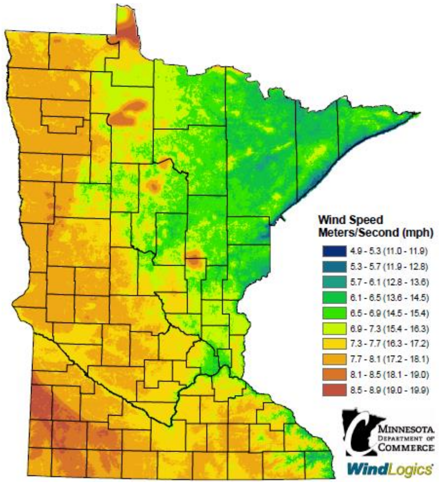
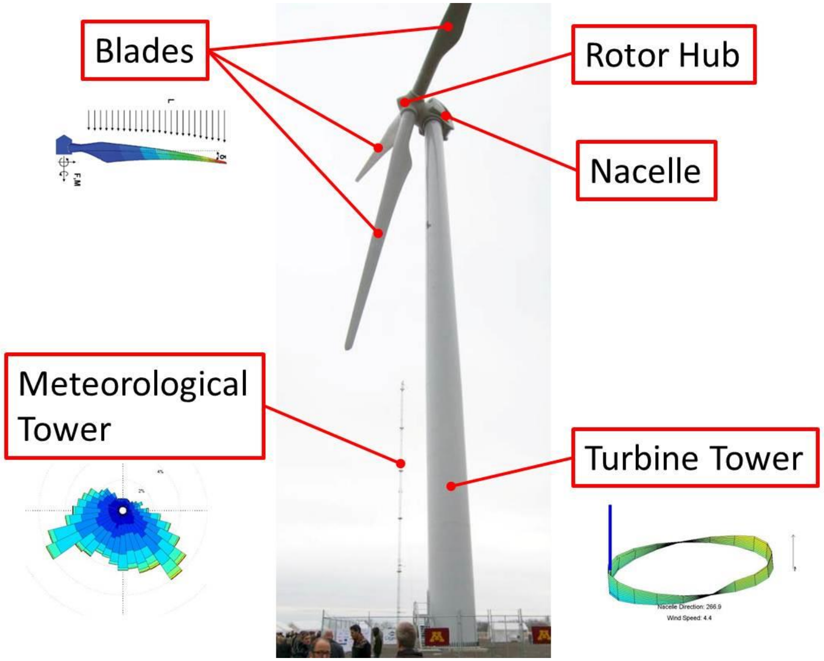
High Reliability Monitoring and Control of Wind Turbines

Peter Seiler
Department of Aerospace Engineering & Mechanics
University of Minnesota



Turbine Components

Eolos Field Station



Blades

Rotor Hub

Nacelle

Meteorological Tower

Turbine Tower

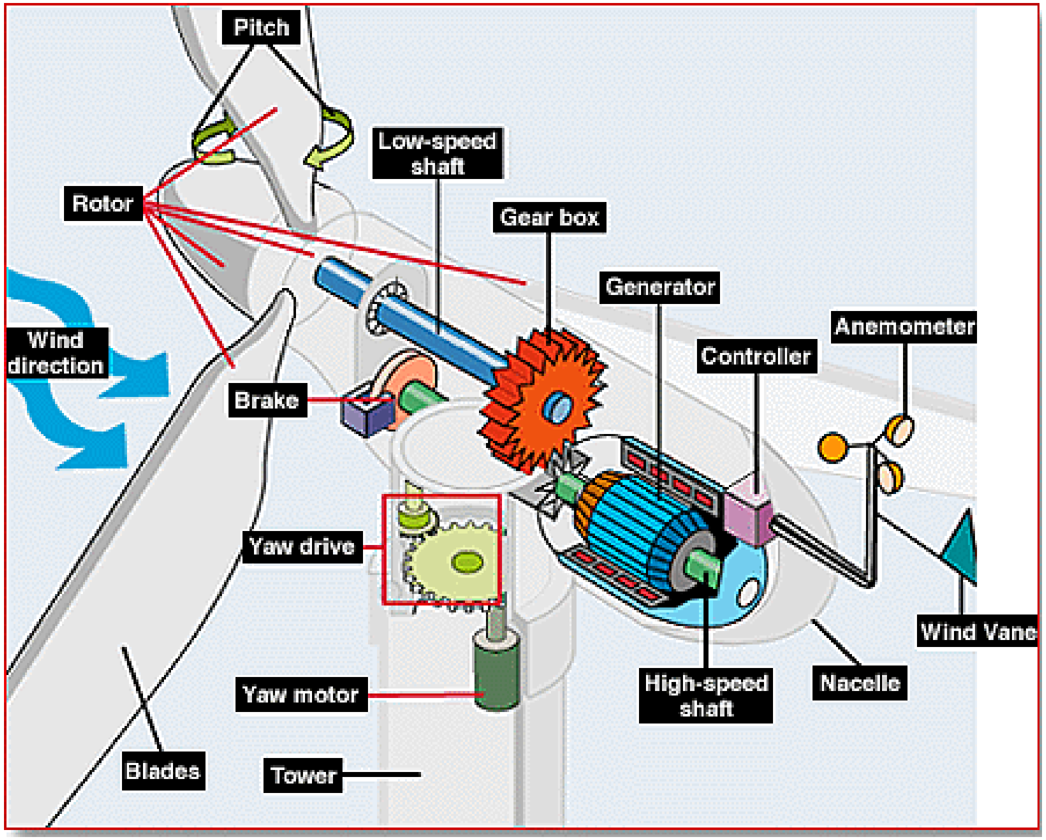


Figure from the US DOE

Performance Objectives

1. Maximize captured power

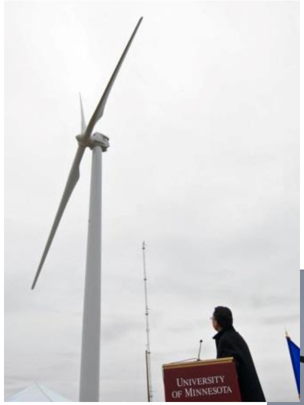
$$P = \boxed{\tfrac{1}{2}\rho A v^3}\,\boxed{C_p}$$

Power in Wind

Power Coefficient: Function of turbine design, wind conditions, and control

2. Minimize structural loads
3. Reduce operational downtime

Outline



1. Overview of UMN / Eolos Research

2. Redundancy Management in Commercial Aviation

3. Blade health monitoring using energy harvesting

4. Conclusions…

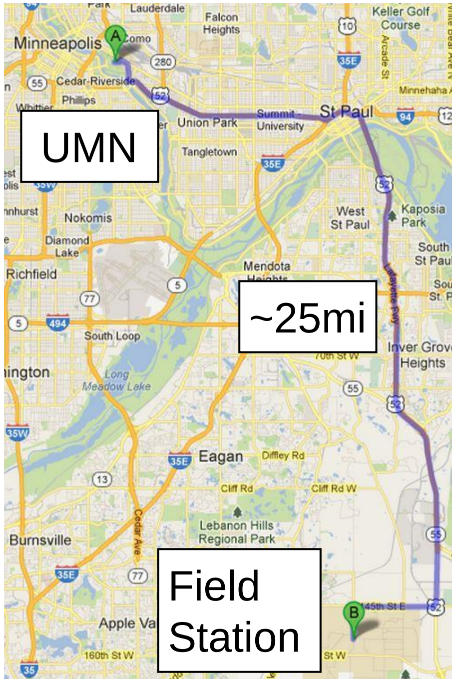
Eolos Consortium

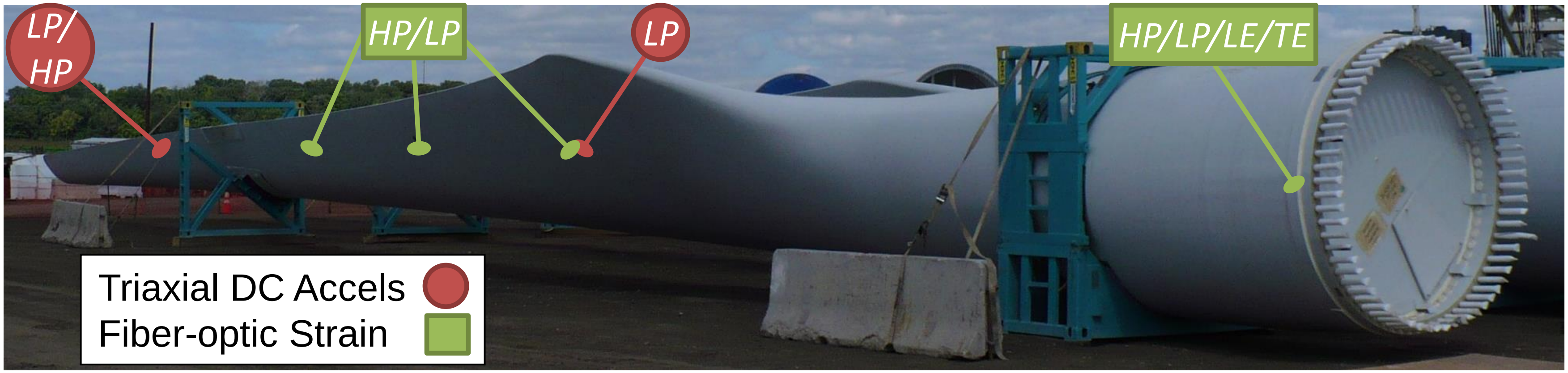
Established via US DOE Grant

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

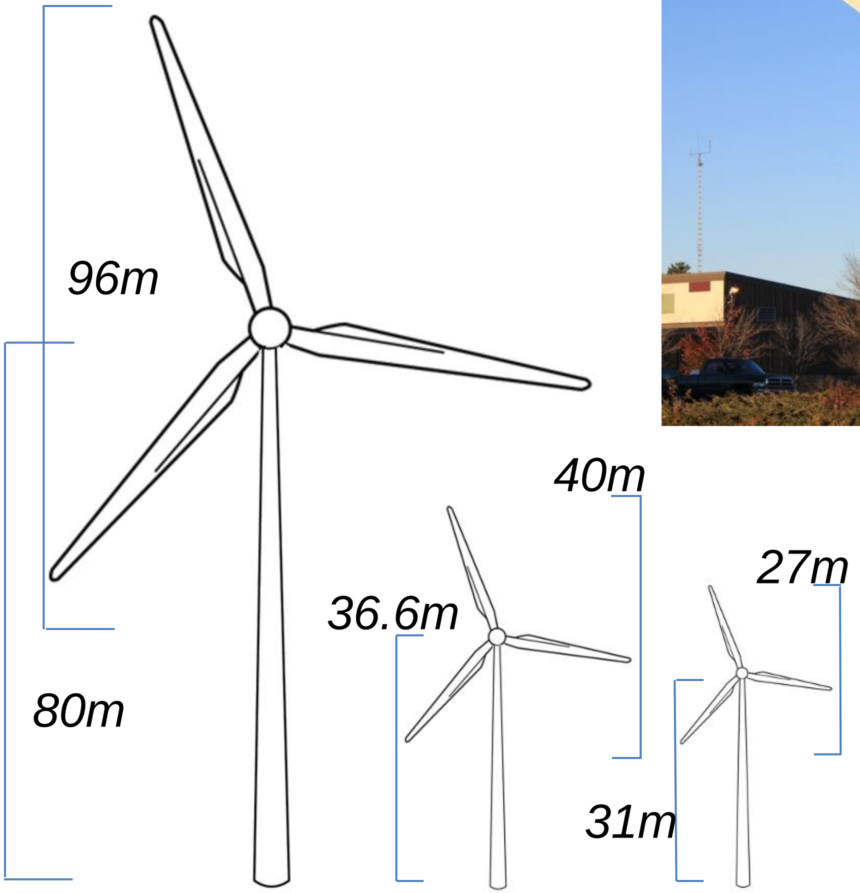
Wind Field Station

- 2.5MW / 96M Clipper Liberty
- (Commissioned on 10/25/2012)





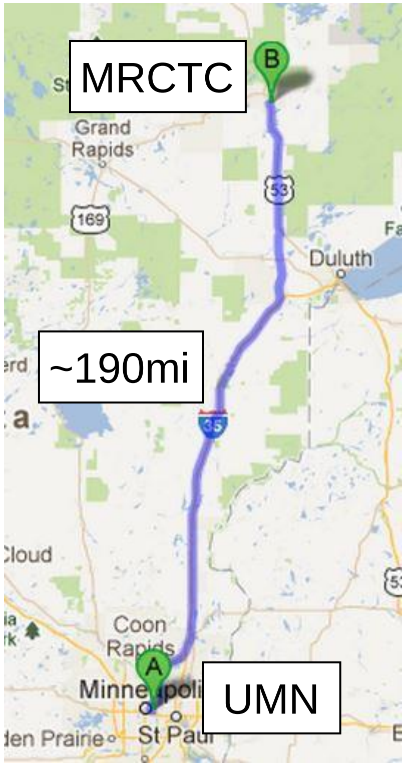
Collaboration with Mesabi Range CTC



Liberty C96
(Eolos)

CART3
(NREL)

225kW Vestas V27
(Mesabi Range)



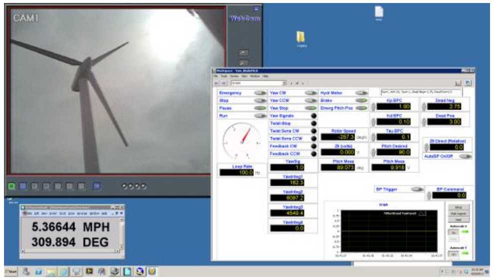
Mesabi Range CTC

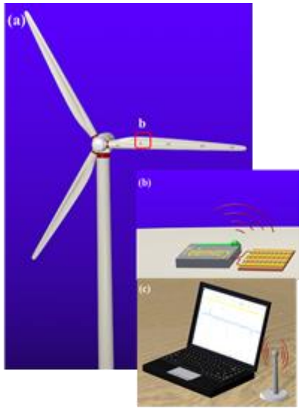
Wind Energy Technology Program offers A.A.S. degree for maintenance of utility scale wind turbines.

(V27 shipped from Antwerp on 9/28/2010)

Overview of Research Projects

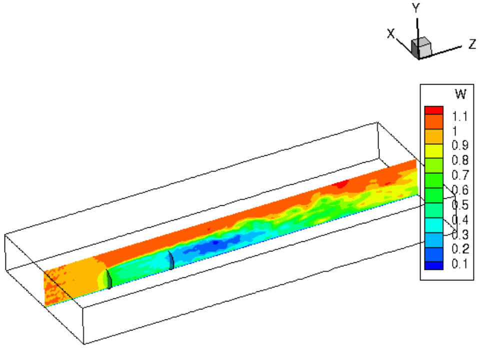
V27 Control (Thorson, *Janisch*)

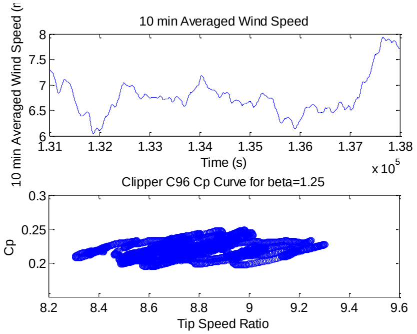




Blade Health Monitoring (Lim, *Mantell, Yang*)

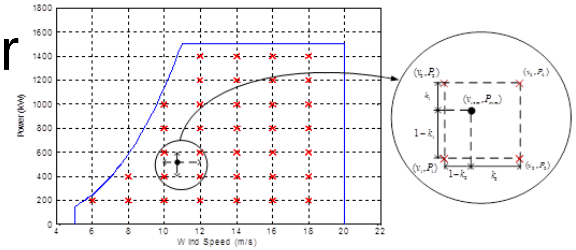
Wind Farm Control (Annoni, Yang, *Sotiropolous, Bitar*)





Distributed Estimation (Showers)

Active Power Control (Wang)



Multivariable Design Tools (Ozdemir, Escobar Sanabria, *Balas*)

V27 Control Design

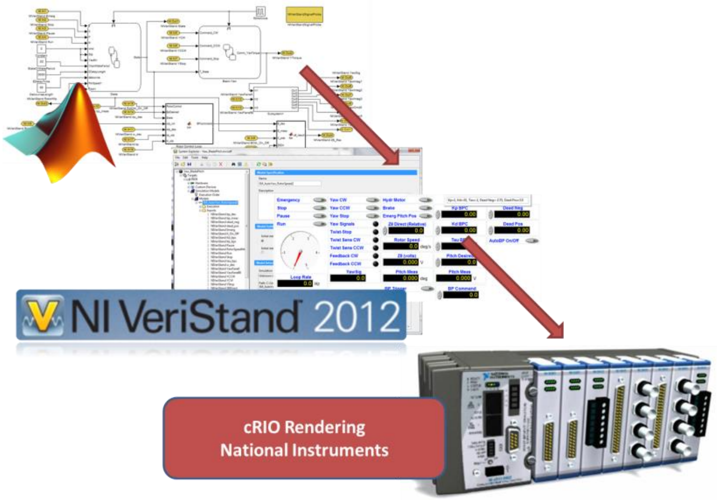
Accomplishments:

- Mesabi Range rewired turbine, removed stock controller and installed Master/Slave CRIOs
- UMN designed turbine state logic and rotor speed tracking.

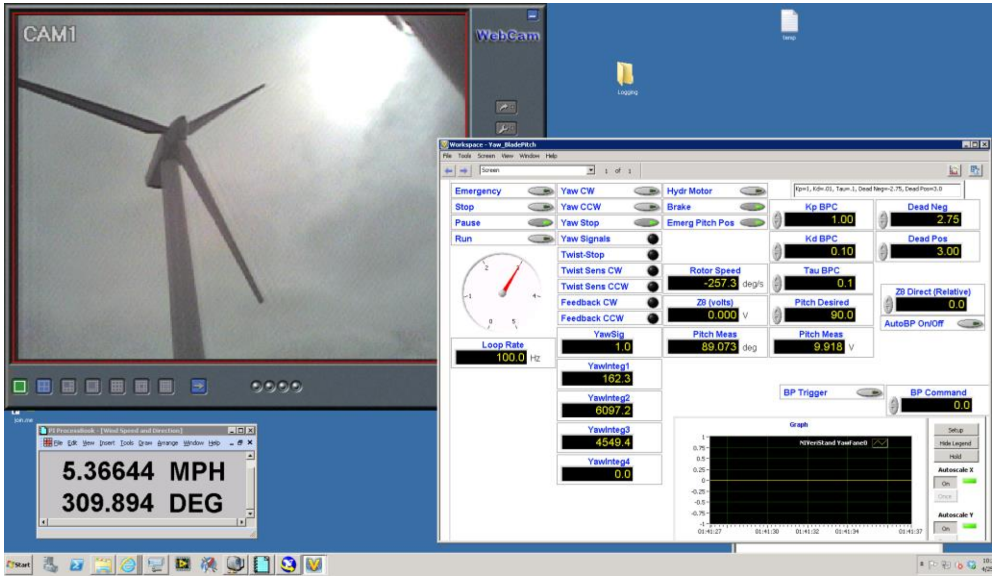
Future: Fixed speed power generation

References:

- Vestas V27 Test, Petersen, 90
- CART Commissioning, Fingersh/Johnson 02, 04



cRIO Rendering
National Instruments



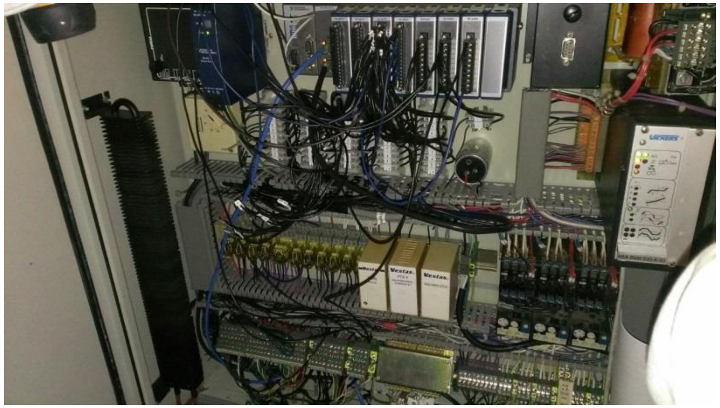
Workspace - Yaw_BladePitch

Kp=1, Kd=.01, Tau=.1, Dead Neg=-2.75, Dead Pos=3.0

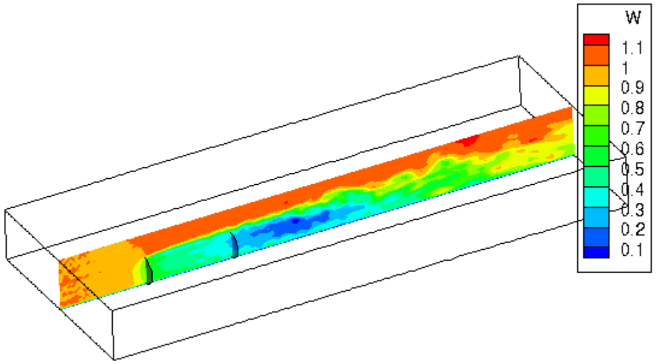
Kp BPC 1.00
Dead Neg 2.75
Kd BPC 0.10
Dead Pos 3.00
Tau BPC 0.1
Rotor Speed -257.3 deg/s
Z8 (volts) 0.000 V
Pitch Desired 90.0
Z8 Direct (Relative) 0.0
Pitch Meas 89.073 deg
Pitch Meas 9.918 V
Loop Rate 100.0 Hz
YawSig 1.0
YawInteg1 162.3
YawInteg2 6097.2
YawInteg3 4549.4
YawInteg4 0.0
BP Command 0.0

PI ProcessBook - [Wind Speed and Direction]

5.36644 MPH
309.894 DEG



Wind Farm Modeling and Control



Objectives:

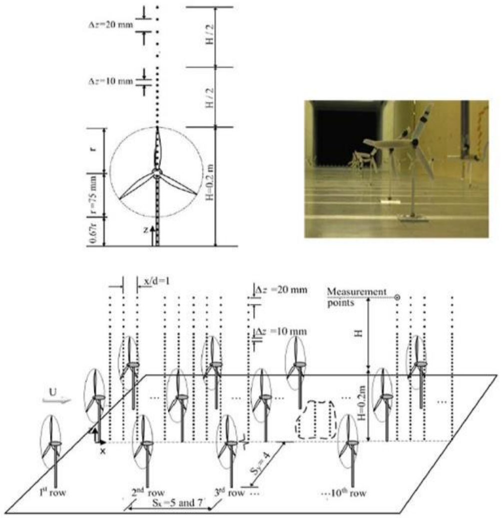
- Develop control-oriented models
- Design control laws for increased power capture and load mitigation (Bitar, Seiler, '13 ACC)

Simulators:

- Saint Anthony Falls **Virtual Wind Simulator** (Yang, Kang, Sotiropoulos 2012; Chamorro, Porte-Agel 2011)
- NREL **SOWFA** (Churchfield, Lee, Michalakes, Moriarty, 2012)

Selected References:

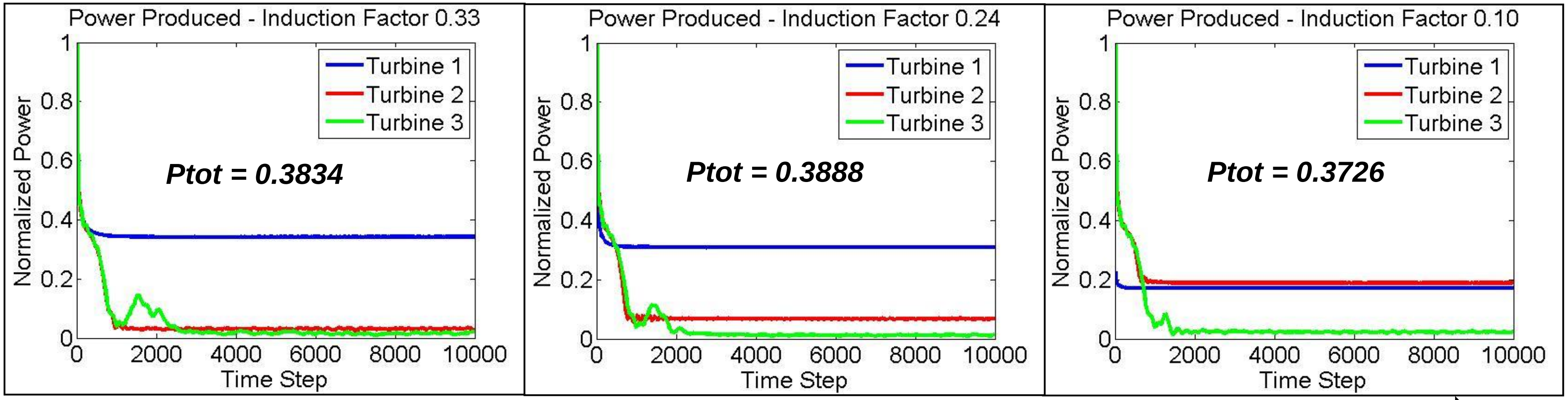
- Jensen, '83 Risø Report
- Steinbuch, de Boer, Bosgra, Peters, Ploeg, '88 JWEIA
- Johnson, Thomas, '09 ACC
- Pao, Johnson, '09 ACC
- Brand, Soleimanzadeh, 11 EWEA
- Marden, Ruben, Pao, '12 ASM
- Wagenaar, Machielse, Schepers, 12 EWEA
- Fleming, Gebraad, van Wingerden, Lee, Churchfield, Scholbrock, Michalakes, Johnson, Moriarty, '13 EWEA



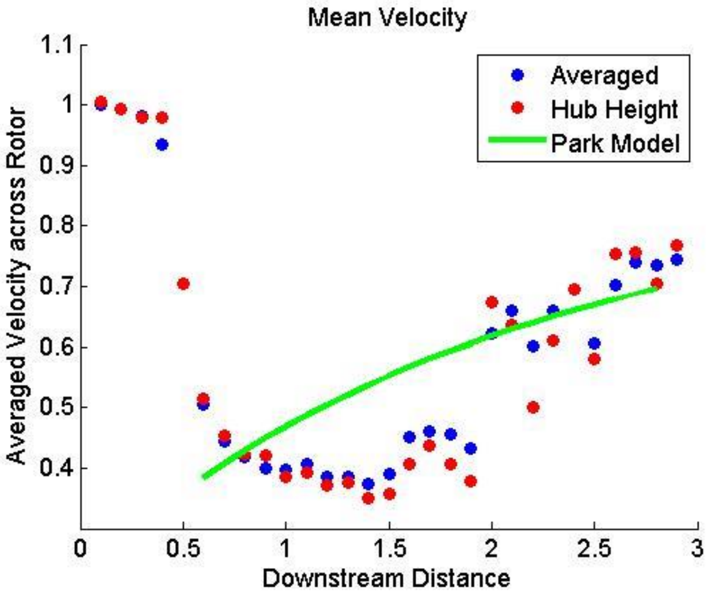
SAFL Wind Tunnel Tests

(Chamorro, Porte-Agel)

CFD Results



Decreasing Lead Turbine Induction Factor



Park Model (Jensen, '83):

$$v = v_\infty(1-\delta v) \text{ where } \delta v = 2a\left(\frac{D}{D+2kx}\right)^2$$

Simulation: Turbine Located at x=0.5
Park model fit shown with k=0.01

Summary: Opportunity to optimize total power output but validated control-oriented models are needed.

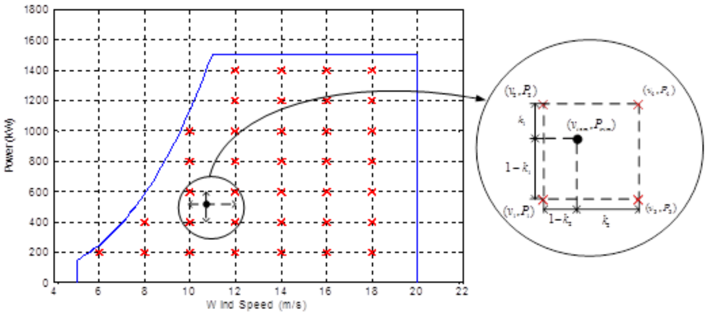
Active Power Control

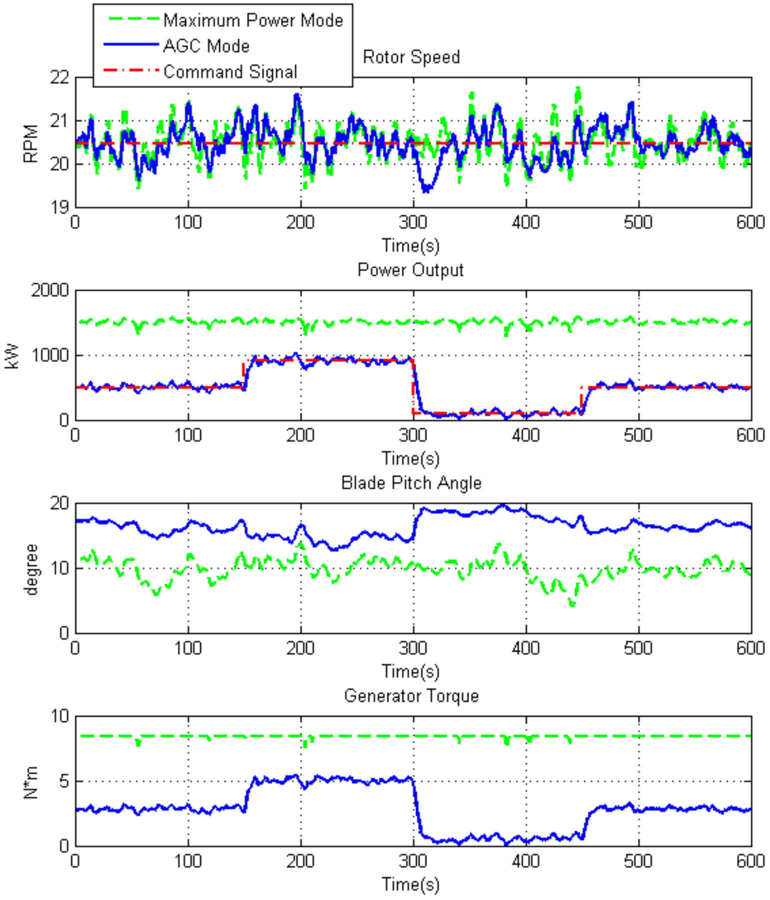
Objectives:

- Use gain-scheduling to track arbitrary power set-point commands (Wang, Seiler, ‘13 Draft)
- Investigate feasibility for ancillary services

Selected References:

- Kirby, Dyer, Martinez, Shoureshi, Guttromson, ‘02 Oak Ridge Report
- Keung, Li, Banakar, Ooi, ‘09 TPS
- Juankorena, Esandi, Lopez, Marroyo, ‘09 CPEEED
- Spudić, Jelavić, Baotić, Perić, ‘10 Torque
- Tarnowski, Kjaer, Dalsgaard, Nyborg, ‘10 PES
- Laks, Pao, Wright, ‘12 ACC
- Aho, Buckspan, Pao, Fleming, ‘13 ASM
- Jeong, Johnson, Fleming, ‘13 WE

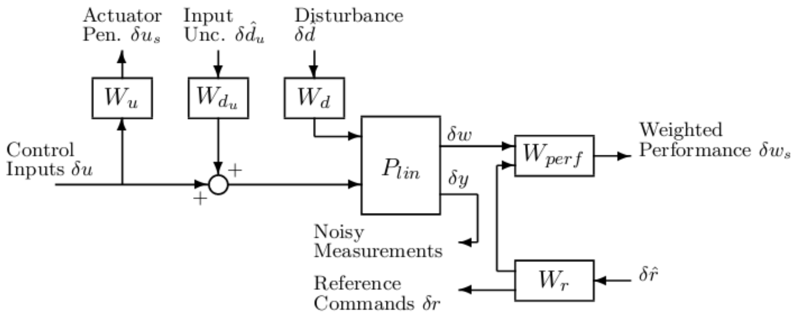




Multivariable Control Design

Objective:

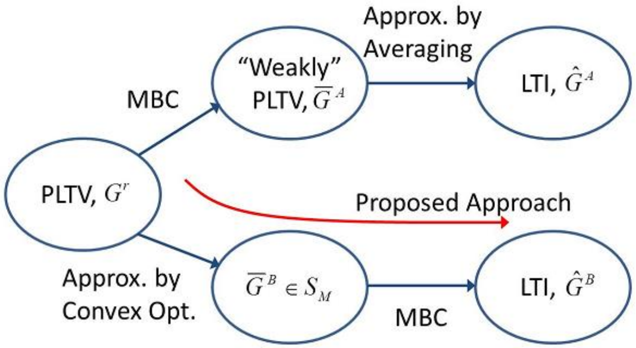
- Develop a framework to easily tune advanced (robust) control designs for wind turbines (Ozdemir, ‘13 PhD)
- Integrate advanced sensors (LIDAR) for preview control (Ozdemir, Seiler, Balas, ‘12 ASM, ‘12 ACC, ‘13 ASM, ‘13 TCST)
- Optimal Multi-Blade Coordinate Transformation (Seiler, Ozdemir, ‘13 ACC)



Selected (LIDAR) References:

- Harris, Hand, and Wright, ’06 NREL Report
- Laks, Pao, Wright, ‘09 ASM
- Mikkelsen, Hansen, Angelou, Sjöholm, Harris, Hadley, Scullion, Ellis, Vives, ‘10 AWEA
- Schlipf, Schuler, Grau, Allgöwer, Kühn, ‘10 Torque
- Laks, Pao, Wright, Kelley, B. Jonkman, ‘10 ASM
- Laks, Pao, Simley, Wright, Kelley, ‘11 ASM
- Dunne, Pao, Wright, B. Jonkman, Kelley, Simley, ‘11 ASM
- Korber, King, ‘11 AWEA

Figure from Harris, Hand, and Wright, ‘06



Distributed Estimation

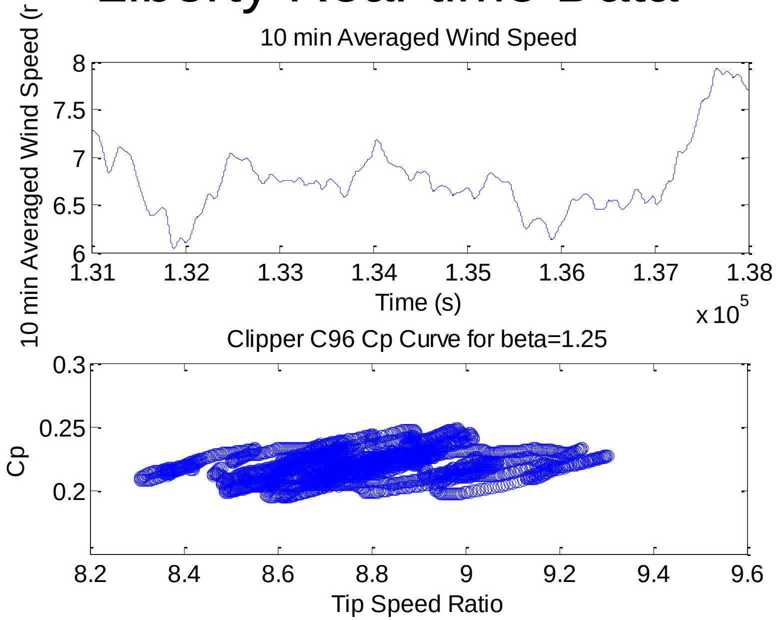
Objectives:

- Identify turbine model from real-time data
- Use measurements from upstream turbines to estimate wind for use as feedforward signal for downstream turbines.

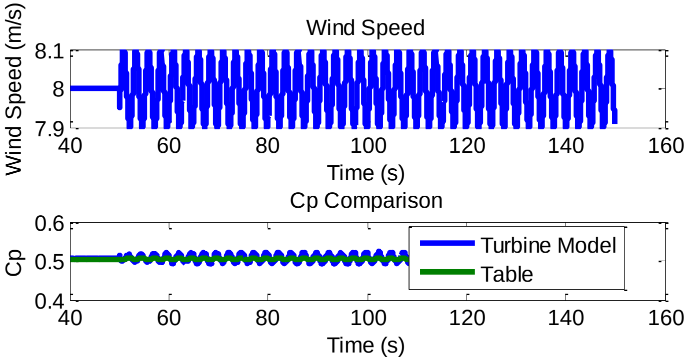
Selected References:

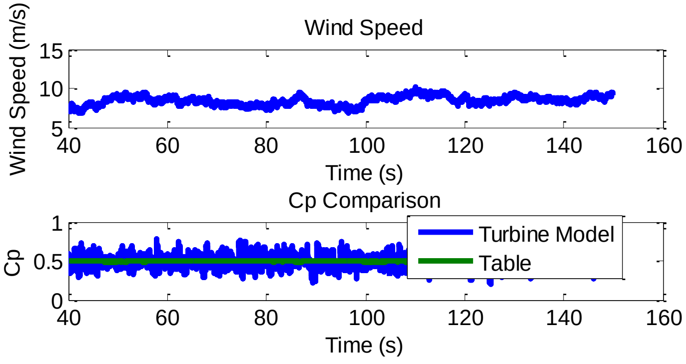
- Odgaard, Damgaard, Nielsen, ‘08 IFAC
- Knudsen, Bak, Soltani, ‘11 WE
- Van Wingerden, Houtzager, Felici, Verhaegen, 09 IJRNC
- Gebraad, van Wingerden, Fleming, Wright, 11 CCA

Liberty Real-time Data



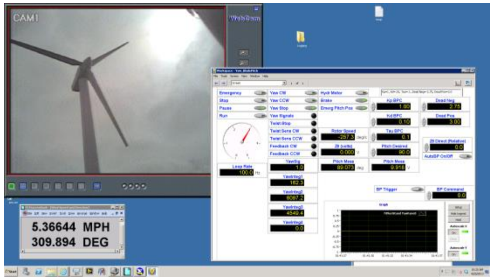
FAST Simulations



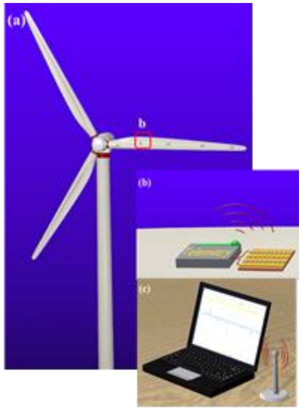


Overview of Research Projects

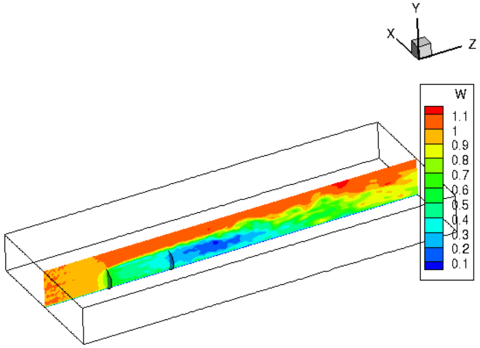
V27 Control (Thorson, *Janisch*)



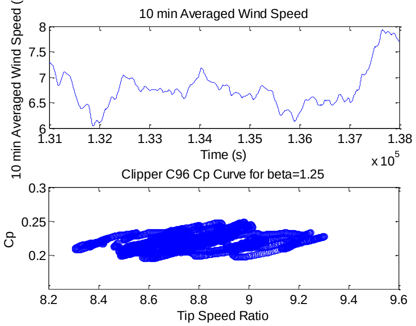
Blade Health Monitoring (Lim, *Mantell*, *Yang*)



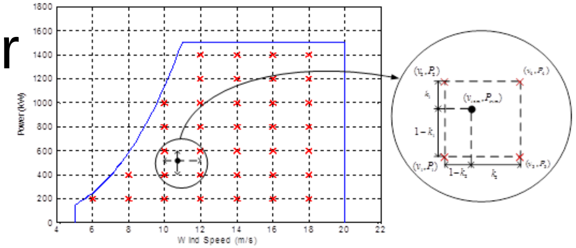
Wind Farm Control (Annoni, Yang, *Sotiropolous*, *Bitar*)



Distributed Estimation (Showers)



Active Power Control (Wang)

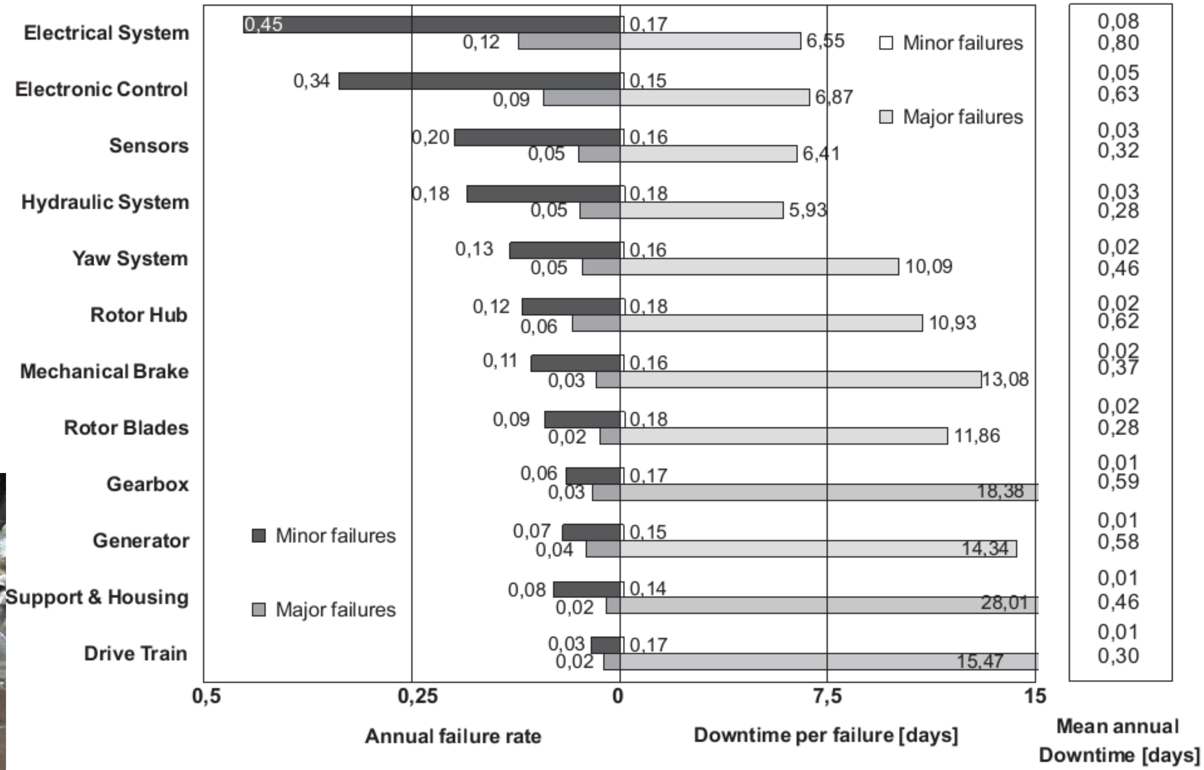


Multivariable Design Tools (Ozdemir, Escobar Sanabria, *Balas*)

Motivation for Monitoring

Damaged Gearbox

(Image courtesy of Mesabi Range Community and Tech. College)



Failures Rates

Table from: “Wind turbine downtime and its importance for offshore deployment”, Faulstich, Hahn, Tavner, Wind Energy, 2010.

Motivation for Monitoring

- Cost of wind energy dominated by capital (installation) + operations & maintenance
- Monitoring can be used to reduce O&M costs
  - Preventative maintenance during low wind
  - Continued operation after failures
- Large literature of wind turbine monitoring
  - 2011 IFAC Competition (Benchmark from Odgaard, Stoustrup, and Kinnaert, 2009 SAFEPROCESS).
  - Variety of methods including model-based, data-driven, physical redundancy
- **Question:** Can design techniques developed for aerospace systems be applied for turbines?

Commercial Fly-by-Wire

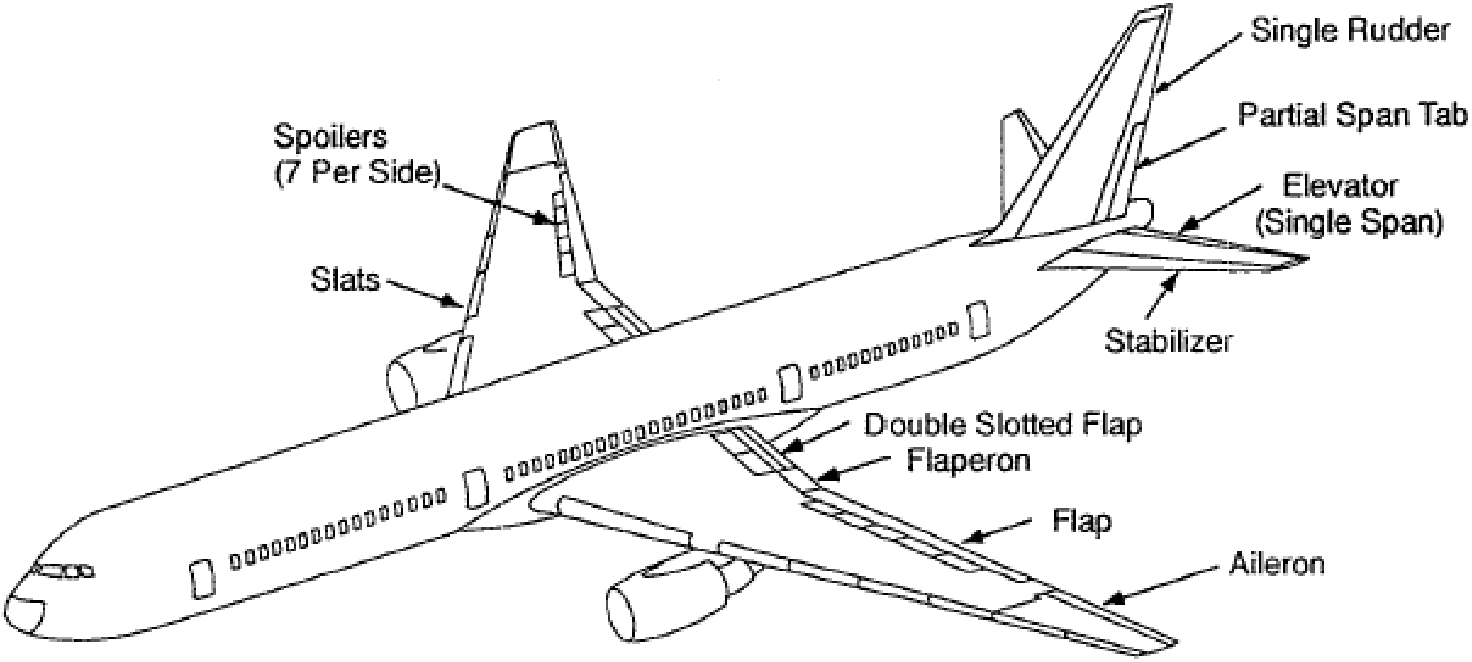
Boeing 787-8 Dreamliner

- 210-250 seats
- Length=56.7m, Wingspan=60.0m
- Range < 15200km, Speed< M0.89
- First Composite Airliner
- Honeywell Flight Control Electronics

Boeing 777-200

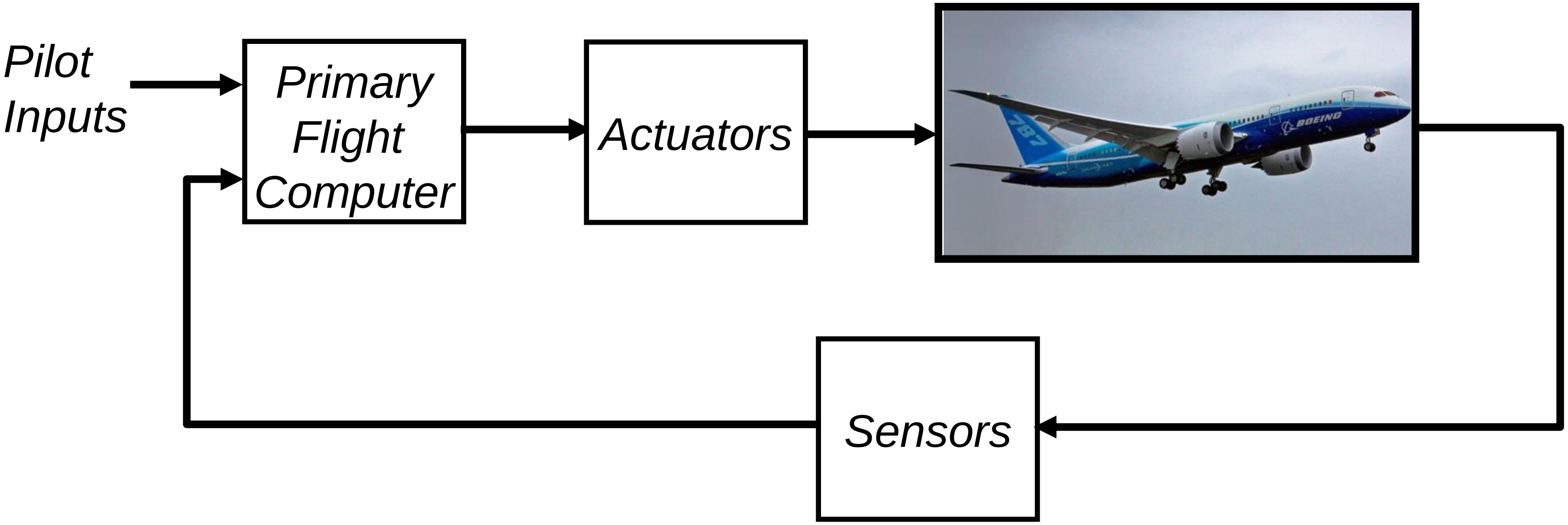
- *301-440 seats*
- *Length=63.7m, Wingspan=60.9m*
- *Range < 17370km, Speed< M0.89*
- *Boeing's 1st Fly-by-Wire Aircraft*
- *Ref: Y.C. Yeh, "Triple-triple redundant 777 primary flight computer," 1996.*

777 Primary Flight Control Surfaces [Yeh, 96]



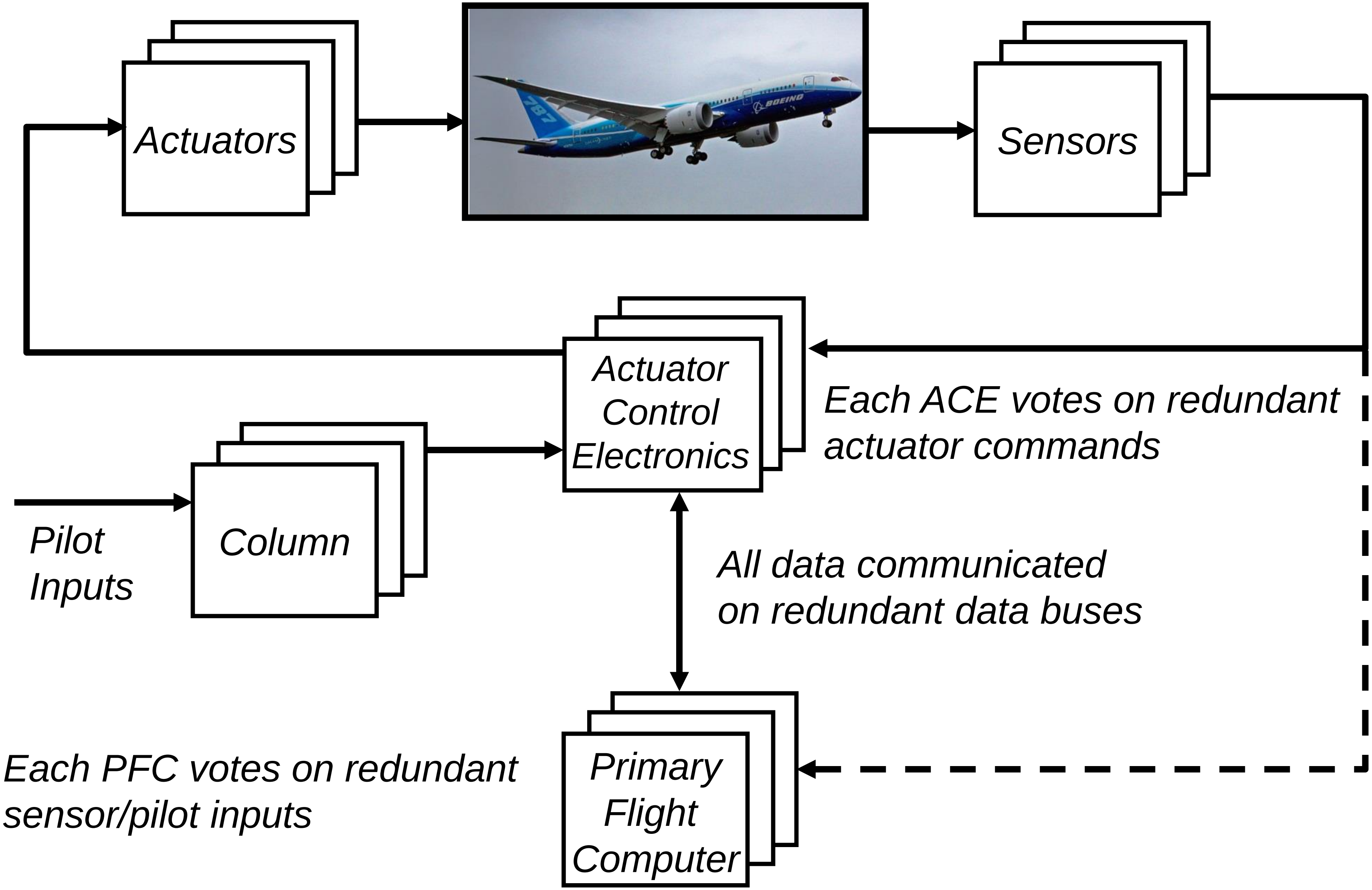
- Advantages of fly-by-wire:
  - Increased performance (e.g. reduced drag with smaller rudder), increased functionality (e.g. “soft” envelope protection), reduced weight, lower recurring costs, and possibility of sidesticks.
- Issues: Strict reliability requirements
  - $<10^{-9}$ catastrophic failures/hr
  - No single point of failure

Classical Feedback Diagram



Reliable implementation of this classical feedback loop adds many layers of complexity.

Triplex Control System Architecture



Actuators

Sensors

Actuator Control Electronics

Each ACE votes on redundant actuator commands

Pilot Inputs

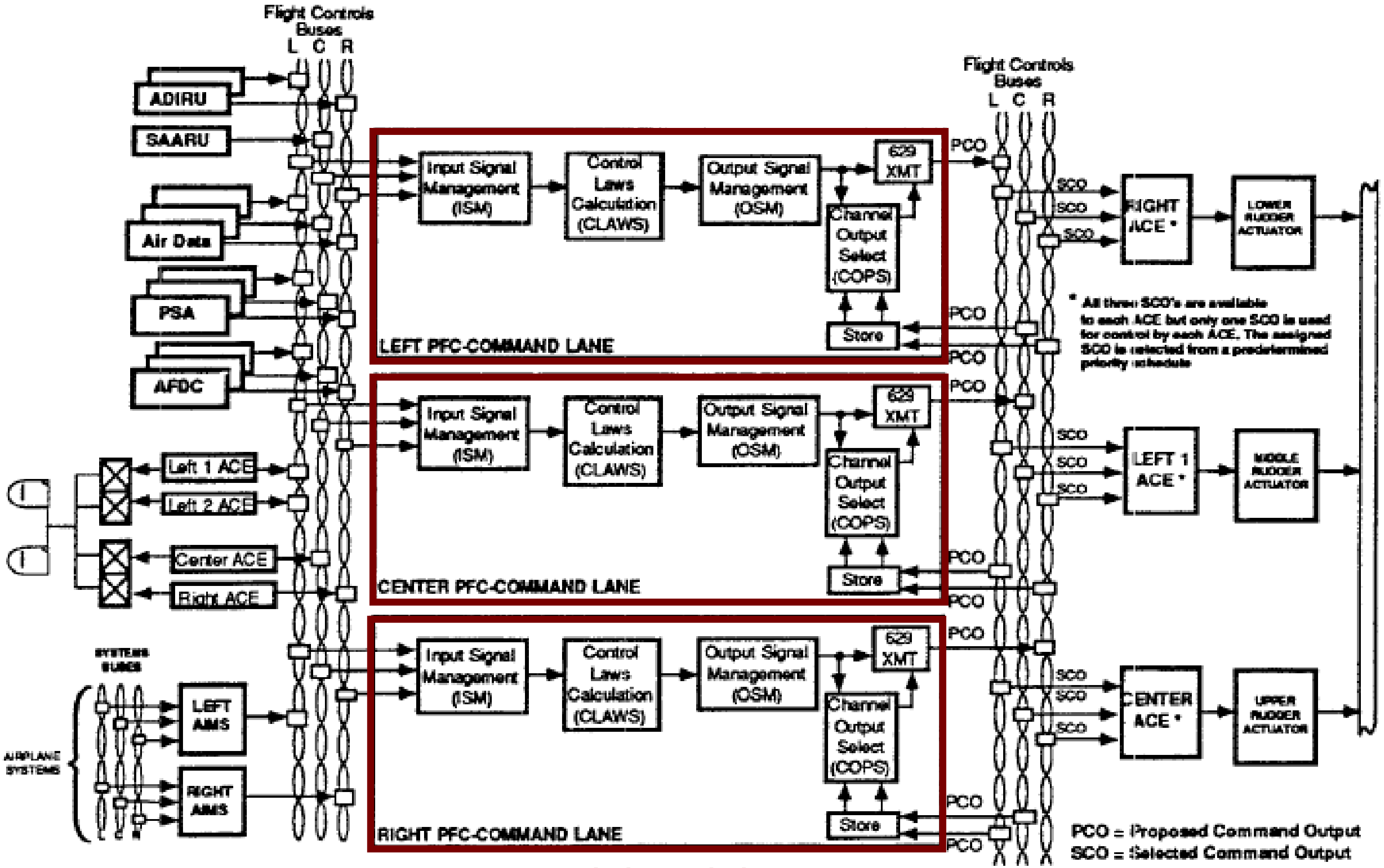
Column

All data communicated on redundant data buses

Each PFC votes on redundant sensor/pilot inputs

Primary Flight Computer

777 Triple-Triple Architecture [Yeh, 96]



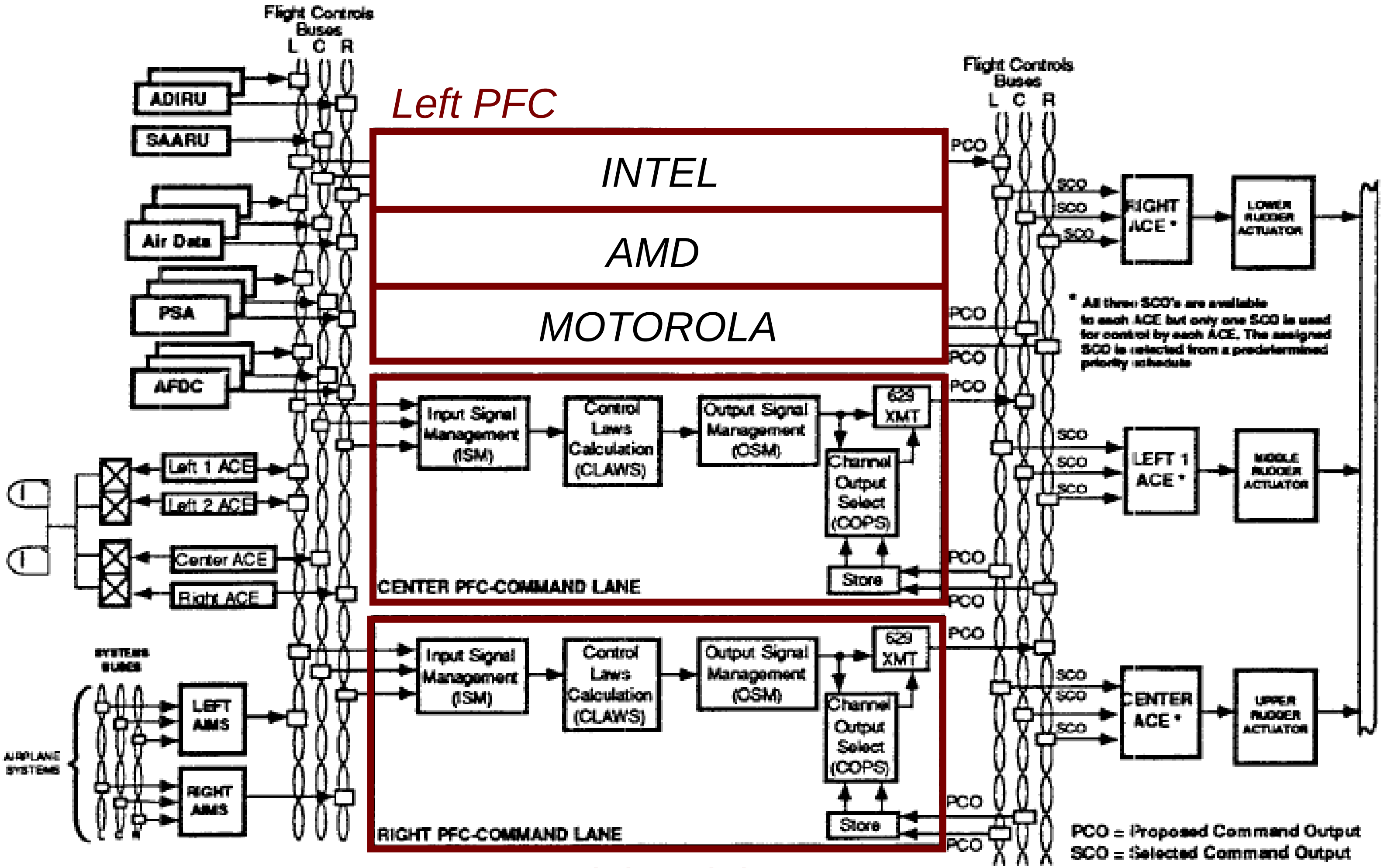
Sensors
x3

Databus
x3

Triple-Triple
Primary Flight
Computers

Actuator Electronics
x4

777 Triple-Triple Architecture [Yeh, 96]



Left PFC

INTEL

AMD

MOTOROLA

Sensors
x3

Databus
x3

Triple-Triple
Primary Flight
Computers

Actuator Electronics
x4

Ram Air Turbine

Ram air turbine: F-105 (Left) and Boeing 757 (Right)
http://en.wikipedia.org/wiki/Ram_air_turbine

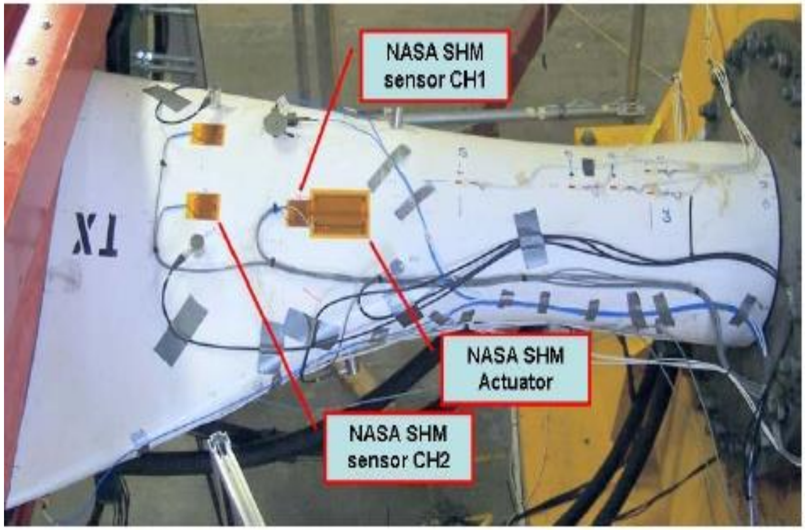
Summary of Redundancy Management

- Main Design Requirements:
  - < 10^{-9} catastrophic failures per hour
  - No single point of failure
  - Must protect against random and common-mode failures
- Basic Design Techniques
  - **Hardware redundancy to protect against random failures**
  - **Dissimilar hardware / software to protect against common-mode failures**
  - **Voting: To choose between redundant sensor/actuator signals**
  - Encryption: To prevent data corruption by failed components
  - Monitoring: Software/Hardware monitoring testing to detect latent faults
  - Operating Modes: Degraded modes to deal with failures
  - Equalization to handle unstable / marginally unstable control laws
  - Model-based design and implementation for software

Blade Structural Health Monitoring (SHM)

SHM benefits

- *Preventative maintenance*
- *Shortened down time*
- *Good for unpredictable working conditions*



SHM Example (Rumsey, Paquette, White, Werlock, Beattie, Pitchford, van Dam, Structural health monitoring of wind turbine blades, 2008)

Challenges

- *Data/Power transportation to/from sensors*
- *Retrofit capability desirable (no cabling)*

Proposed SHM System

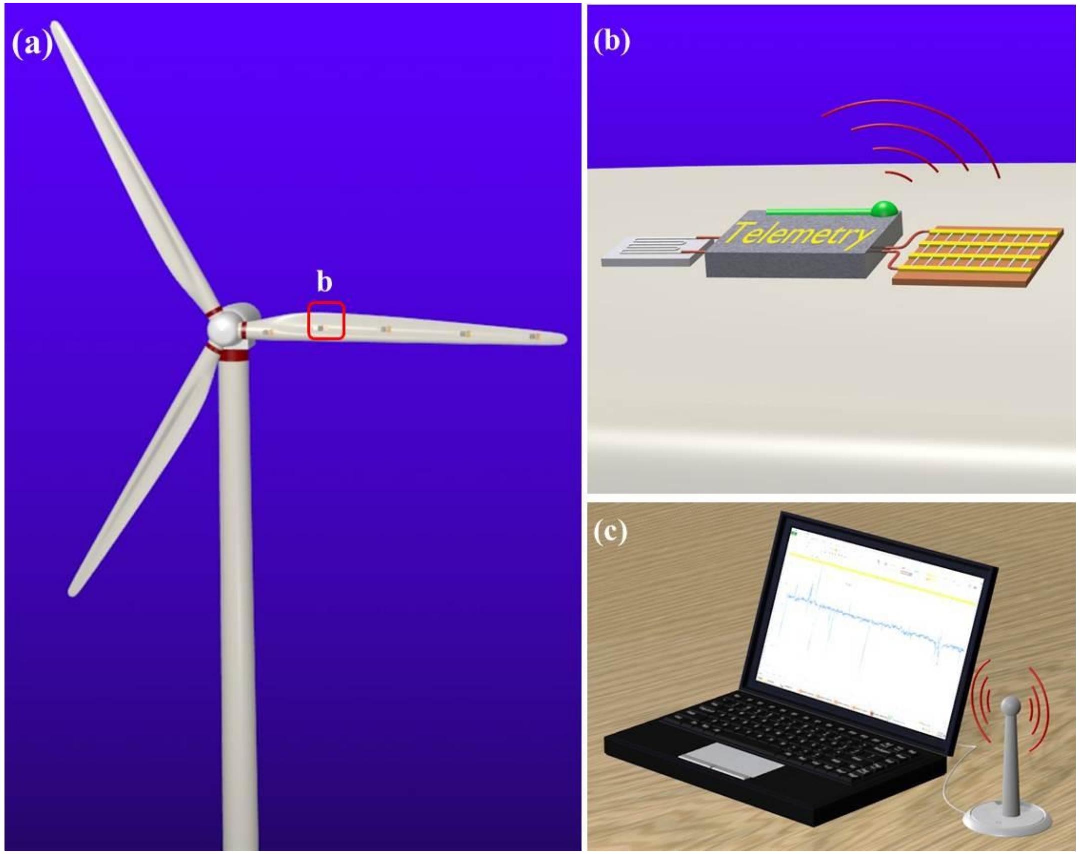
Sensors
(Strain/Acceleration)

+

Telemetry
(Wireless transceiver)

+

Energy Harvester
(Piezo-electric)



Issues:

1. Low power in blade vibration
2. Blade loading difficult to model / measure

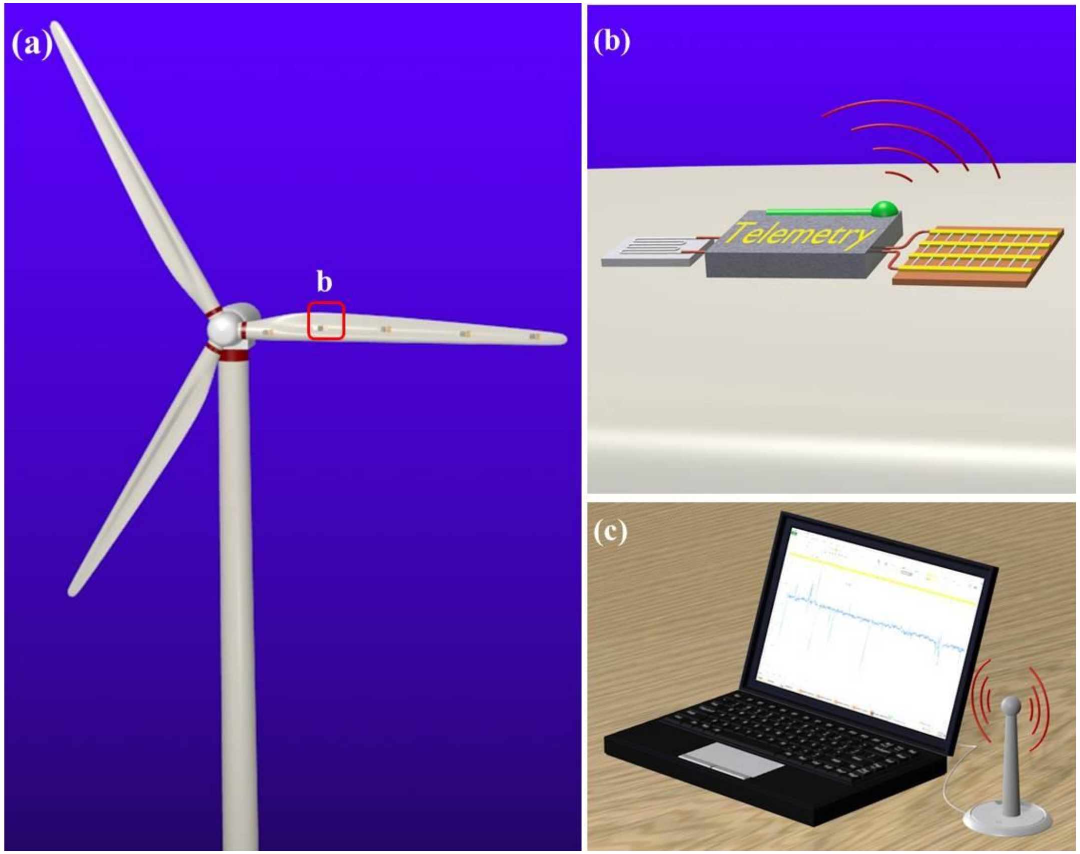
Proposed SHM System

Energy Harvestor = Sensor

+

Telemetry

(Wireless transceiver)



Solution:

1. Use harvested energy as the sensor
2. Rely on triple redundant measurements

Approach

- Estimate harvested energy
    - Properties of energy harvester (size, efficiency, etc)
    - Power available in blade vibrations
- Design low-rate health monitoring algorithm
- Assess feasibility of proposed SHM algorithm

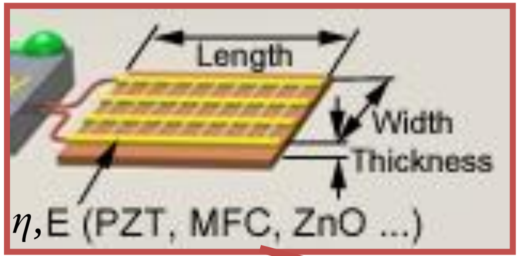
Harvested Strain Energy

Harvested Strain Energy

$$w_{strain} = \eta V_0 \frac{E}{E_0} \cdot E_0 \varepsilon^2 f \cdot \Delta t$$

Harvested Strain Energy

EH Design Variables:



Harvested Strain Energy

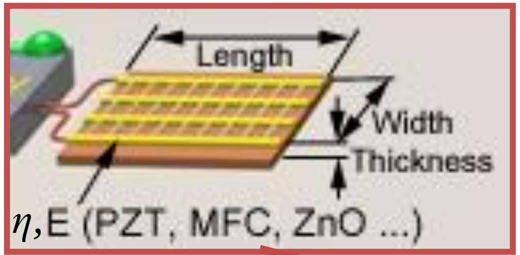
$$w_{strain} = \boxed{\eta V_0 \frac{E}{E_0}} \cdot E_0 \varepsilon^2 f \cdot \Delta t$$

$= K_{EH}$,

EH Design Factor

Harvested Strain Energy

EH Design Variables:



Harvested Strain Energy

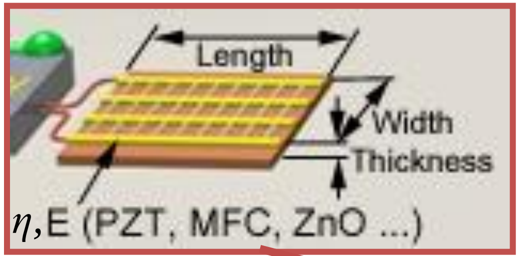
$$w_{strain} = \underbrace{\boxed{\eta V_0 \frac{E}{E_0}}}_{= K_{EH}} \cdot \underbrace{\boxed{E_0 \varepsilon^2 f}}_{= P_{avail}} \cdot \Delta t$$

$= K_{EH}$, **EH Design Factor**

$= P_{avail}$, **Available Strain Power**

Harvested Strain Energy

EH Design Variables:



Charging Time

Harvested Strain Energy

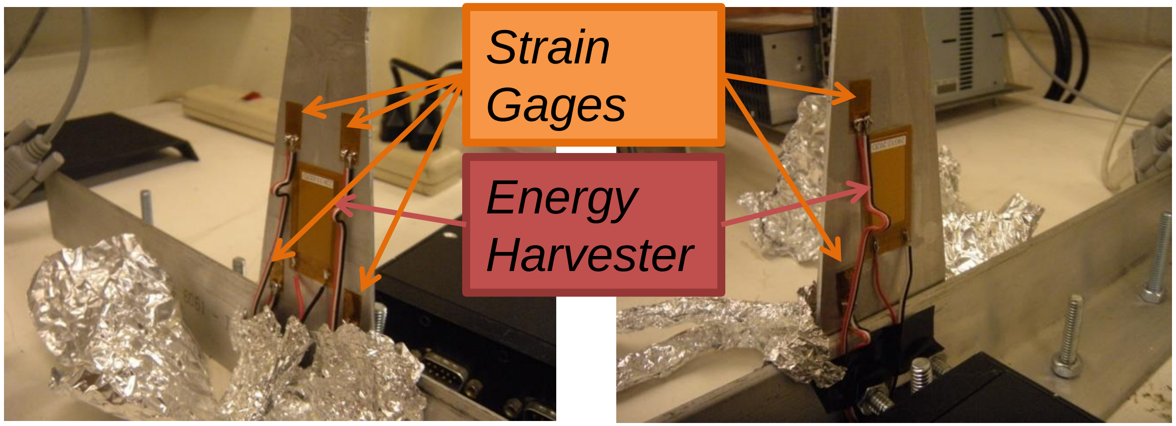
$$W_{strain} = \boxed{\eta V_0 \frac{E}{E_0}} \cdot \boxed{E_0 \varepsilon^2 f} \cdot \boxed{\Delta t}$$

$= K_{EH}$,
EH Design Factor

$= P_{avail}$,
Available Strain Power

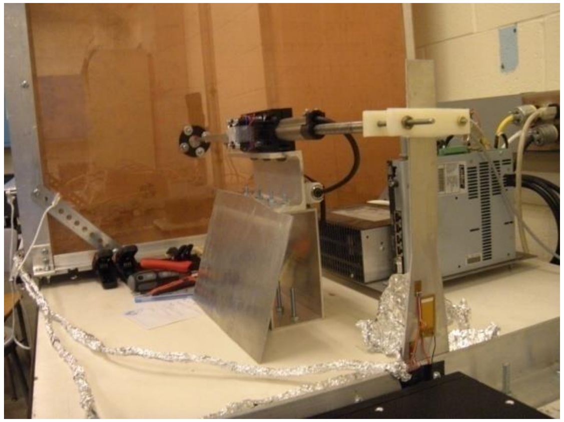
Experimental Set-up

SMART MATERIAL MFC P2 M2814 Energy Harvester



Front Side P1 Type

Back Side P2 Type



Overall set-up

Signal Conditioner Transceiver

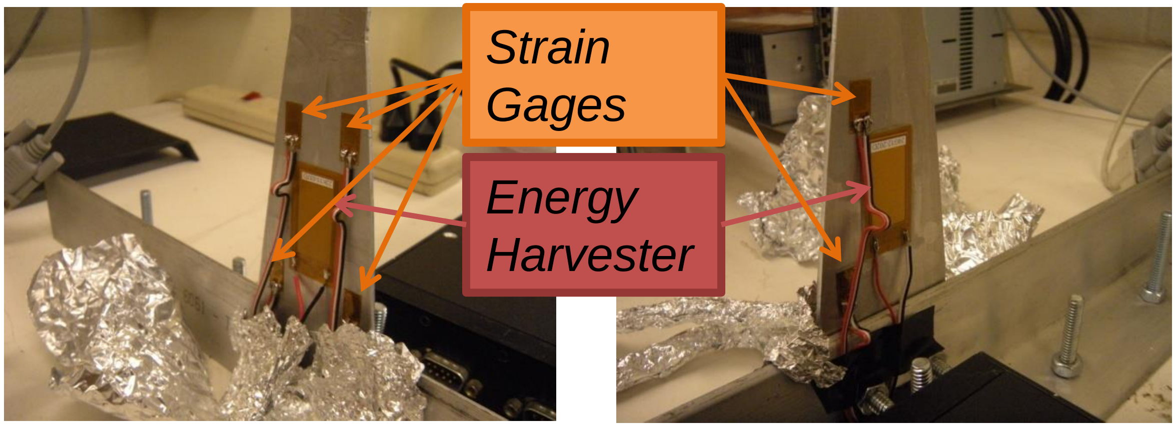
$$\boxed{w_{strain}} = \boxed{\eta V_0 \frac{E}{E_0}} \cdot E_0 \varepsilon^2 f \cdot \Delta t$$

92.4µJ (Transmission)
280µJ (Strain Meas.+Trans.)

$$K_{eh} = 0.004 \cdot 117.60 \cdot 30.34 = 14.27 mm^3$$

Experimental Set-up

SMART MATERIAL MFC P2 M2814 Energy Harvester

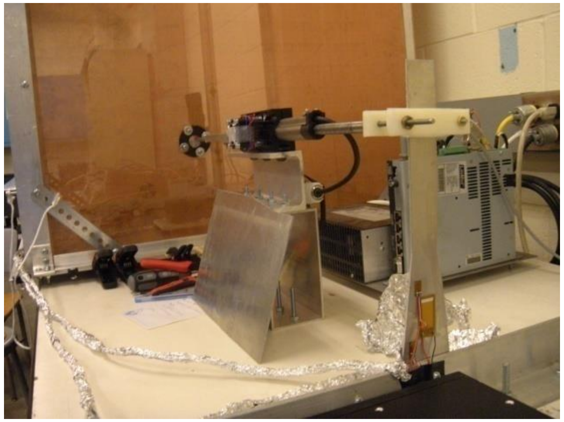


Strain Gages

Energy Harvester

Front Side P1 Type

Back Side P2 Type



Overall set-up

Signal Conditioner Transceiver

$$\boxed{w_{strain}} = \boxed{\eta V_0 \frac{E}{E_0}} \cdot \boxed{E_0 \varepsilon^2 f} \cdot \Delta t$$

92.4μJ (Transmission)
280μJ (Strain Meas.+Trans.)

Need to estimate available strain power in blade vibrations

$$K_{eh} = 0.004 \cdot 117.60 \cdot 30.34 = 14.27 mm^3$$

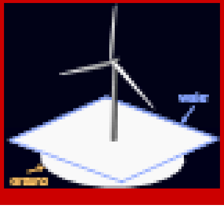
Modeling Blade Strain

Inputs

- *Flap DOF*
- *Edge DOF*
- *Initial conditions*
- *Number of Blades*
- *Blade Mode Shapes*
- *Wind Conditions*
- *. . .*

Full Turbine Simulations

(NREL FAST)



Outputs

- *Blade Displacement*
- *Shear Force*
- *Bending Moments*
- *. . .*

Ref. Jonkman, J. M., Buhl Jr, M. L., “FAST user’s guide,” NREL, Golden, Colorado, USA, 2005.

Modeling Blade Strain

Inputs

Flap DOF

Edge DOF

Initial conditions

Number of Blades

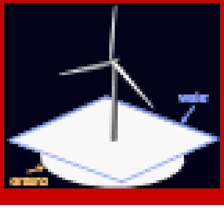
Blade Mode Shapes

Wind Conditions

. . .

Full Turbine Simulations

(NREL FAST)



Outputs

Blade Displacement

Shear Force

Bending Moments

. . .

Ref. Jonkman, J. M., Buhl Jr, M. L., "FAST user's guide," NREL, Golden, Colorado, USA, 2005.

Result: Calculate blade edge/flap strain using (FAST) simulated nodal bending moments

$$\varepsilon_{e,i} = \frac{M_{E,i} c_i}{2(EI)_{E,i}} \qquad \varepsilon_{f,i} = \frac{M_{F,i} t_i}{2(EI)_{F,i}}$$

Wind Turbine Case Studies

Characterize the strain energy available for typical wind turbines:

	CART3	*WindPact*	*Offshore*
Rated Power	*600 kW*	*1.5 MW*	*5.0 MW*
Rated Speed	*37.1 rpm*	*20.5 rpm*	*12.1 rpm*
Wind Speed	*6, 14, 20 m/s*	*3, 12, 28 m/s*	*3, 11, 25 m/s*
Length/Weight	*20m/1.8ton*	*35m/3.9ton*	*63m/17.7ton*
Hub Height	*34.9 m*	*84 m*	*87.6 m*

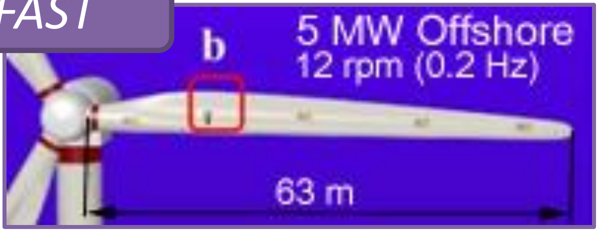
Wind Conditions : 6 m/s, Rated Speed, 24 m/s
+ Low / High Turbulence

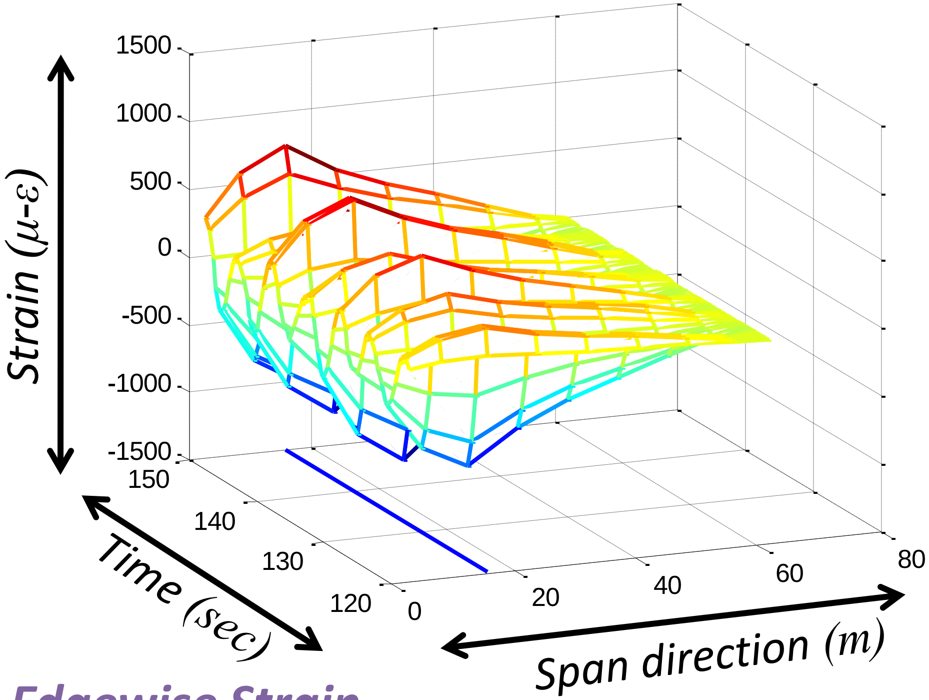
Strain Simulation in Time & Span

Wind Conditions

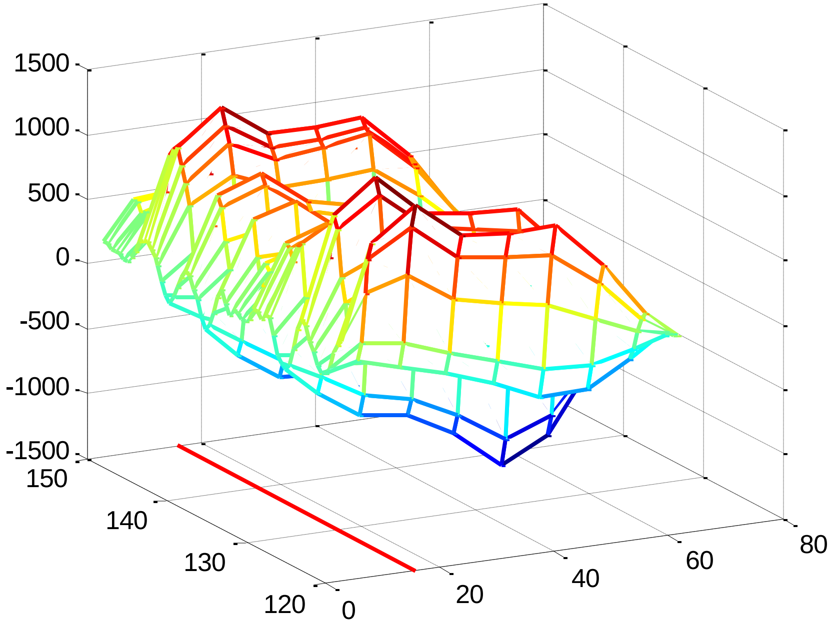
24 m/s, Low Turbulence

FAST





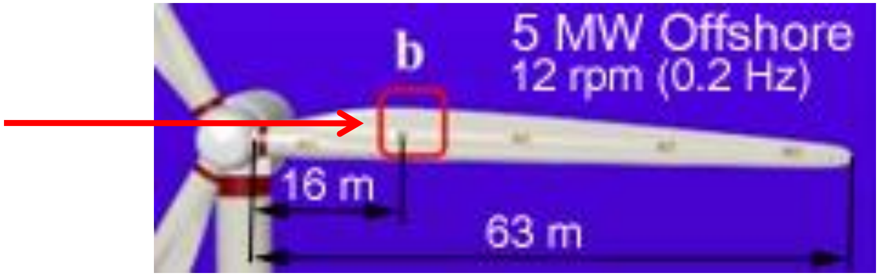
Edgewise Strain

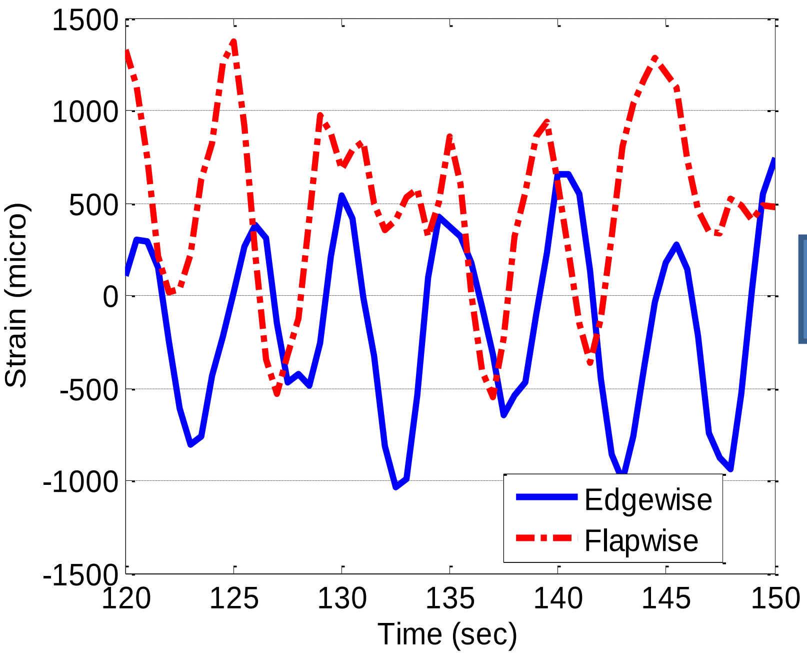


Flapwise Strain

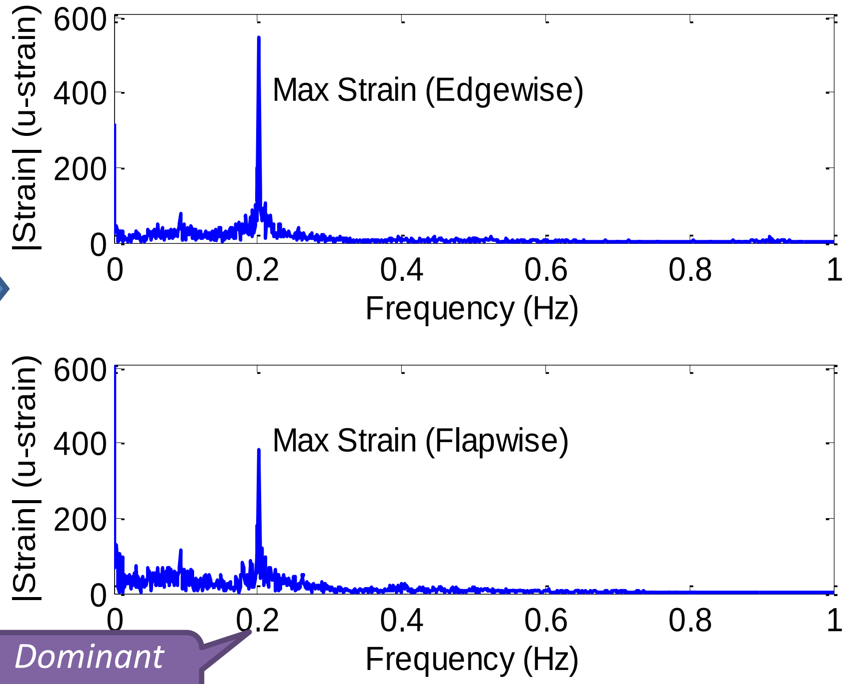
Strain Analysis

Pick one location





FFT



Dominant Freq.

Available Strain Power in Blade Span

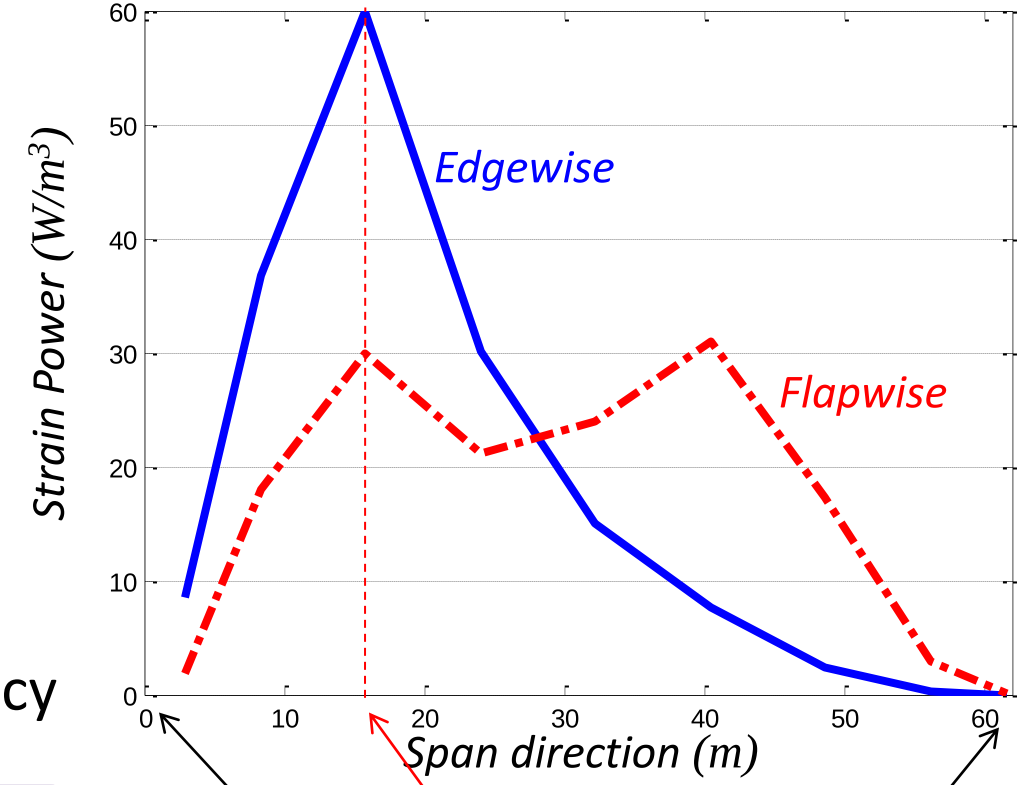
$$P_{avail} = E_0 \varepsilon^2 f$$

Nominal E_0 = 1 GPa

FFT analysis for 9 locations

ε = Strain Amplitude
(mean to peak)

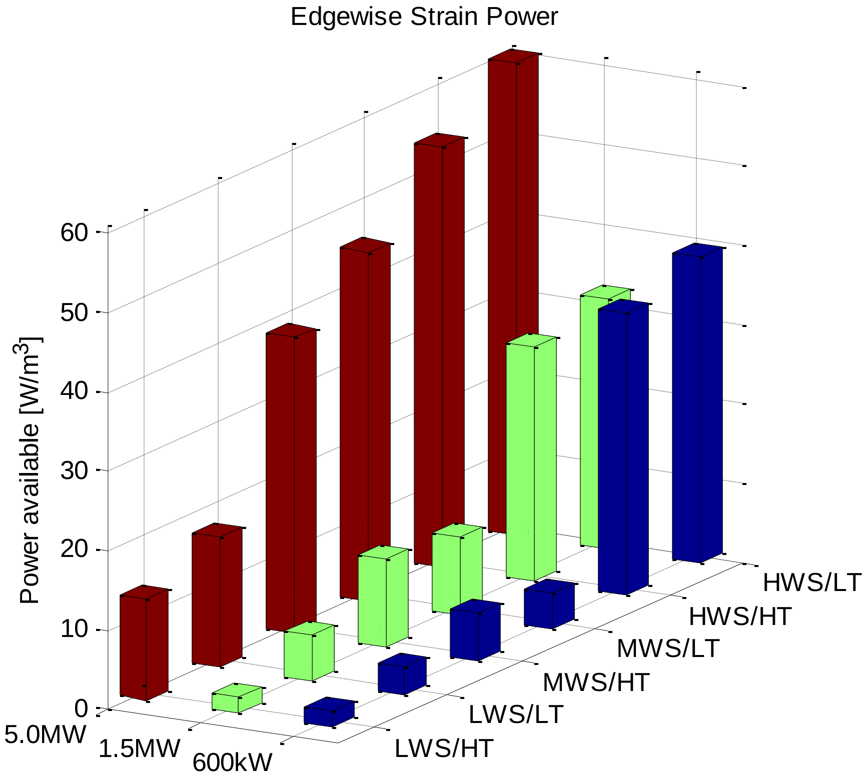
f = Dominant Frequency

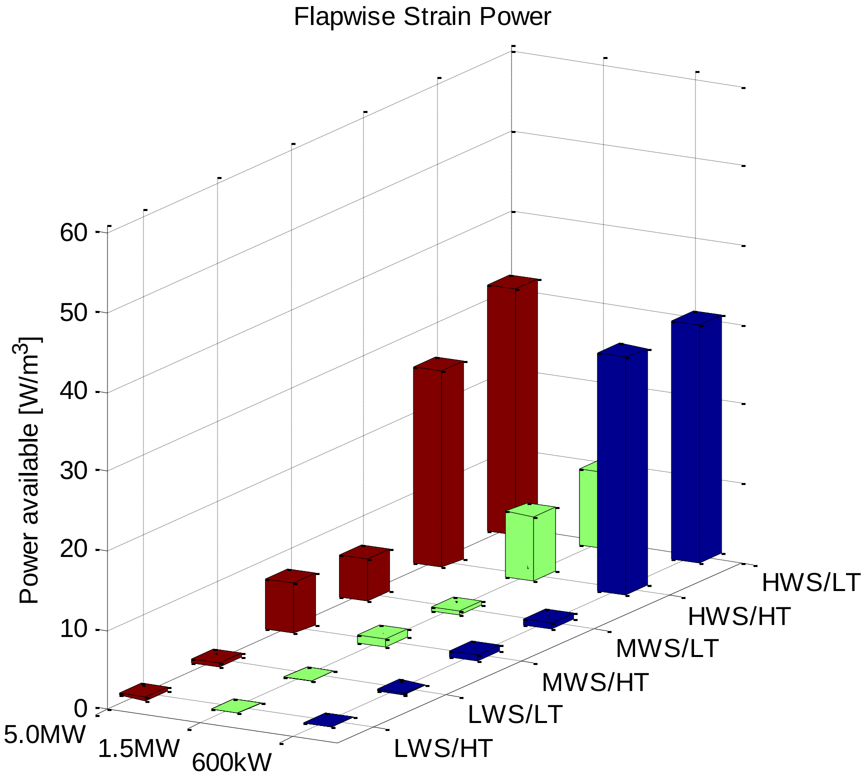


5 MW WT model
24 m/s, Low Turbulence

Available Strain Power

3 Wind Turbines: 600 kW, 1.5 MW, 5.0 MW





6 Wind Conditions:

Wind Speed {
LWS: 6 m/s
MWS: Rated
HWS: 24 m/s

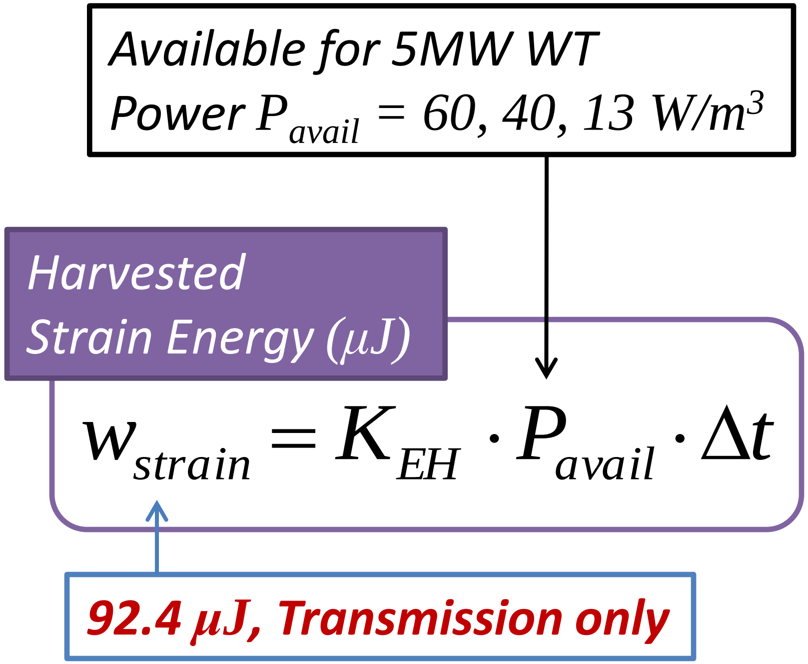
LT: Low
HT: High
} *Turbulence Intensity*

Apply to EH/Telemetry Design

Harvested Strain Energy (μJ)

$$w_{strain} = K_{EH} \cdot P_{avail} \cdot \Delta t$$

Apply to EH/Telemetry Design



Available for 5MW WT
Power $P_{avail} = 60, 40, 13\ W/m^3$

Harvested
Strain Energy (μJ)

$$w_{strain} = K_{EH} \cdot P_{avail} \cdot \Delta t$$

92.4 μJ, Transmission only

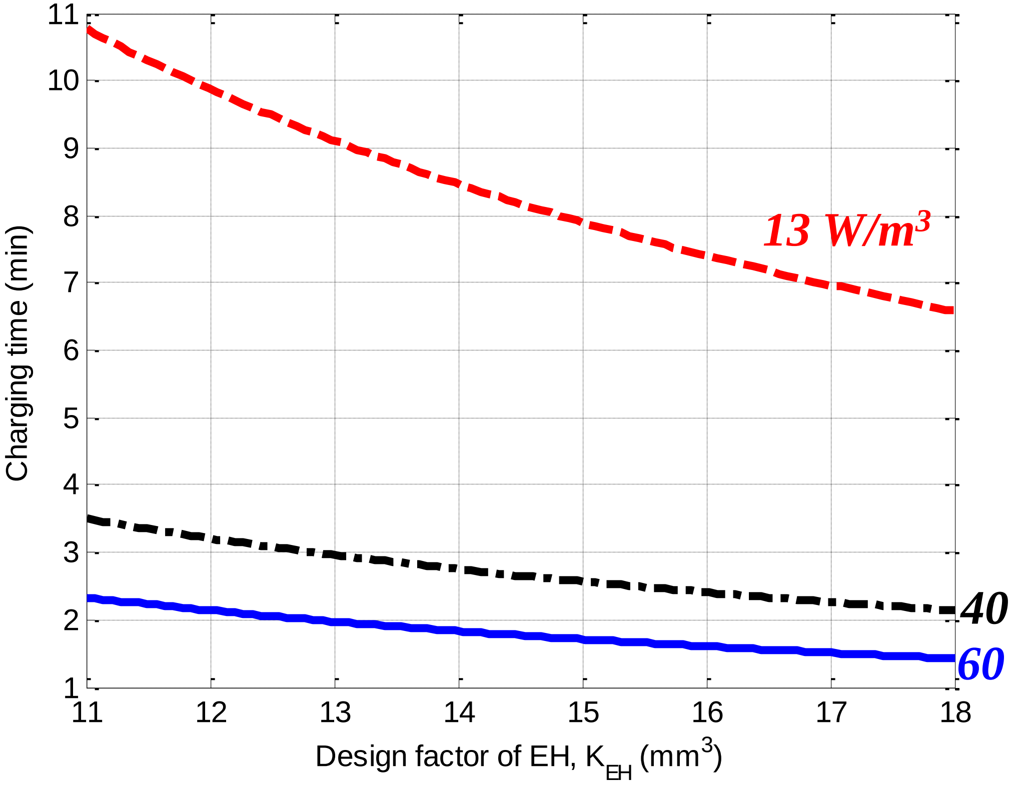
Apply to EH/Telemetry Design

Available for 5MW WT
Power $P_{avail} = 60, 40, 13\ W/m^3$

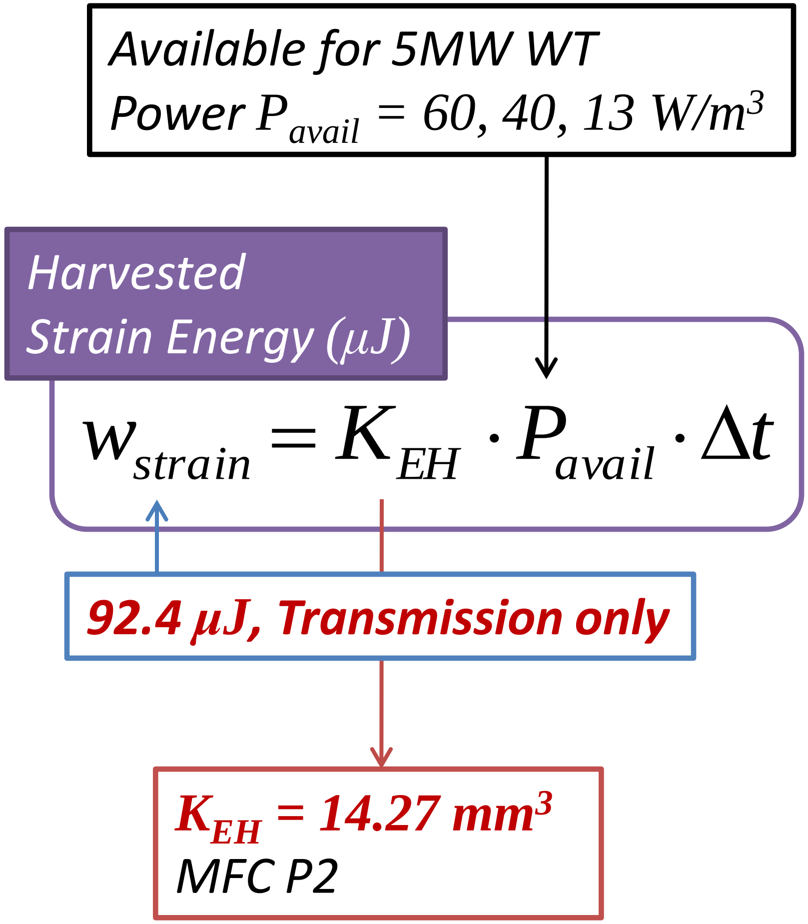
Harvested
Strain Energy (μJ)

$$w_{strain} = K_{EH} \cdot P_{avail} \cdot \Delta t$$

92.4 μJ***, Transmission only***



Apply to EH/Telemetry Design



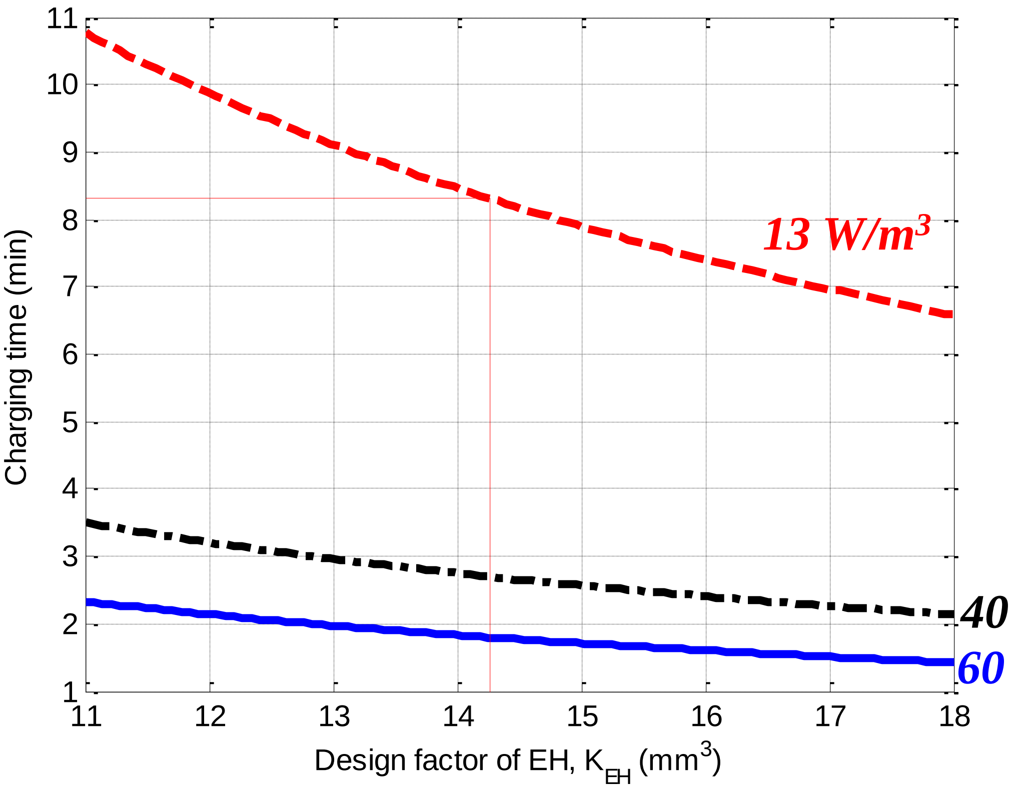
Available for 5MW WT
Power $P_{avail} = 60, 40, 13\ W/m^3$

Harvested Strain Energy (μJ)

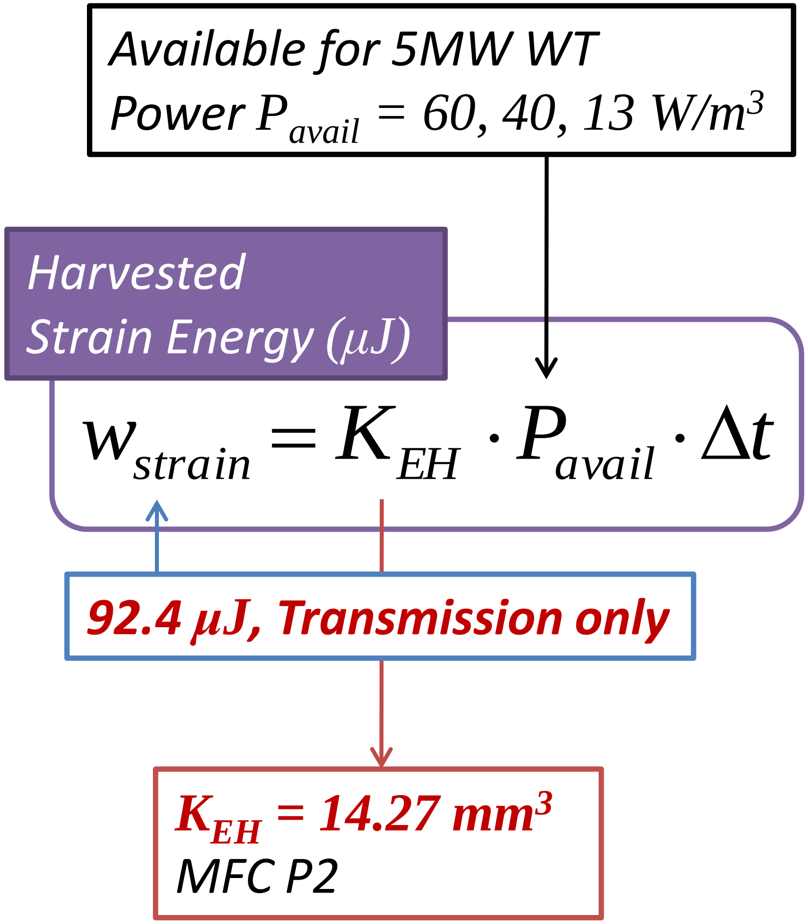
$$w_{strain} = K_{EH} \cdot P_{avail} \cdot \Delta t$$

92.4 μJ, Transmission only

$K_{EH} = 14.27\ mm^3$
MFC P2



Apply to EH/Telemetry Design



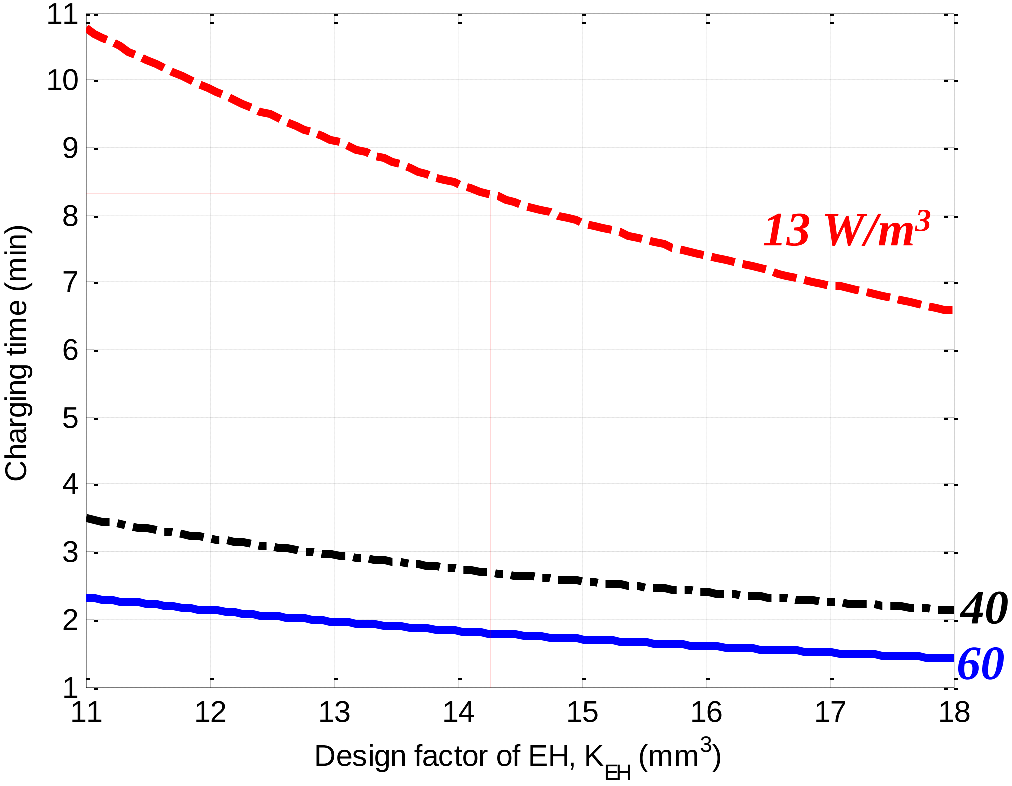
Available for 5MW WT
Power $P_{avail} = 60, 40, 13\ W/m^3$

Harvested Strain Energy (μJ)

$$w_{strain} = K_{EH} \cdot P_{avail} \cdot \Delta t$$

92.4 μJ, Transmission only

$K_{EH} = 14.27\ mm^3$
MFC P2



Summary: Power only sufficient for very low transmission rates.
Question: Can blades be monitored with low rate data?

Apply to EH/Telemetry Design

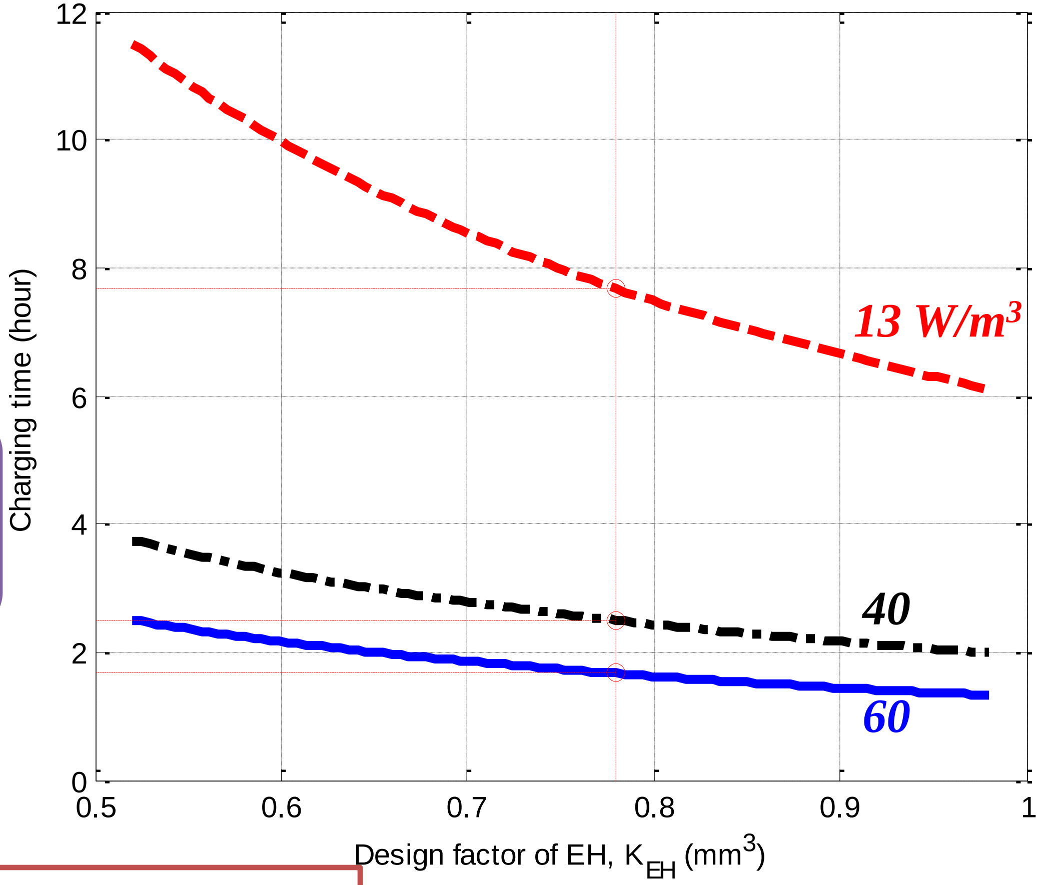
Available for 5MW WT
Power $P_{avail} = 60, 40, 13\ W/m^3$

Harvested
Strain Energy (μJ)

$$w_{strain} = K_{EH} \cdot P_{avail} \cdot \Delta t$$

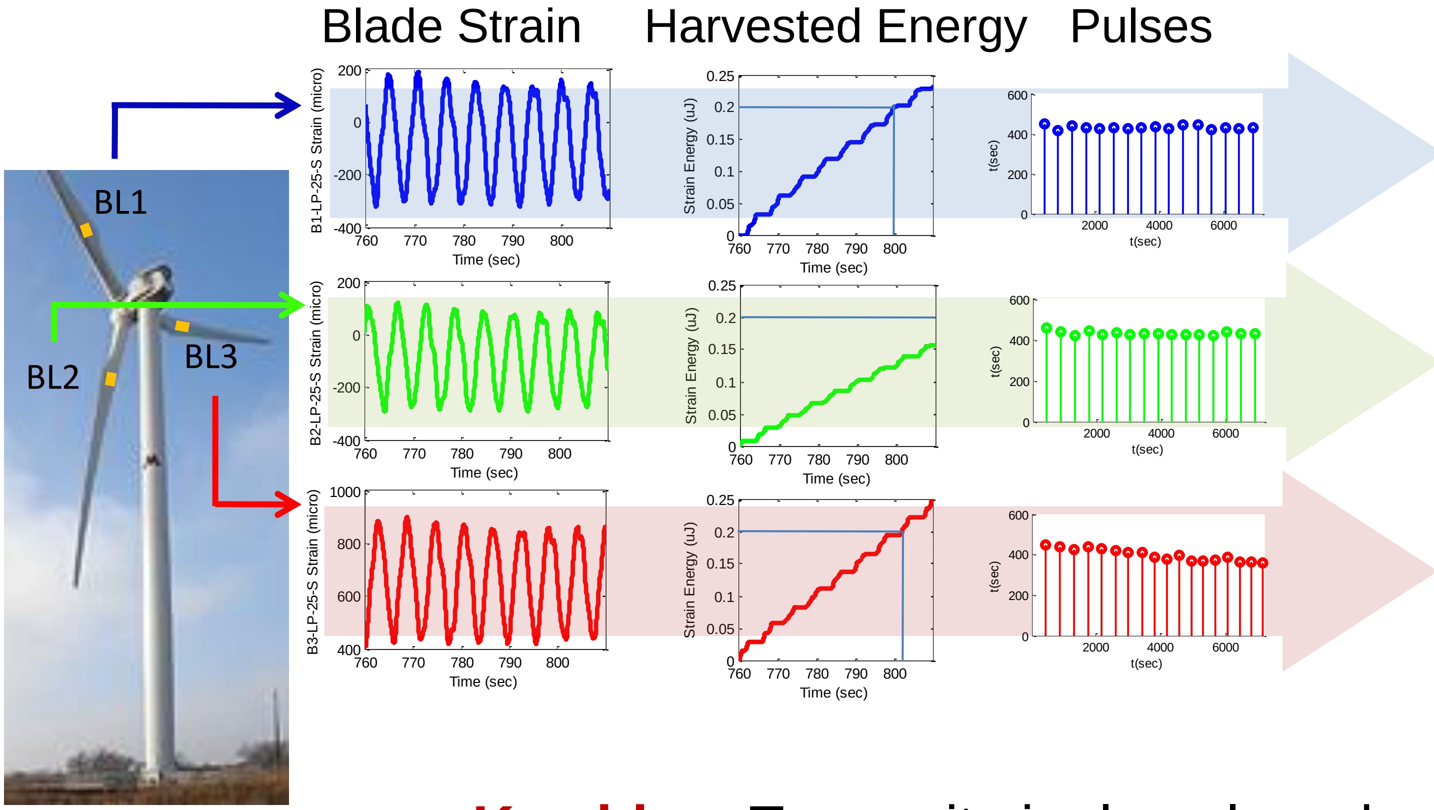
$280\ \mu J$*, Single data packet measurement/transmission*

$K_{EH} = 0.78\ mm^3$
(ZnO Nanowire EH)
$\eta=6.8\%,\ E=30GPa,\ V=0.38mm^3 (10x20cm^2,\ 20\ layers)$



Ref. G. Zhu, et al. Flexible High-Output Nanogenerator Based on Lateral ZnO Nanowire Array, 2010

Proposed SHM Algorithm



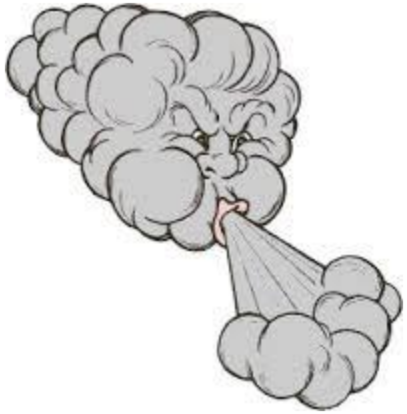
Turbine

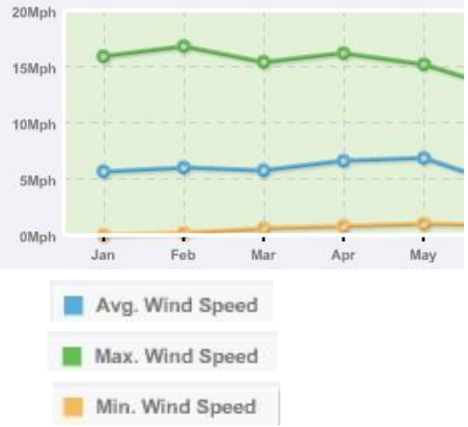
SHM Algorithm

Detect blade damage based on pulse timing

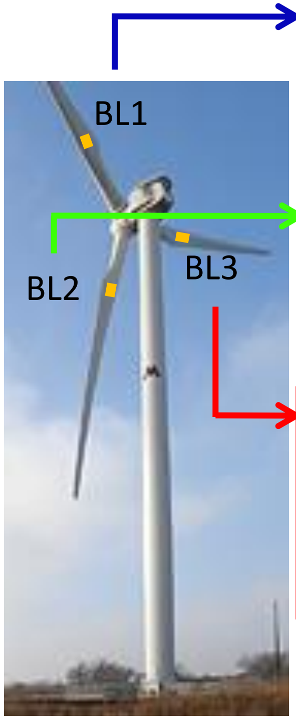
Key idea: Transmit single pulse when harvested energy exceeds threshold (Harvested energy is correlated with damage)

Problem Set-up





Rosemount, MN Wind Data

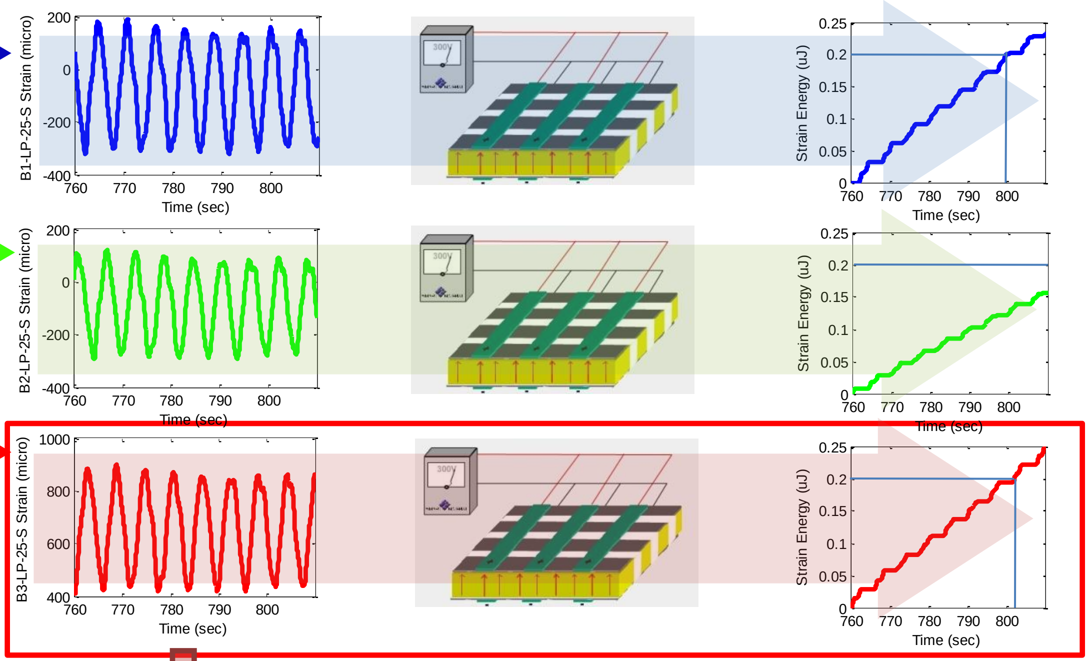


FAST / EOLOS Wind Turbine

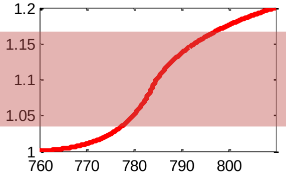
Blade Strain

Piezo-electric Energy Harvester

Strain Energy Accumulation



Synthesizing Blade Damage



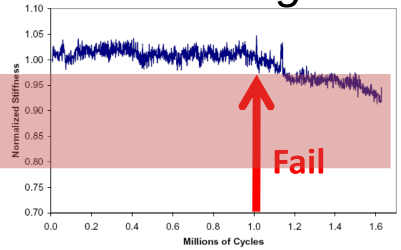
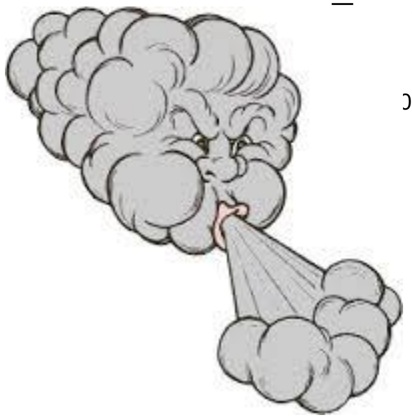


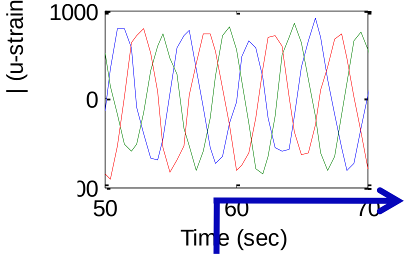
Figure 12: Normalized stiffness at saddle for CX-100 fatigue test.

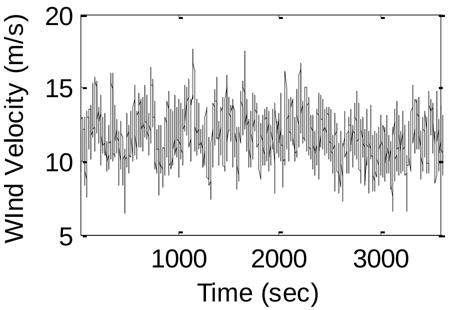
Simplified Damage Model

(Paquette, et al. *46th AIAA ASM,* '08)

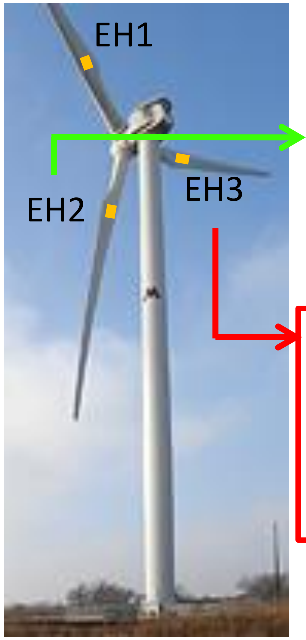
FAST Simulation Result (OS5MW WT)





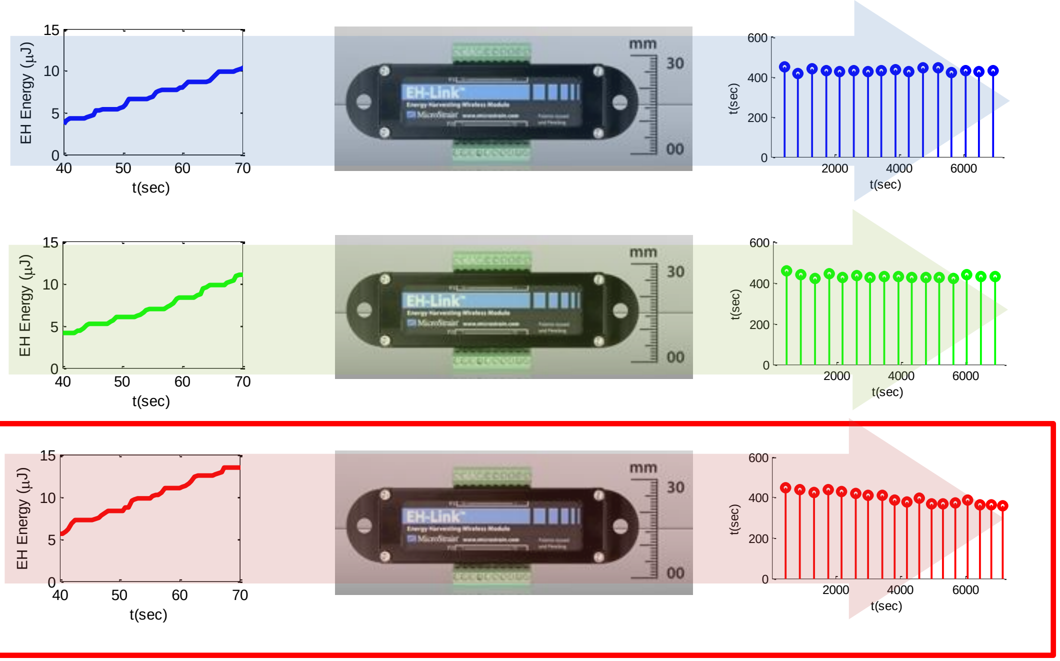


TurbSim
Wind Data

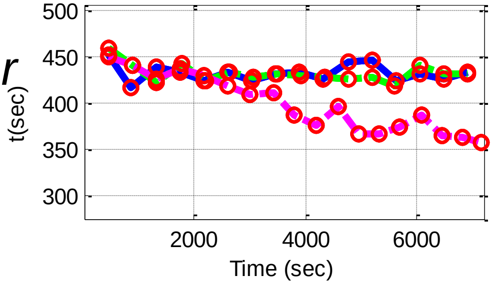


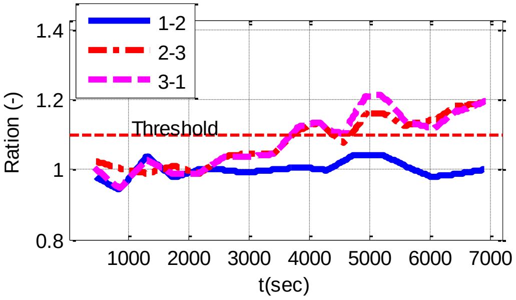
FAST Simulator
(OS5MW WT)

Strain Energy *Transceiver Signal Cond.* *Signal Transmission*

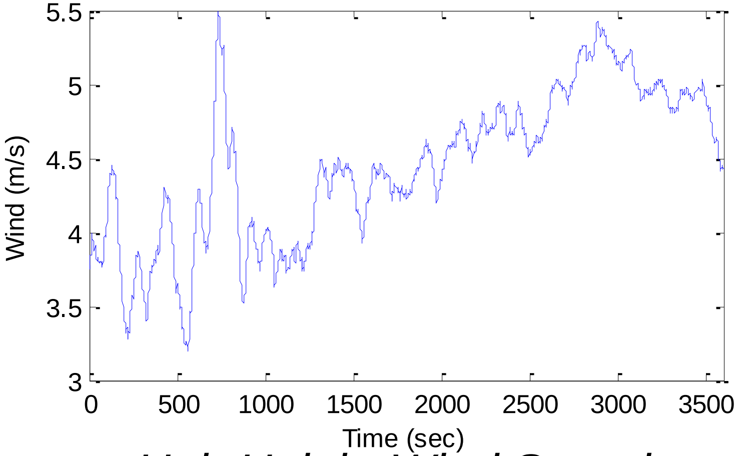


Damaged Blade (Progressive)

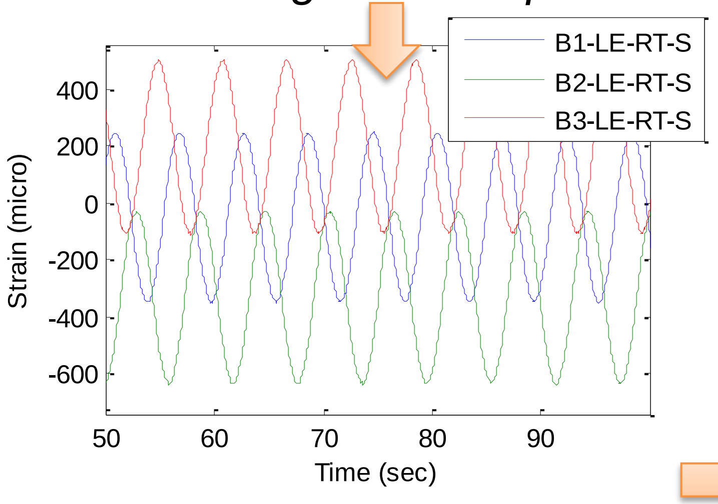




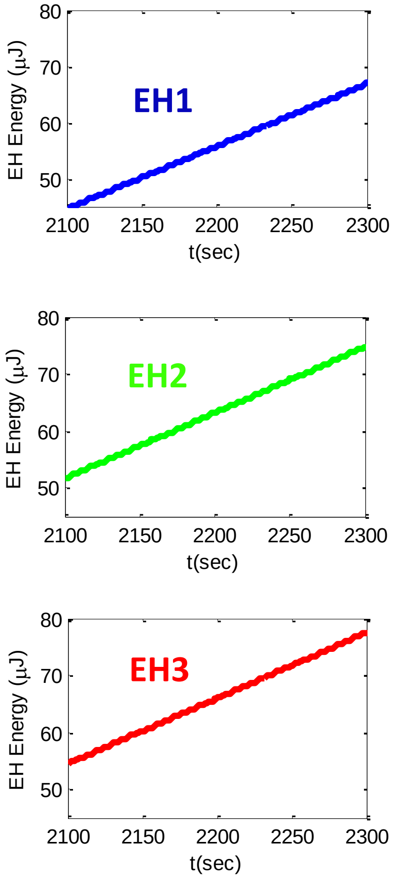
Clipper Raw Data Result (Healthy)



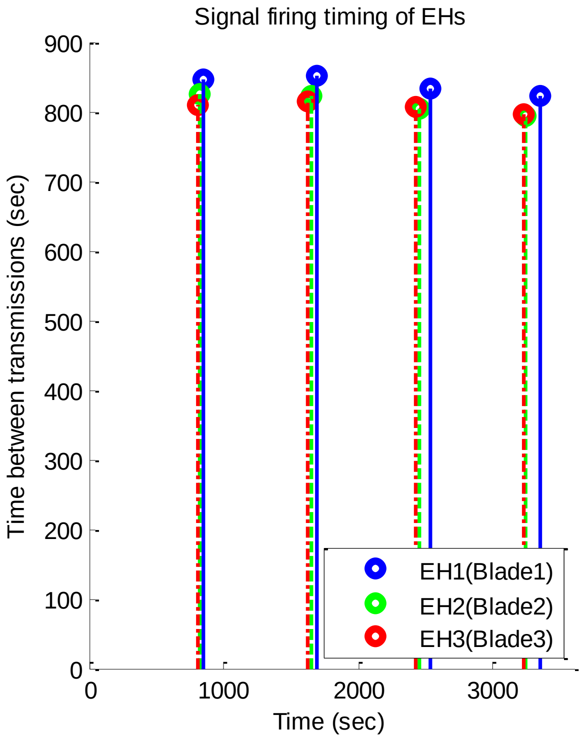
Hub Height Wind Speed



Strain @ 3 Blades



Strain Energy



Signal Transmission

Clipper Data (same data) with Synthetic Fault

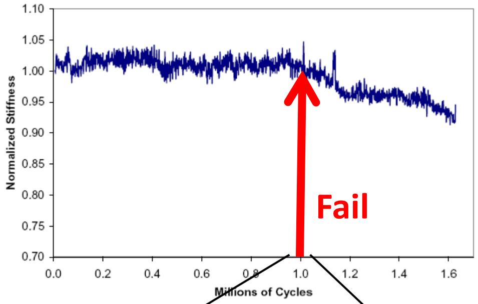
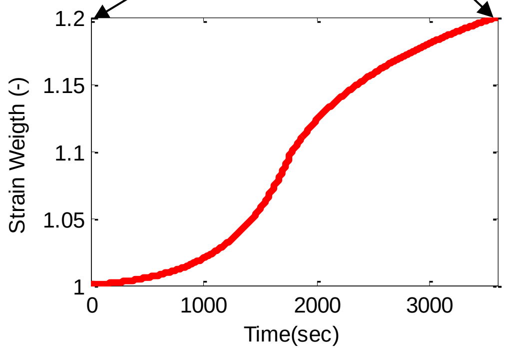
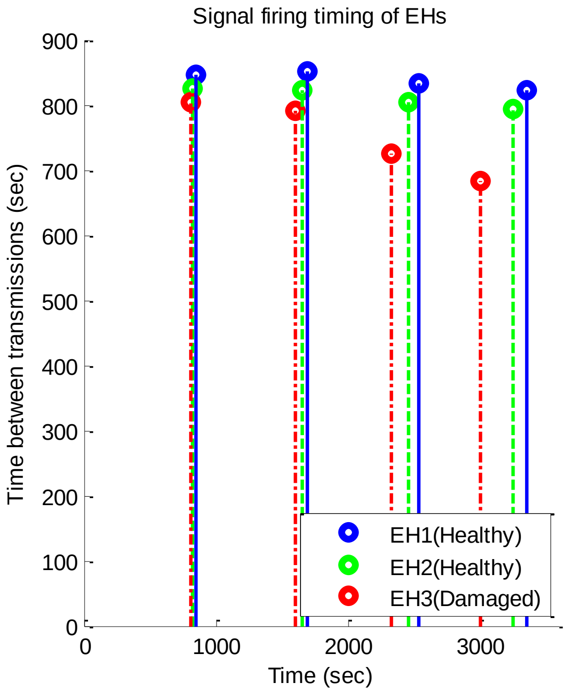


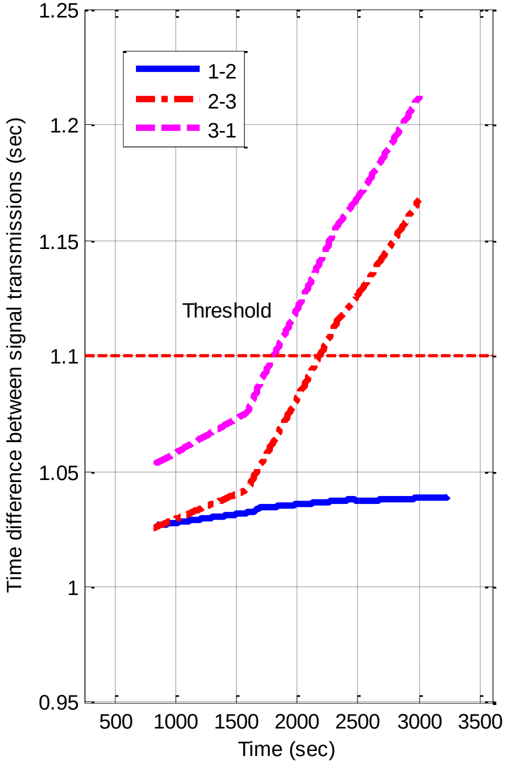
Figure 12: Normalized stiffness at saddle for CX-100 fatigue test.

(Paquette, J., et al. *46th AIAA ASM, NV* 2008)



Blade 3 Strain Output





Damage Model → *Signal Transmission* → *Interpretation*

Conclusions

- Advanced monitoring and control techniques can continue to reduce the costs of wind energy.

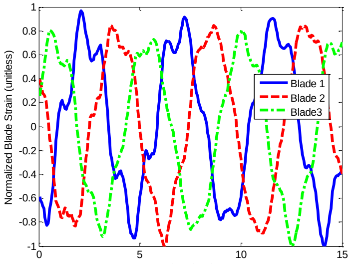
- Energy harvesting can be used to power sensors
  - Max. strain: ~20 to 33% of the blade length
  - Max. available strain power for harvesting: ~60 W/m^3
  - Long charging time is required given current EH technology

- Total harvested energy can be used to monitor blade
  - Harvested energy is correlated with damage
  - Transmit single pulse when harvested energy exceeds threshold
  - Rely on triple redundant measurements

Future Work

1. Experimental validation of proposed SHM algorithm
   - Build test beam specimens with variety of damage types
   - Design a power conditioner/booster to maximize EH performance (matched resistance).
   - Vibrate test specimen to mimic realistic operating conditions
   - Evaluate ability of SHM algorithm to detect damage
2. EH development: ZnO Nanowire array
   - Ref: Zhu, Yang, Wang, Wang, Flexible High-Output Nanogenerator Based on Lateral ZnO Nanowire Array, '10 Nano Letters

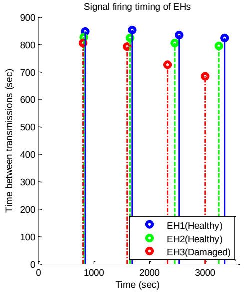
EOLOS Wind Turbine



Blade Strain

Energy Harvester

Lab-scale Set-up



Pulses

Acknowledgments

- Institute for Renewable Energy and the Environment
  - Grant No. RL-0010-12: “Design Tools for Multivariable Control of Large Wind Turbines.”
  - Grant No. RS-0039-09: “Improved Energy Production for Large Wind Turbines.”
  - Grant No. RS-0029-12: “Development of self-powered wireless sensor for structural health monitoring in wind turbine blades”
- US Department of Energy
  - Grant No. DE-EE0002980: “An Industry/Academe Consortium for Achieving 20% wind by 2030 through Cutting-Edge Research and Workforce Training”
  - Eolos Wind Energy Consortium: Provided Liberty data
- US National Science Foundation
  - Grant No. NSF-CMMI-1254129: “CAREER: Probabilistic Tools for High Reliability Monitoring and Control of Wind Farms”