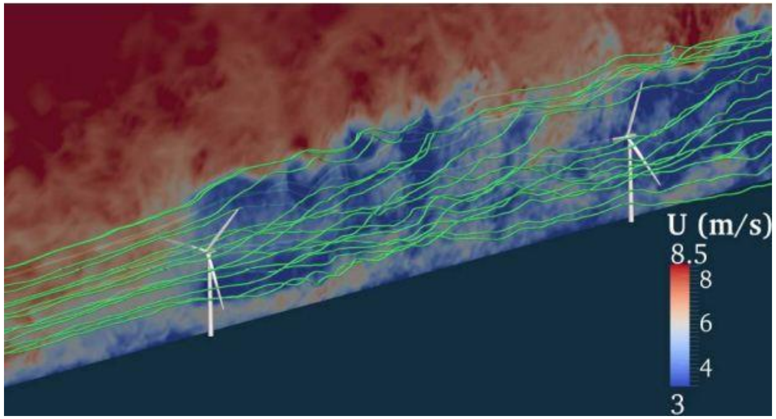
# Wind Farm Modeling

1. Experimental (black-box) models
2. First-principles, reduced order models

# Differences in Modeling Approaches

- Experimental
  - Data driven
  - Site specific
  - **Apply to : Existing wind farms**

- First-principles
  - General approach
  - Gain insight for farms that are not yet built
  - **Apply to: Design of new farms**



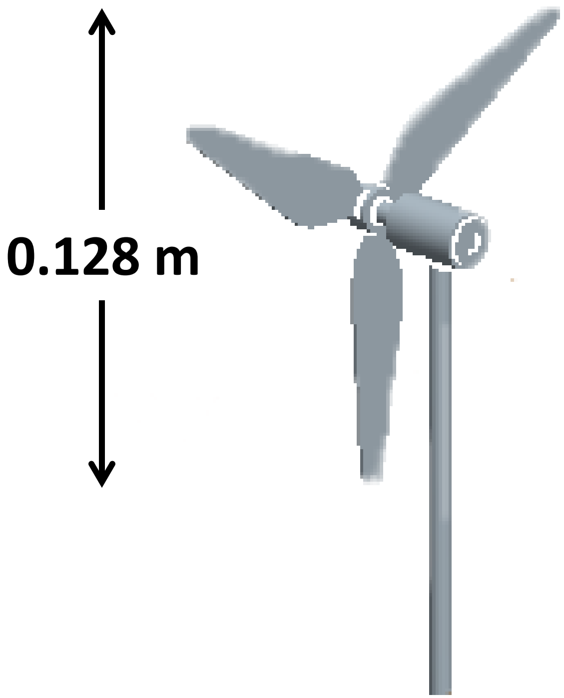
# Wind Farm Modeling

1. **Experimental (black-box) models**

Ref: "An experimental investigation on the effect of individual turbine control on wind farm dynamics", by Annoni, Howard, Seiler, and Guala, In preparation.

2. First-principles, reduced order models

# Model Turbines




- Scale ⟶ 1:750
- 4.5 m/s
- 10% turbulence intensity

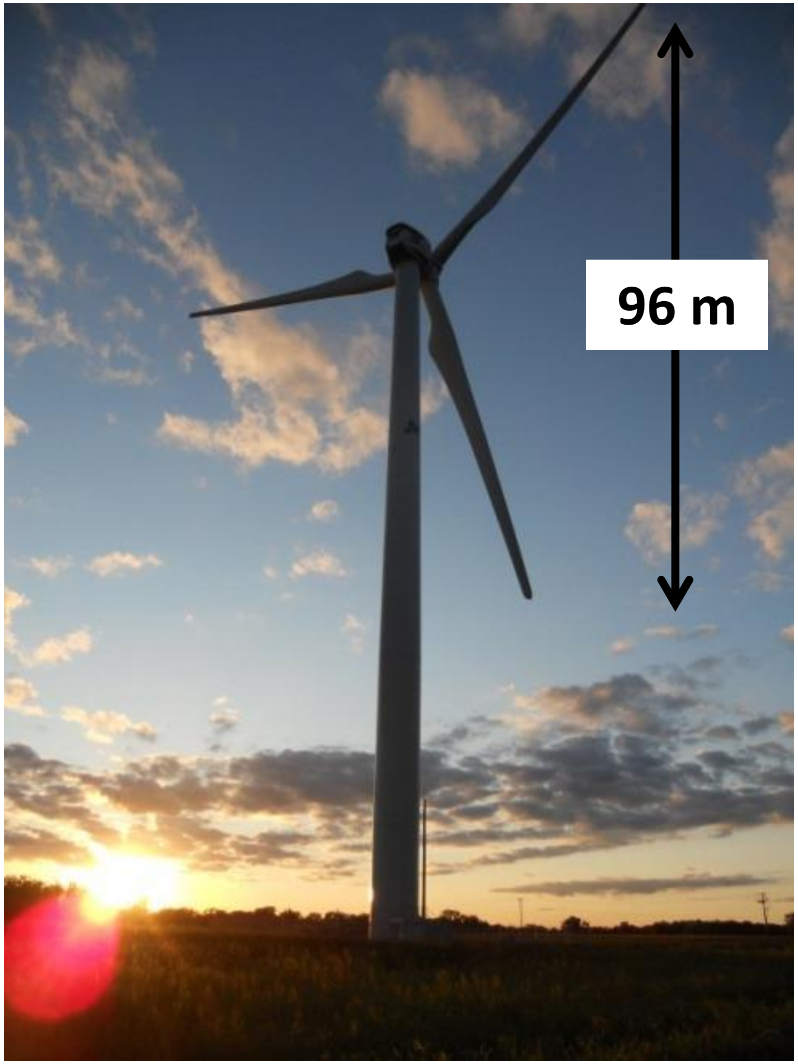
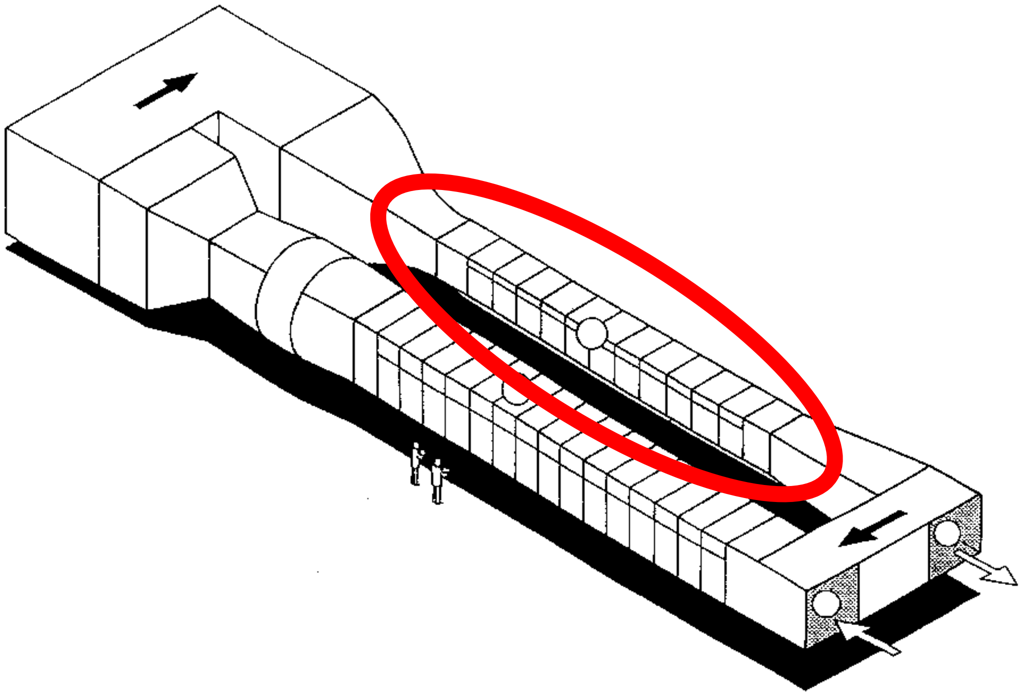



*Photo credits: Kevin Howard*

# SAFL Wind Tunnel



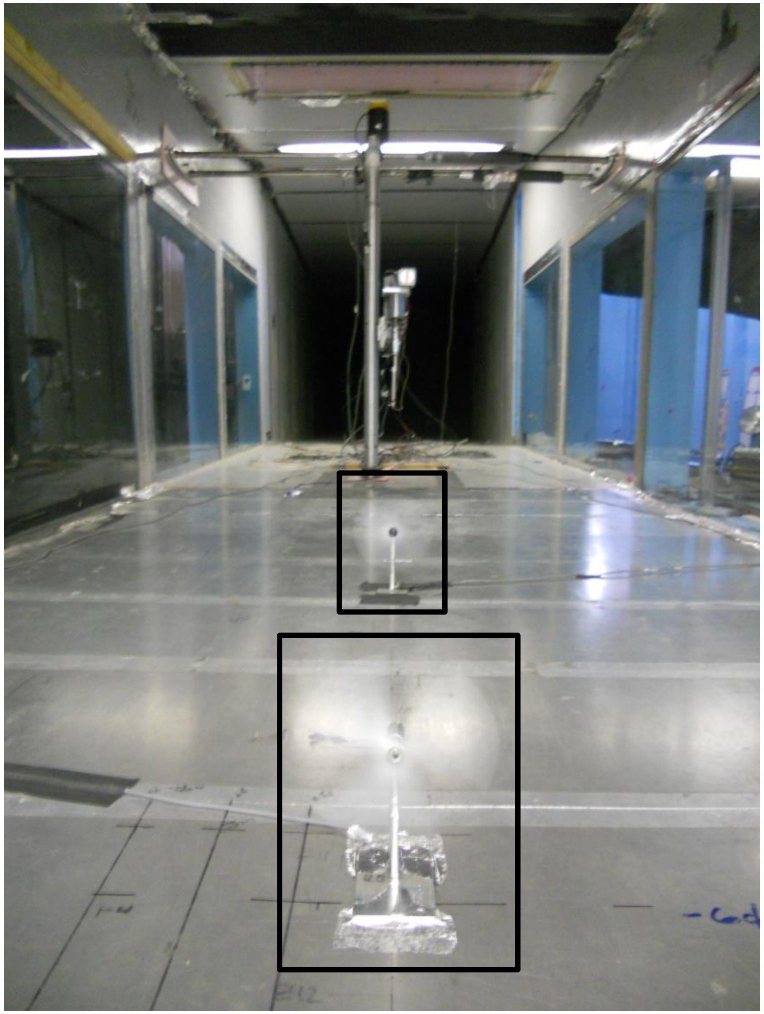
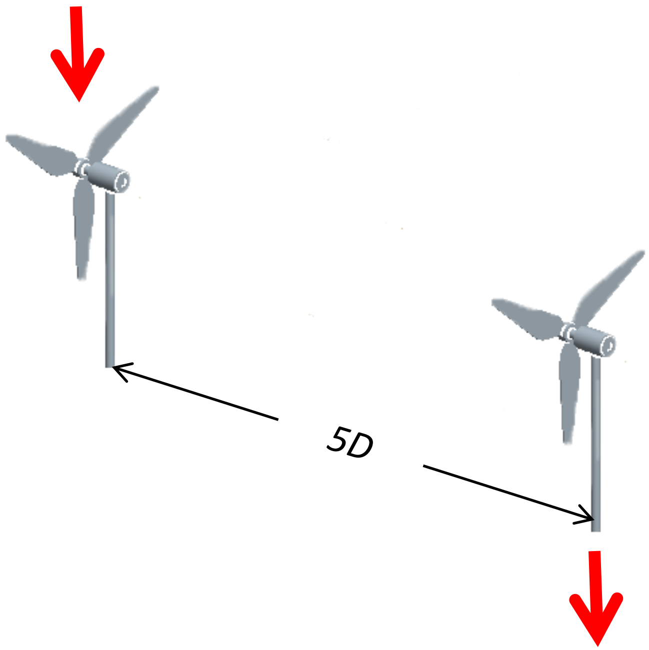


*Photo credits: Kevin Howard*

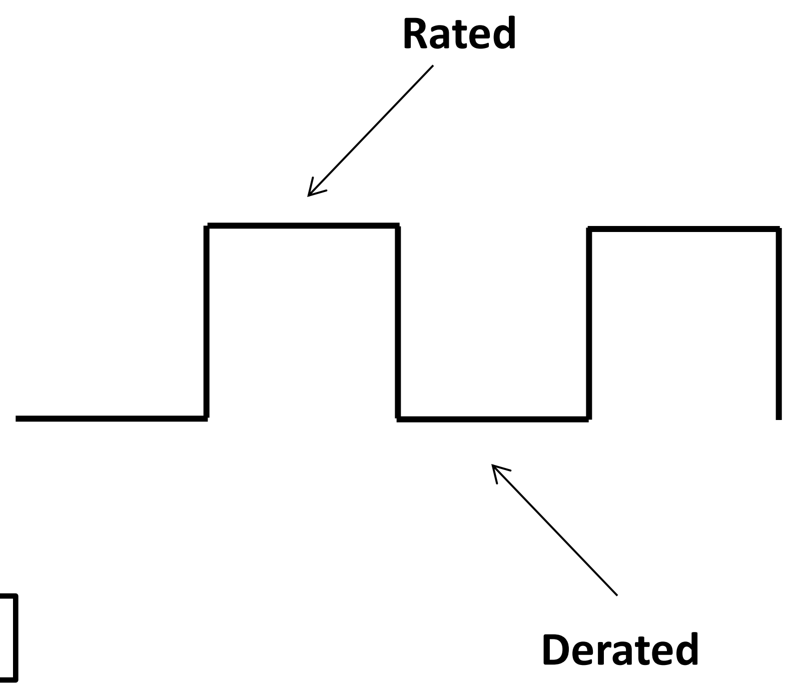
# Voltage Measurements

- Understand the input/output dynamics

**Input voltage ⟶ generator torque**

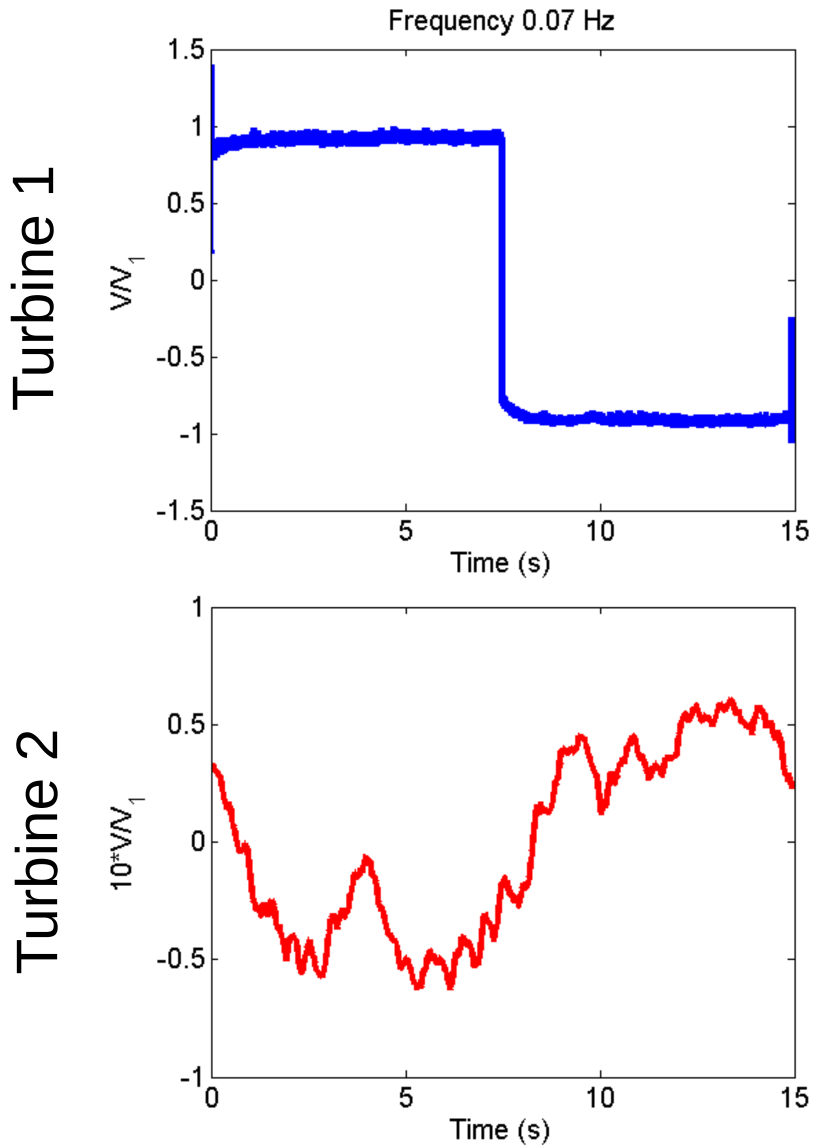



**Output voltage ⟶ Power**

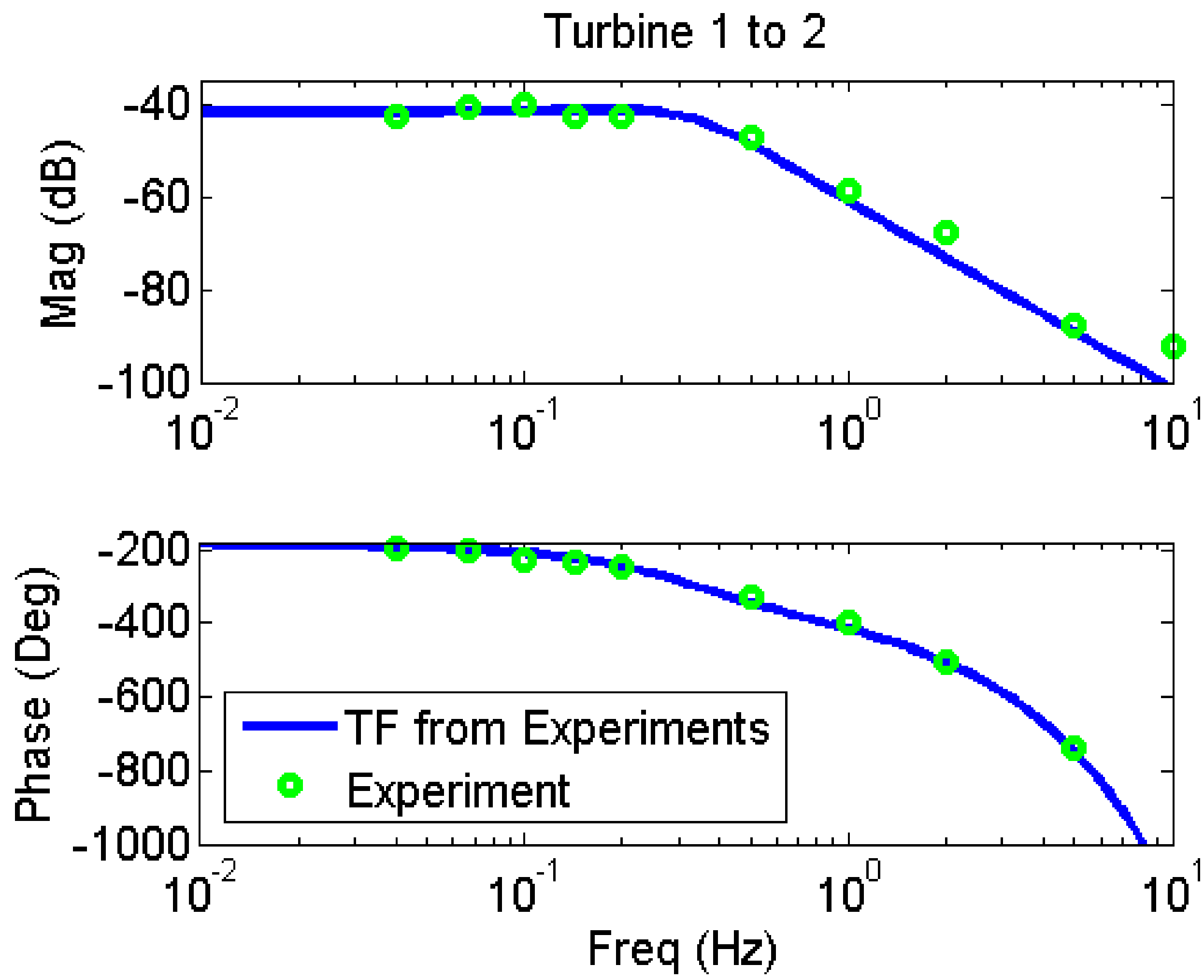



- Square waves with varying frequencies: 0.02Hz to 10Hz

# Typical Result



# Dynamic Response

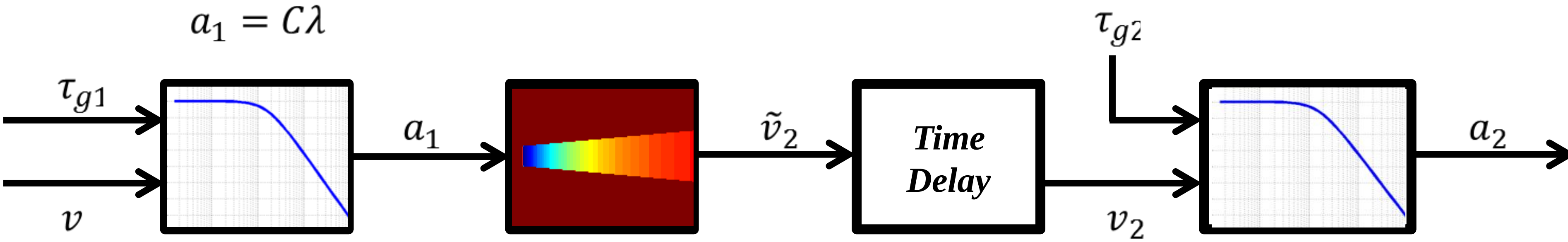


# Dynamic Park Model

*First Order Dynamics*

$$\dot{\lambda} = A\lambda + B\tau_{g1}$$

$$a_1 = C\lambda$$

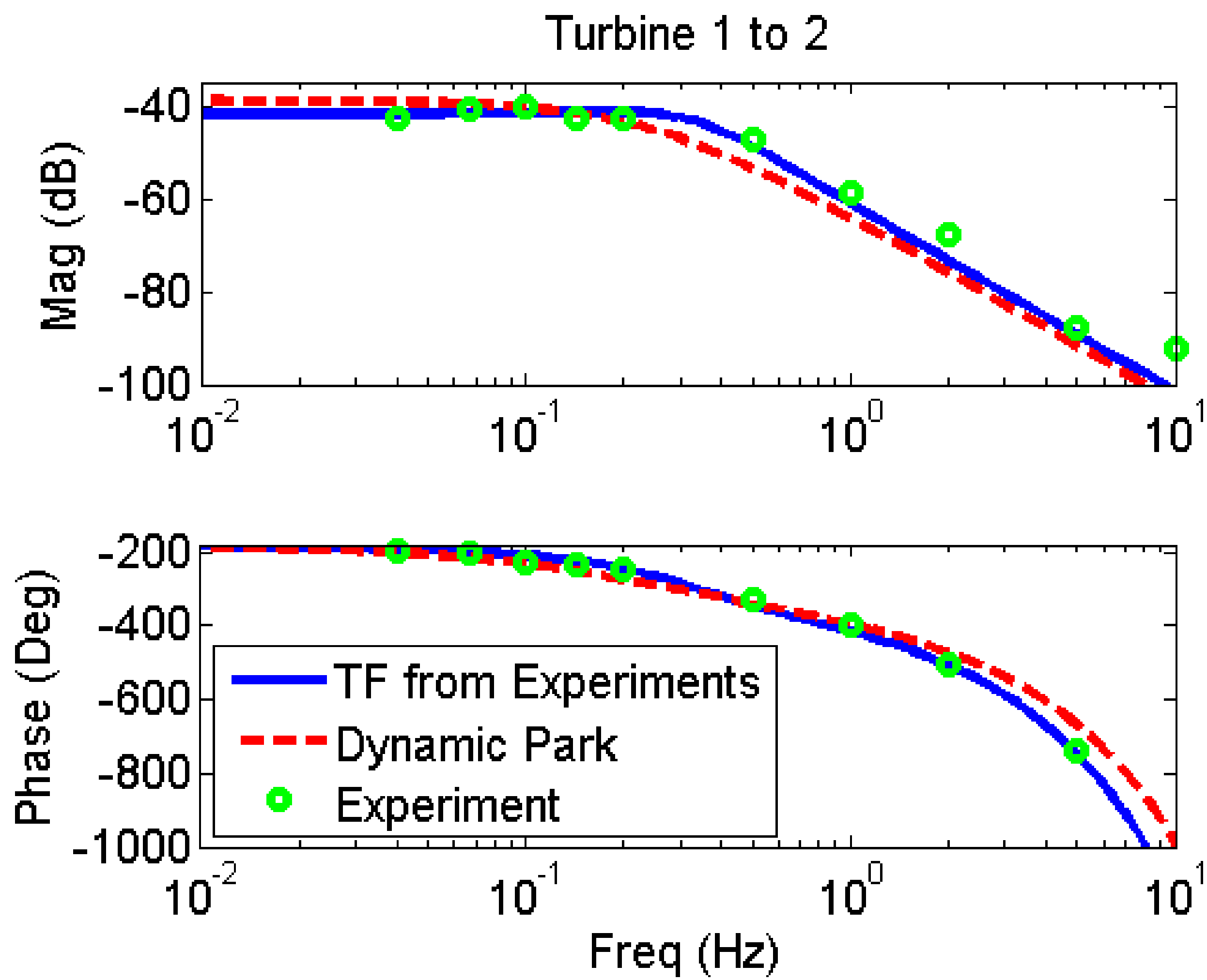



*First Order Dynamics*

$$\dot{\lambda} = A\lambda + B\tau_{g2}$$

$$a_2 = C\lambda$$

# Dynamic Park Model



# Wind Farm Modeling

1. Experimental (black-box) models

2. **First-principles, reduced order models**

Ref: “A low-order model for wind farm control,” by Annoni and Seiler, Submitted to the 2015 ACC.

# Flow Snapshot

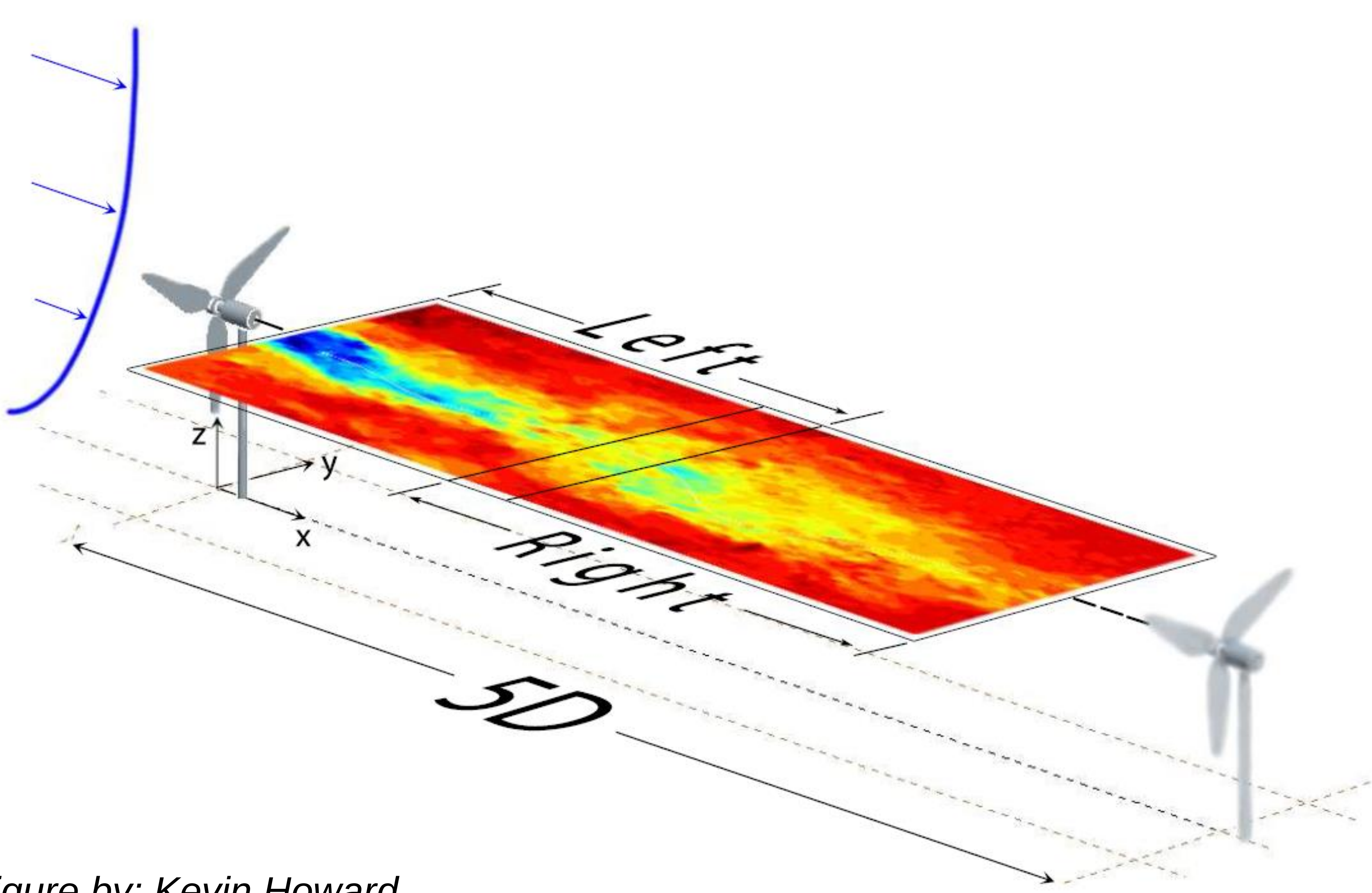
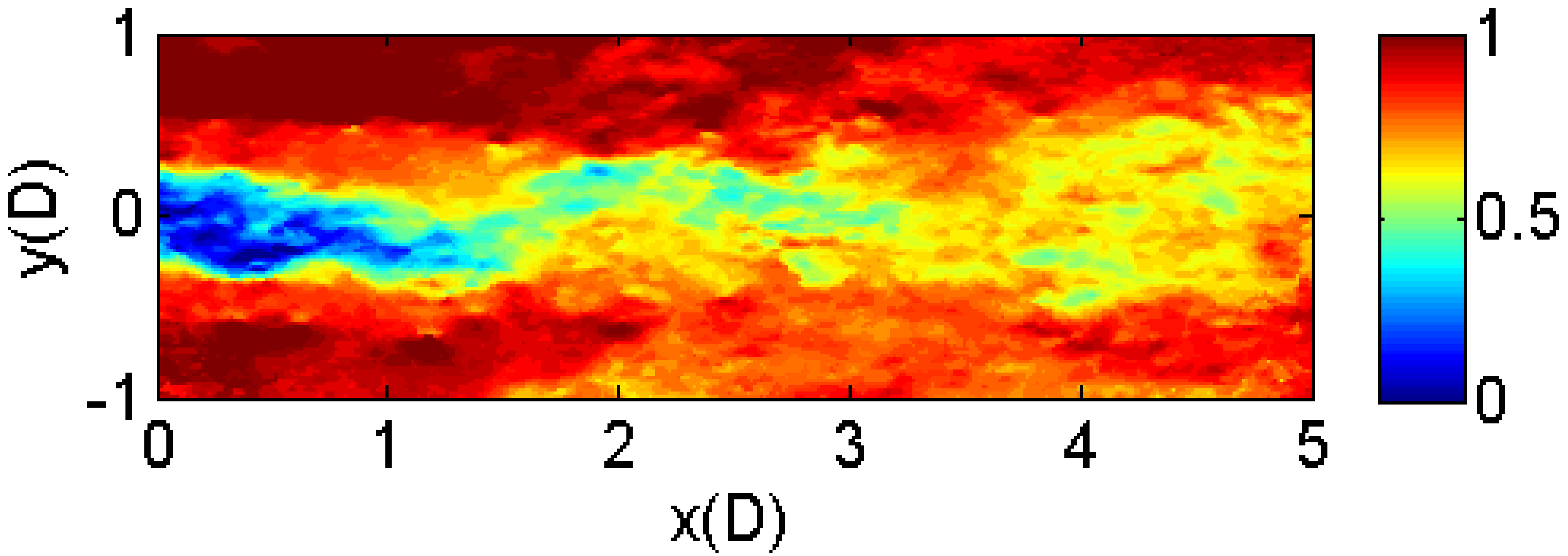



*Figure by: Kevin Howard*

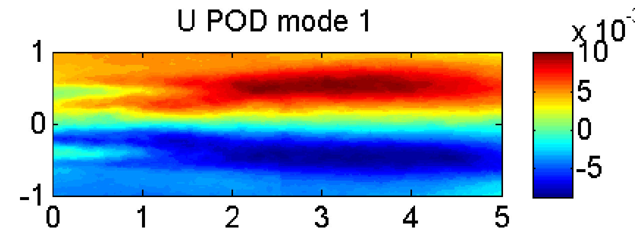
# Proper Orthogonal Decomposition (POD)

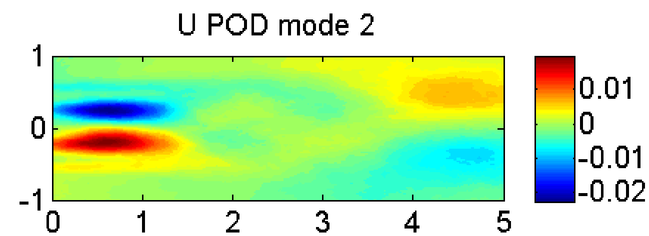
- Technique to compress data in flow *v(x,y,t)*
  - Holmes et. al, "Turbulence, Coherent Structures, Dynamical Systems and Symmetry." 1996
  - K. Willcox and J. Peraire, "Balanced model reduction via the proper orthogonal decomposition," 2002

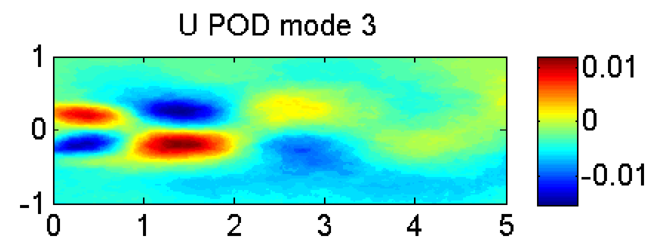


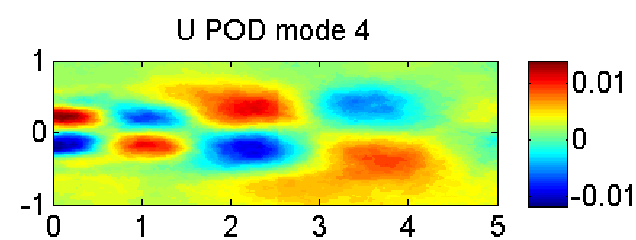
# Proper Orthogonal Decomposition (POD)

- Construct most energetic modes in flow $\{v_k\}$

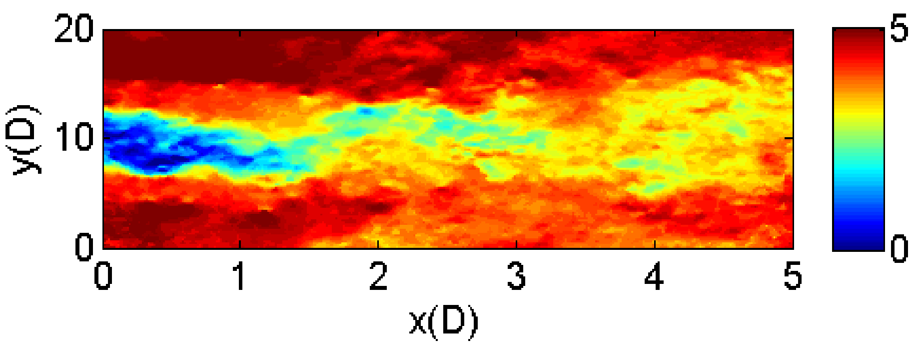



Snapshot



# Proper Orthogonal Decomposition (POD)

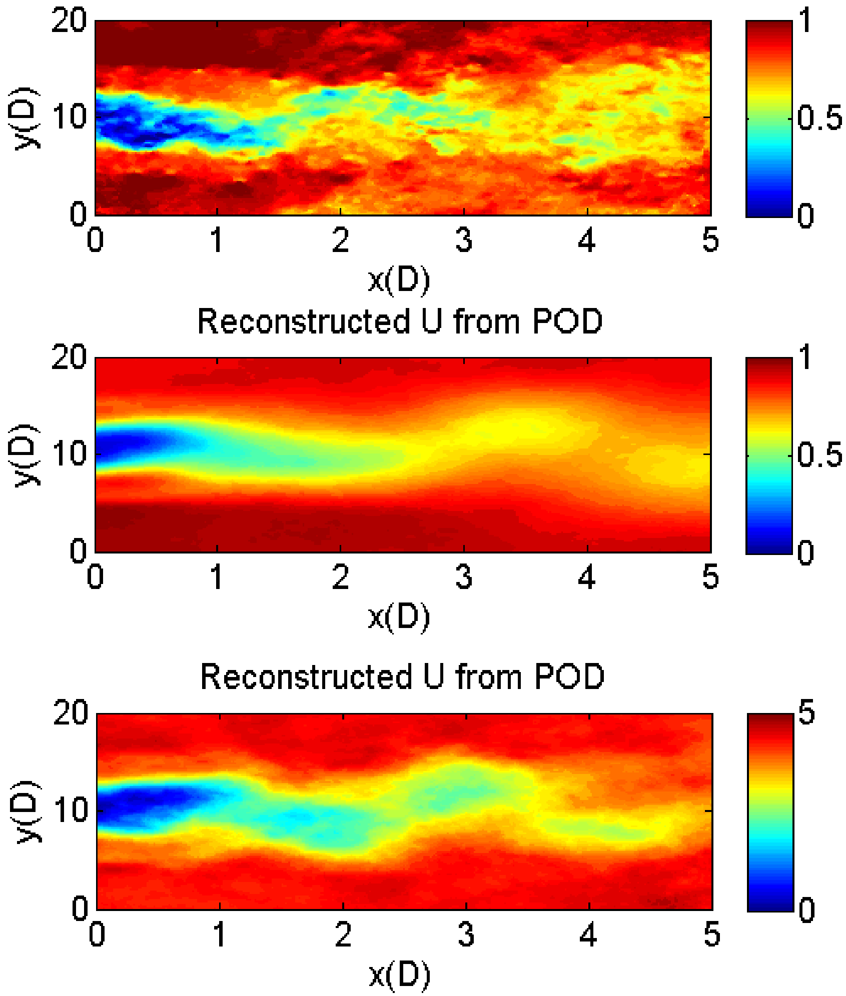
- Construct most energetic modes in flow $\{v_k\}$
- Approximate flow by projection onto energetic modes

$$v \approx \sum_k c_k \, v_k$$

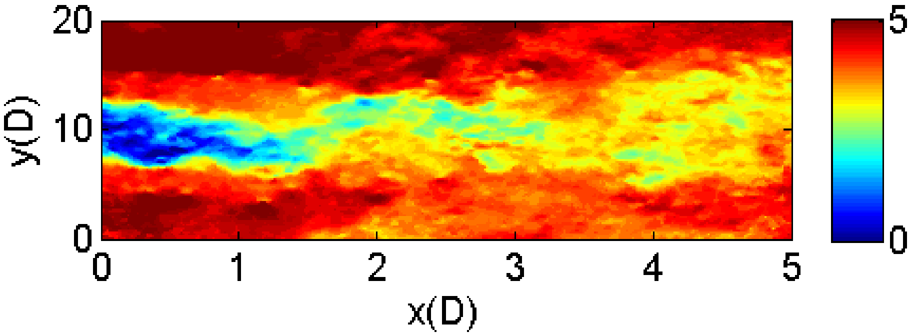
Snapshot

10 Modes

100 Modes




Snapshot



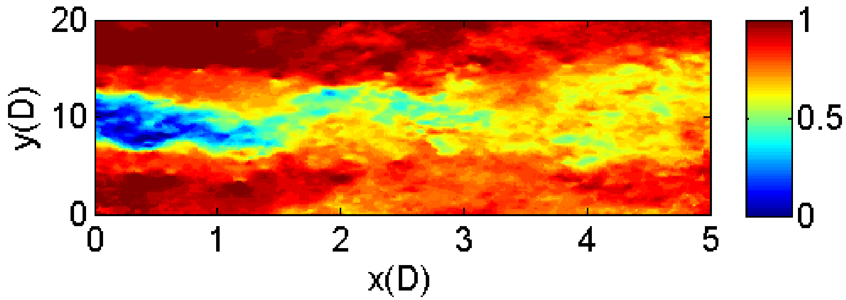
# Proper Orthogonal Decomposition (POD)

- Construct most energetic modes in flow $\{v_k\}$
- Approximate flow by projection onto energetic modes

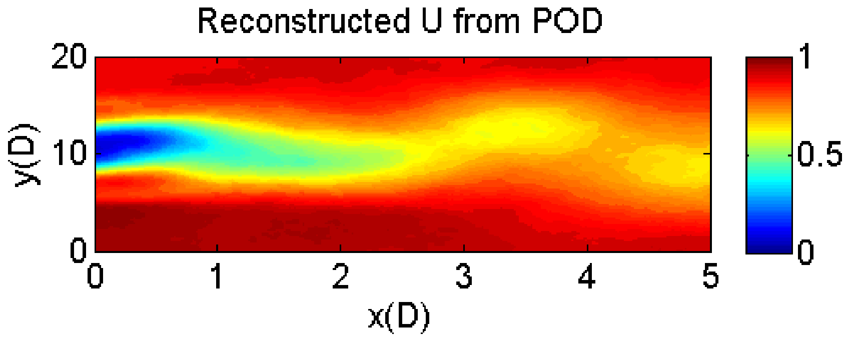
$$v \approx \sum_k c_k v_k$$

- Obtain low-order ODE model of PDE by Galerkin projection

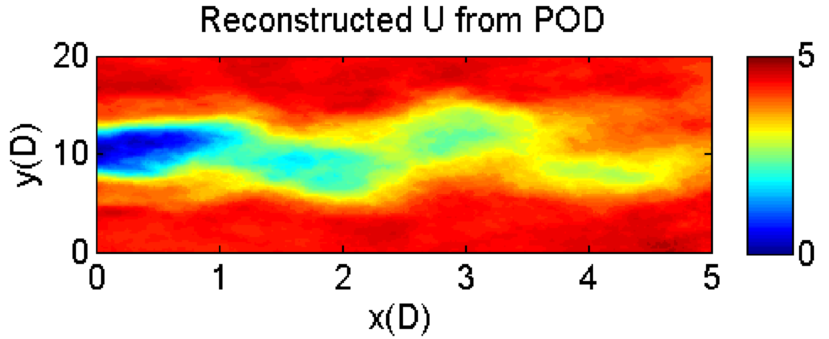
Snapshot



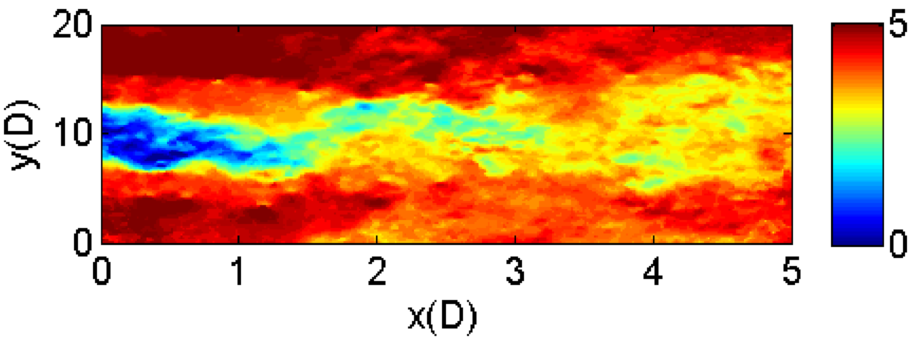

10 Modes




100 Modes

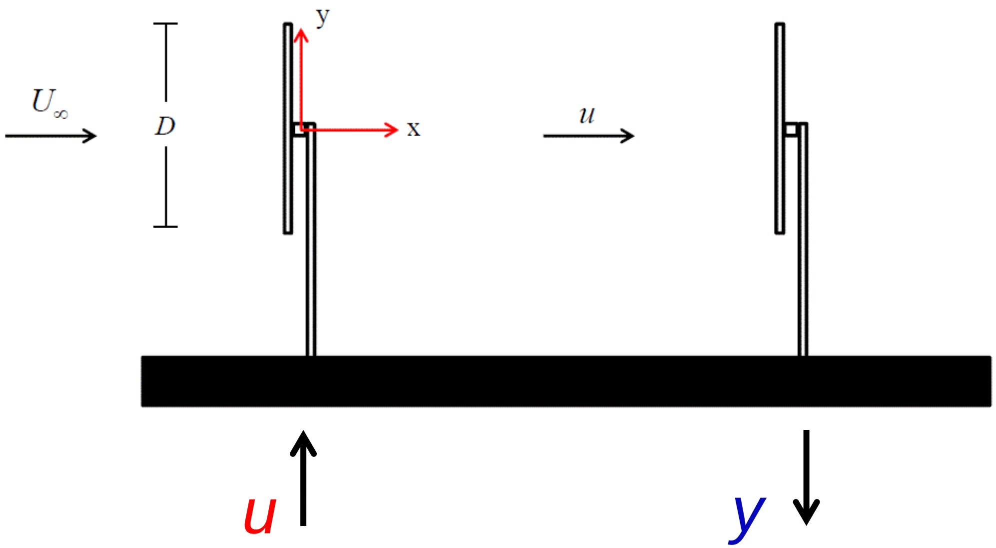



Snapshot



# Balanced Truncation

- Model reduction technique for state-space systems
  - Controllability Gramian gives input energy to reach a state.
  - Observability Gramian gives output energy from a state.
  - Balancing state transformation to yield equal observability/controllability properties.
  - Truncate less observable/controllable states.

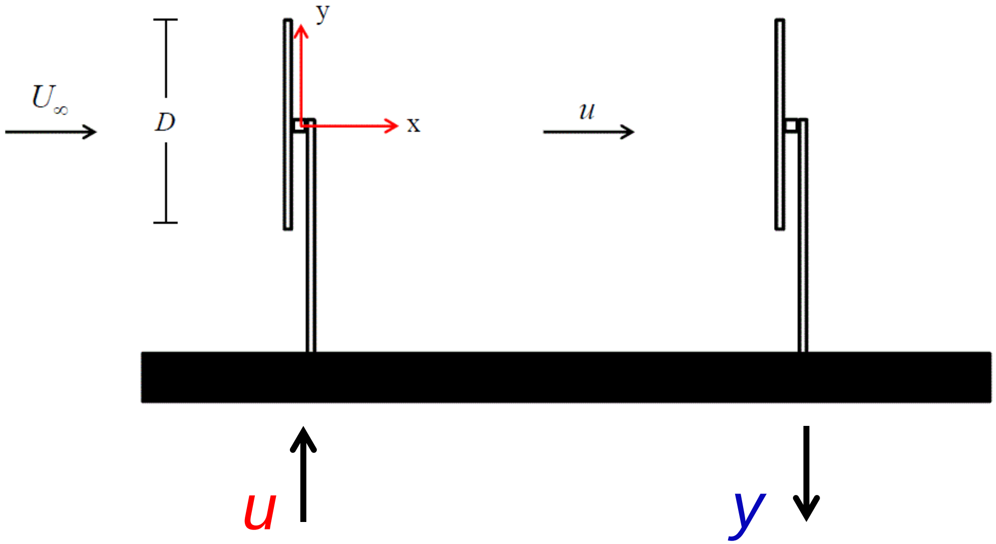



$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

**Refs:** Moore, Pernebo & Silverman, Enns

# Balanced Truncation

- Model reduction technique for state-space systems
- **Issue:** Gramians obtained via a Lyapunov equation.
  - Computational cost is $O(n^3)$ where $n$ is the state dim.

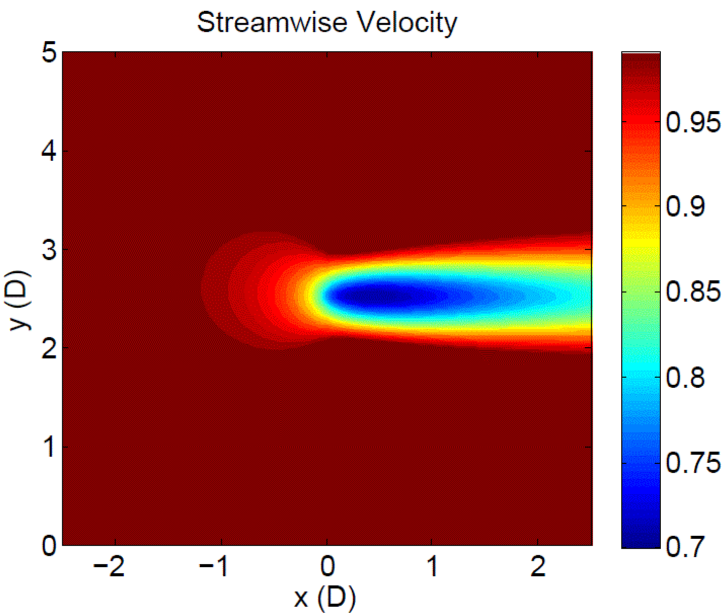


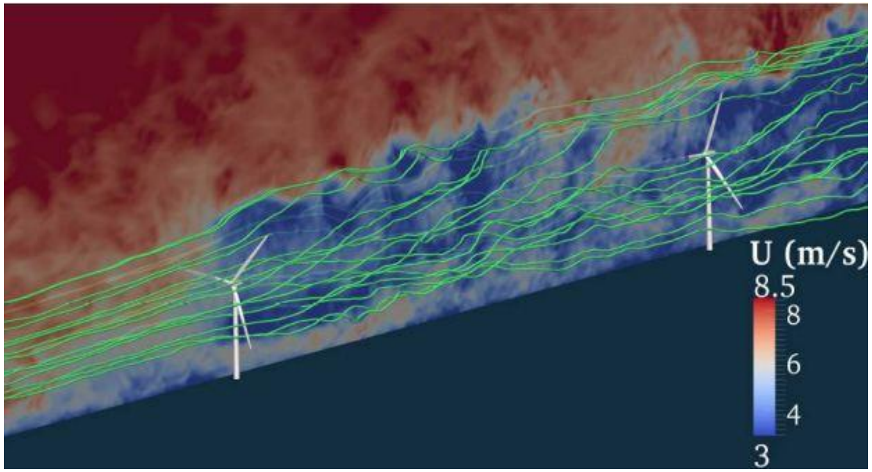

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

**Refs:** Moore, Pernebo & Silverman, Enns

# Balanced POD

- Combination of POD and balanced truncation
  - Scalable numerical implementation
- **Goal:** Obtain model for wind farm feedback control

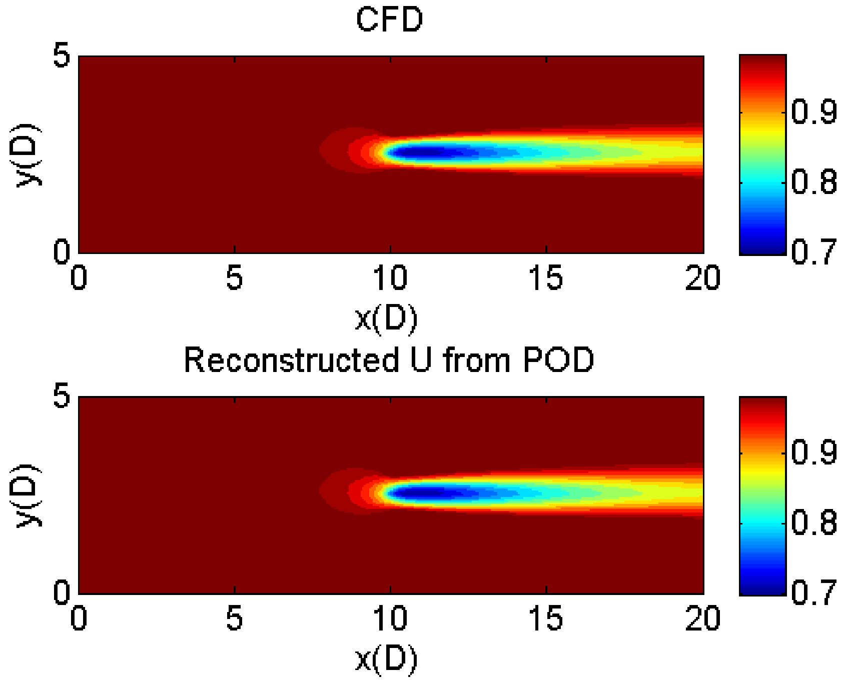


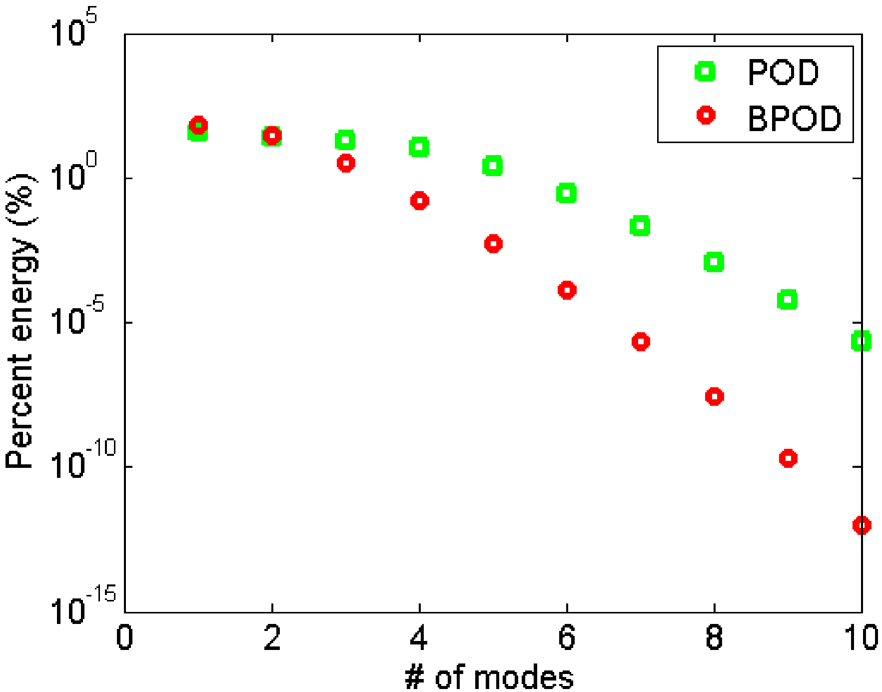




Rowley et. al. “Model Reduction for fluids, using Balanced Proper Orthogonal Decomposition” 2004
Willcox et. al., “Balanced model reduction via the proper orthogonal decomposition,” 2002.
Lall et. al., “A subspace approach to balanced truncation for model reduction of nonlinear control systems,” 2002.

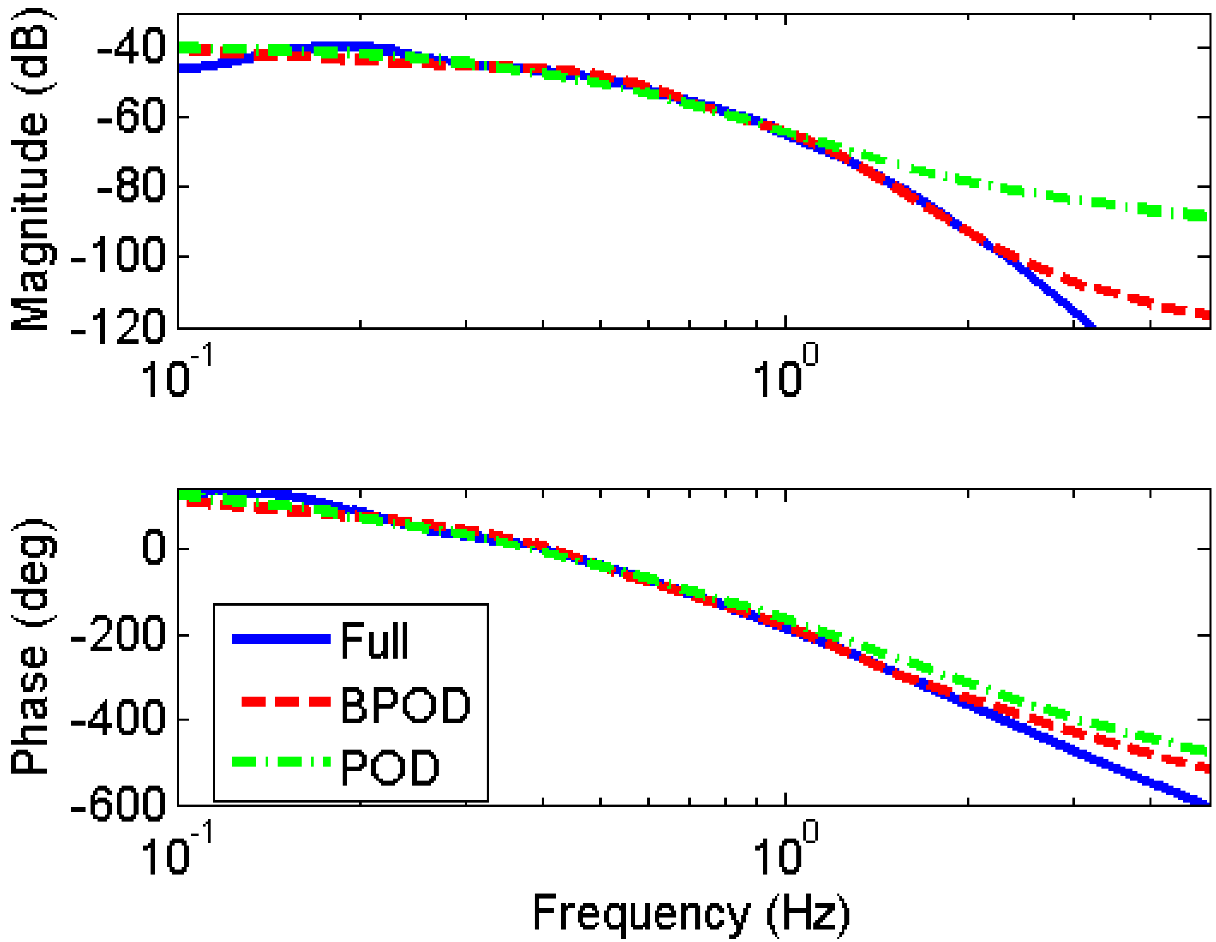
# Balanced POD

- Example: Actuator Disk
  - Actuator Disk: 80,000 states
  - Represented with 5 modes
- Fewer BPOD modes needed to obtain low-order model



# Reduced Order Models



# Conclusions

- **Goal:** Construct control-oriented models for wind farms
  - Models need to be low-order but of sufficient fidelity.
  - Use models to design coordinated wind farm controllers
- **Approaches:**
  - Experimental (black-box) models
  - First-principles, reduced order models via BPOD
- **Next Steps:**
  - Extend BPOD method from actuator disk to higher fidelity models
  - Use models for simple control designs
  - Test controllers in simulation and wind tunnel.

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  - http://www.safl.umn.edu/
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