System Level, Mechanical Model Validation of a 7.5 MW Wind Turbine Test Bench

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Clemson University Wind Turbine Drivetrain Testing Facility
North Charleston, SC

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SCE&G Energy Innovation Center

Campus Overview

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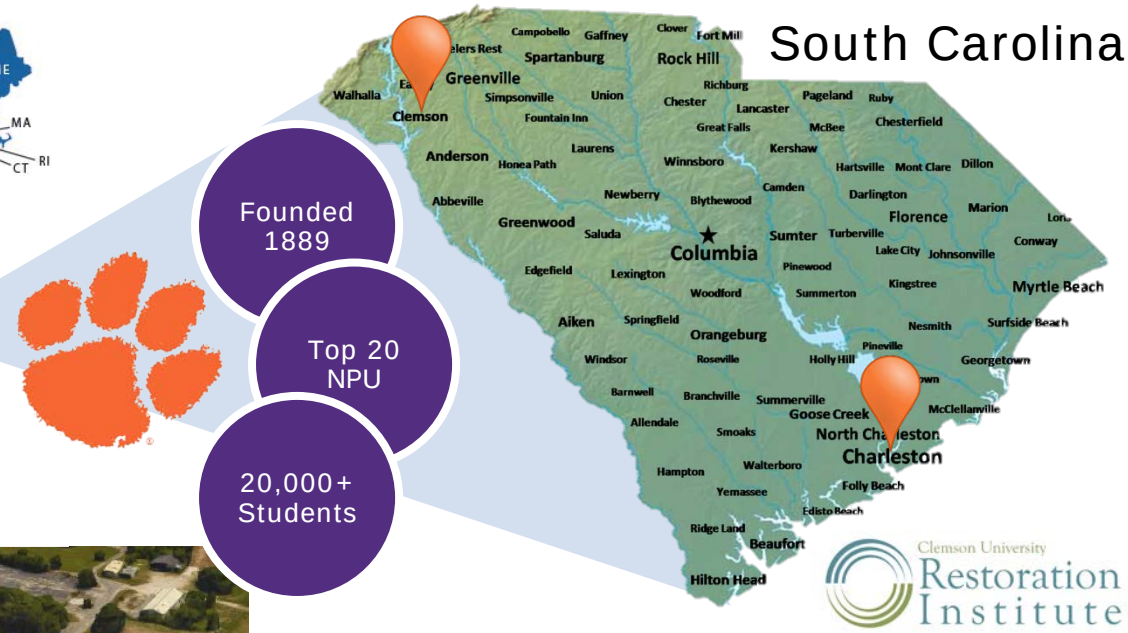
ENERGY INNOVATION CENTER



Founded 1889

Top 20 NPU

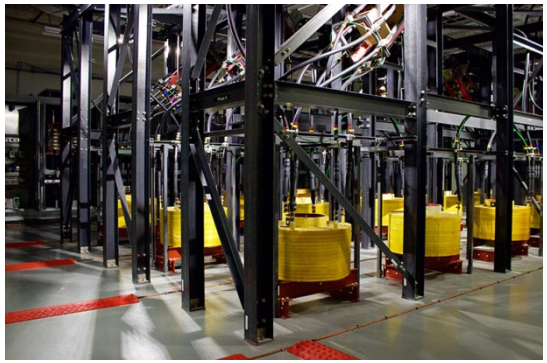
20,000+ Students

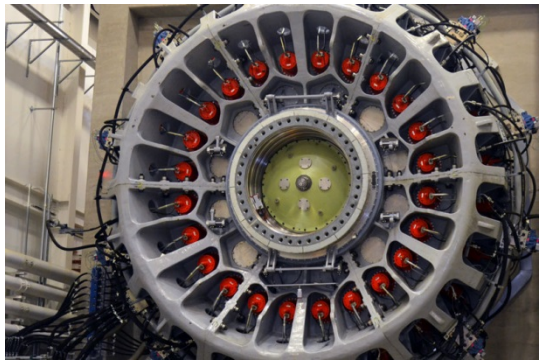
- Rail Access
- Energy Innovation Center
- Warren Lasch Conservation Center
- Zucker Family Graduate Education Center (targeted 20 faculty, 200 students)
- Dock Access (1,000 ton)

CURI Campus Organization

CLEMSON UNIVERSITY ENERGY INNOVATION CENTER

- Clemson University Restoration Institute
  - SCE&G Energy Innovation Center
    - Duke Energy eGRID Center
      - 15 MW HIL Grid Simulator
    - Wind Turbine Drivetrain Testing Facility
      - 7.5 MW Test Bench
      - 15 MW Test Bench





Equipment Capabilities: 7.5 MW TB and 15 MW TB

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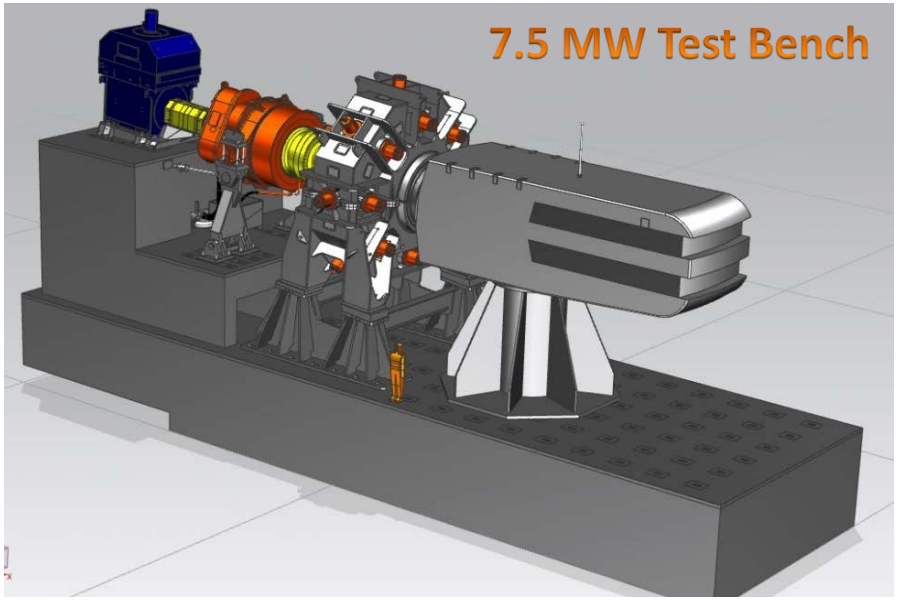

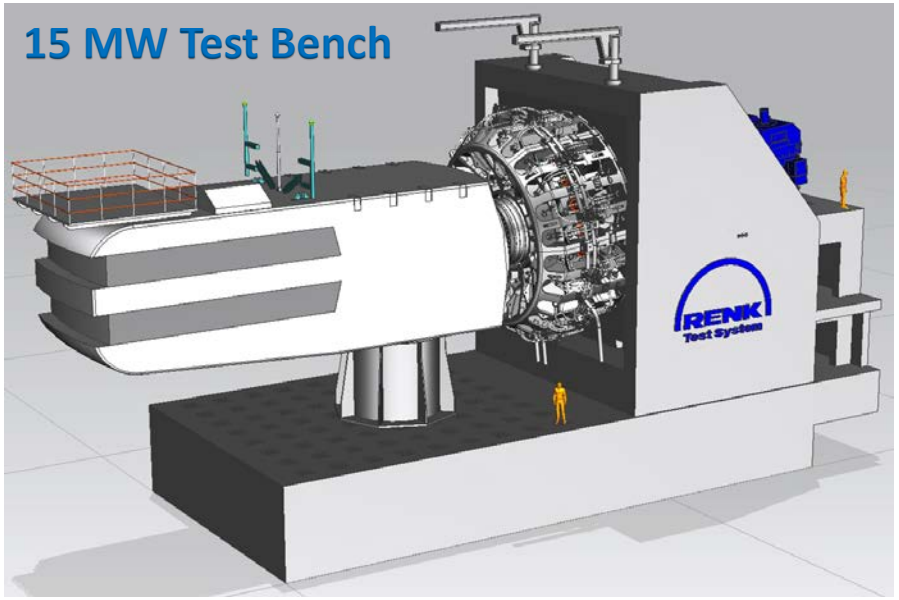

7.5 MW Test Bench Performance Specifications	
Test Power	7,500 kW
Maximum Torque	6,500 kNm
Maximum Speed	20 rpm
Inclination	4 ° to 6 °
Static Axial Force	± 2,000 kN
Static Radial Force	± 2,000 kN
Static Bending Moment	± 10,000 kNm

15 MW Test Bench Performance Specifications	
Test Power	15,000 kW
Maximum Torque	16,000 kNm
Maximum Speed	17 rpm
Inclination	6 °
Static Axial Force	± 4,000 kN
Static Radial Force	± 8,000 kN
Static Bending Moment	± 50,000 kNm

Equipment Capabilities: 7.5 MW TB and 15 MW TB

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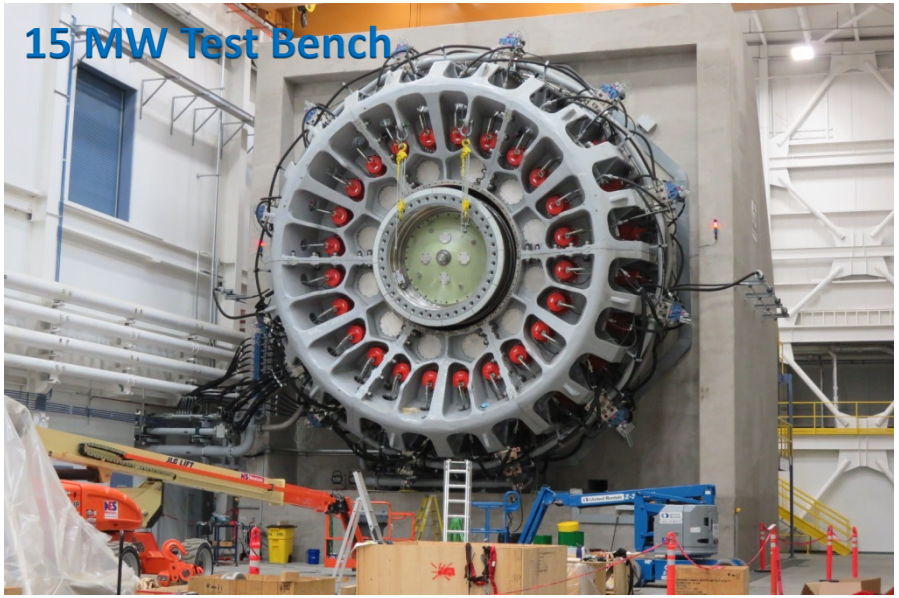

7.5 MW Test Bench Performance Specifications	
Test Power	7,500 kW
Maximum Torque	6,500 kNm
Maximum Speed	20 rpm
Inclination	4 ° to 6 °
Static Axial Force	± 2,000 kN
Static Radial Force	± 2,000 kN
Static Bending Moment	± 10,000 kNm

15 MW Test Bench Performance Specifications	
Test Power	15,000 kW
Maximum Torque	16,000 kNm
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Inclination	6 °
Static Axial Force	± 4,000 kN
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Test Capabilities

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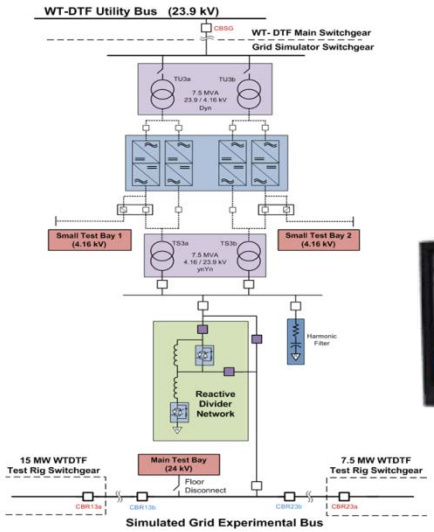
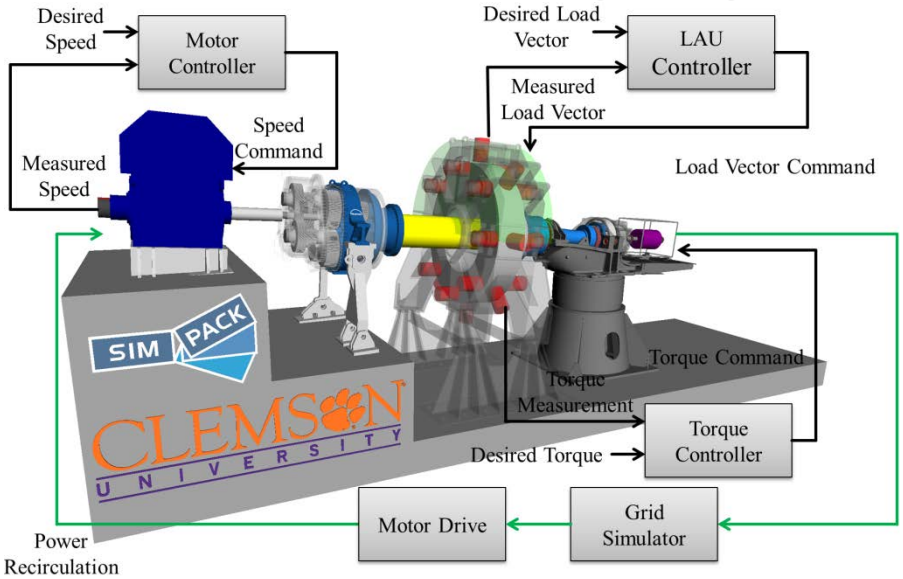
15 MW HIL Grid Simulator



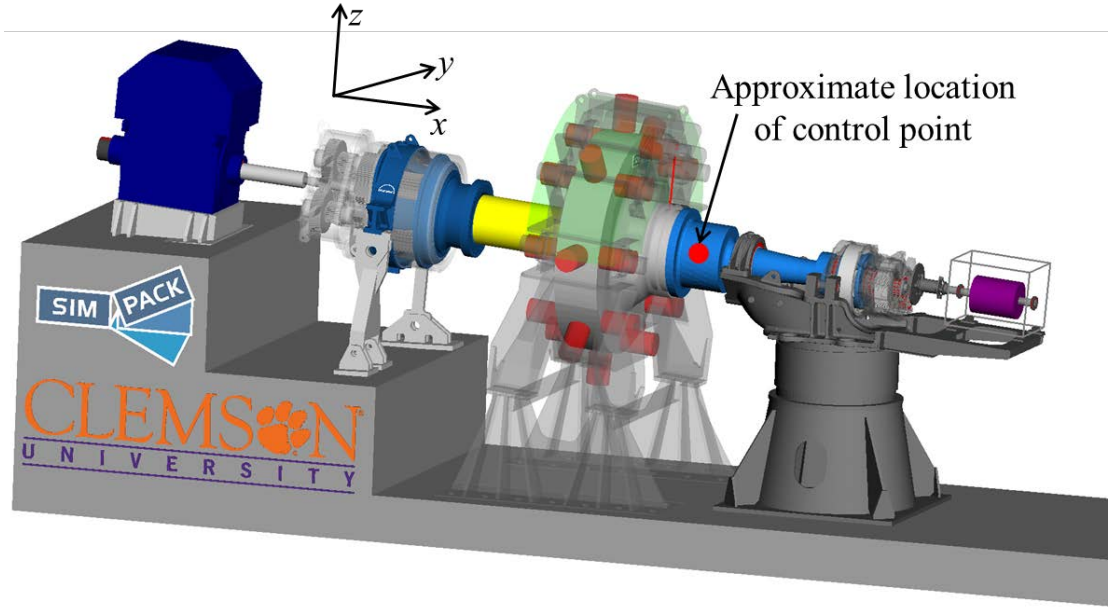
Virtual Test Bench Test Capability



15 MW HIL Grid Simulator Performance Specifications	
Test Power	15000 kVA
Frequency range	45...65 Hz
Sequence capability	3 and 4 wire
High Voltage Ride Through HVRT	100...145%
Low Voltage Ride Through LVRT	100...0%
Unsymmetrical LVRT	yes
Power quality PQ evaluation	yes

Virtual Test Bench Simulator Performance Specifications	
Virtual testing and validation	yes
Multi-domain modeling	yes
Test protocol verification and optimization	yes
Flexible model configuration	yes
Uncertainty in analyses	reduced
Operator training	yes
Students involvement	high

System Configuration



- Large disk rigidly mounted to driveline
- Hydraulic actuators push on disk to create forces and moments at hub point

Topics

- What we have modeled

- How we have validated
- How we are validating

- What these models facilitate

Topics

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Modeling and Simulation Objectives

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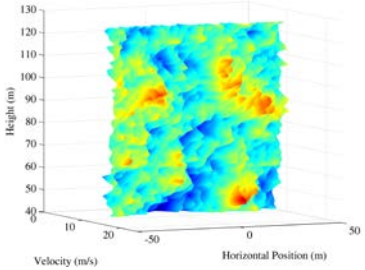
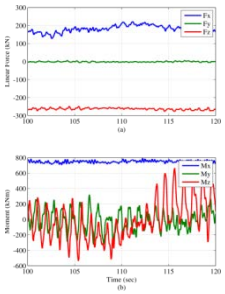
Aerodynamic Load Analysis

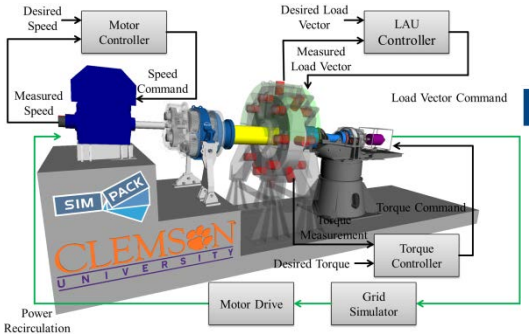
- Wind and rotor, TurbSim & AeroDyn
- Full turbine simulation, FAST
- Generation of main shaft loads





Pure Simulation Based Analysis

- Detailed component simulation
- Collaborative multidomain modeling
- Involve faculty, students, etc.



SIM PACK

MATLAB SIMULINK

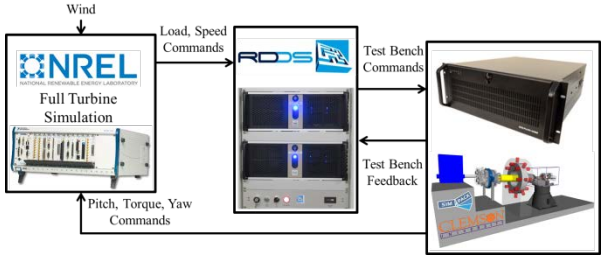
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Hardware In the Loop Simulation

- Model reduction for realtime
- Integrate actual HMI hardware
- Virtual test bay

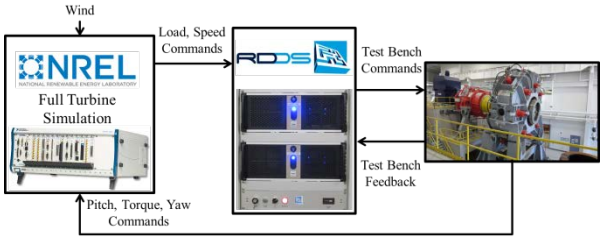
concurrent REAL-TIME

RED HAWK



Test Bench Operation

- Increased utilization
- Advanced test profile execution
- Confident performance



RENK

Model Development Domains

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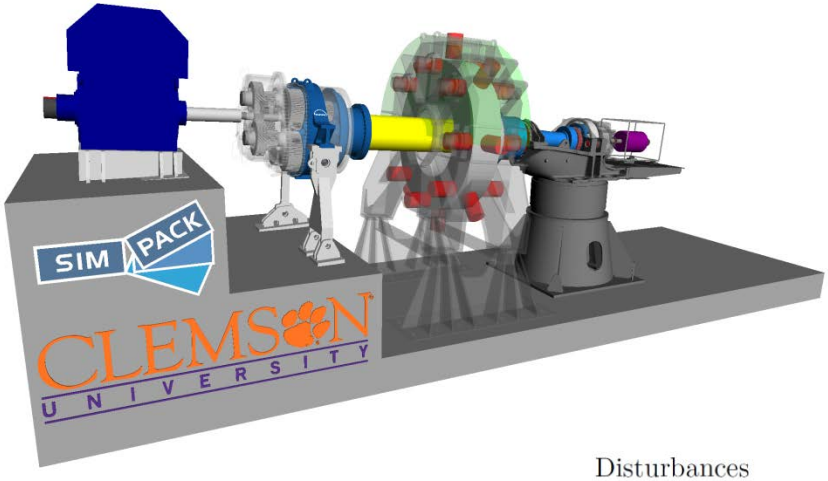
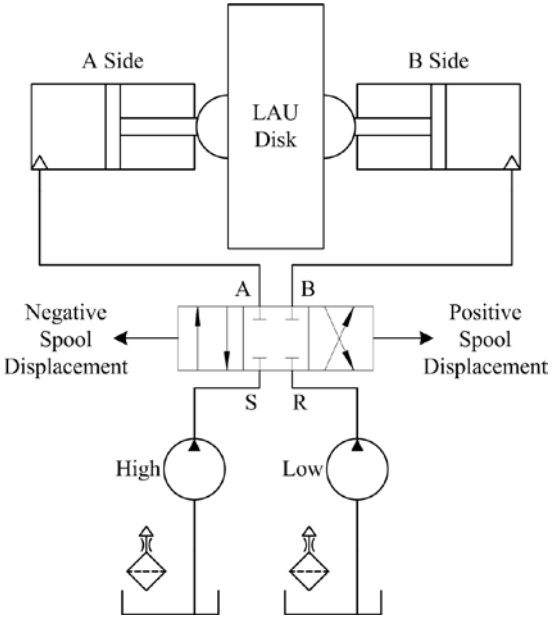
Objectives

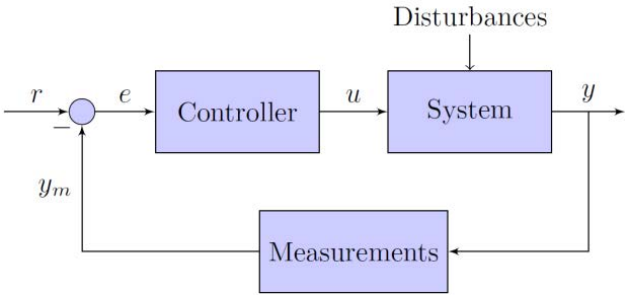
- Capture system level dynamic behavior in addition to component dynamics

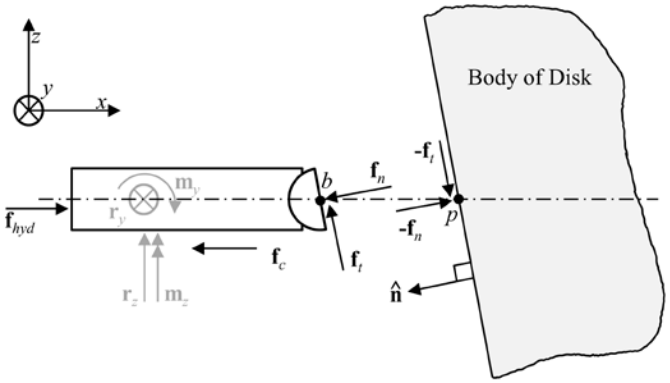
Models include:

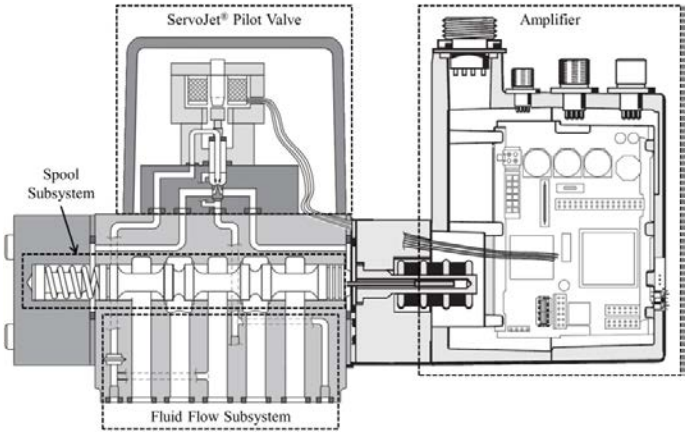
- Multi-body Dynamic Elements
- FEA & Flexible Element
- Control Systems
- Actuator Models
- Hydraulic Systems
- Interaction Models
- Aero elastic codes
- Electro mechanical interaction











Actual Test Rig

Multibody Simulation

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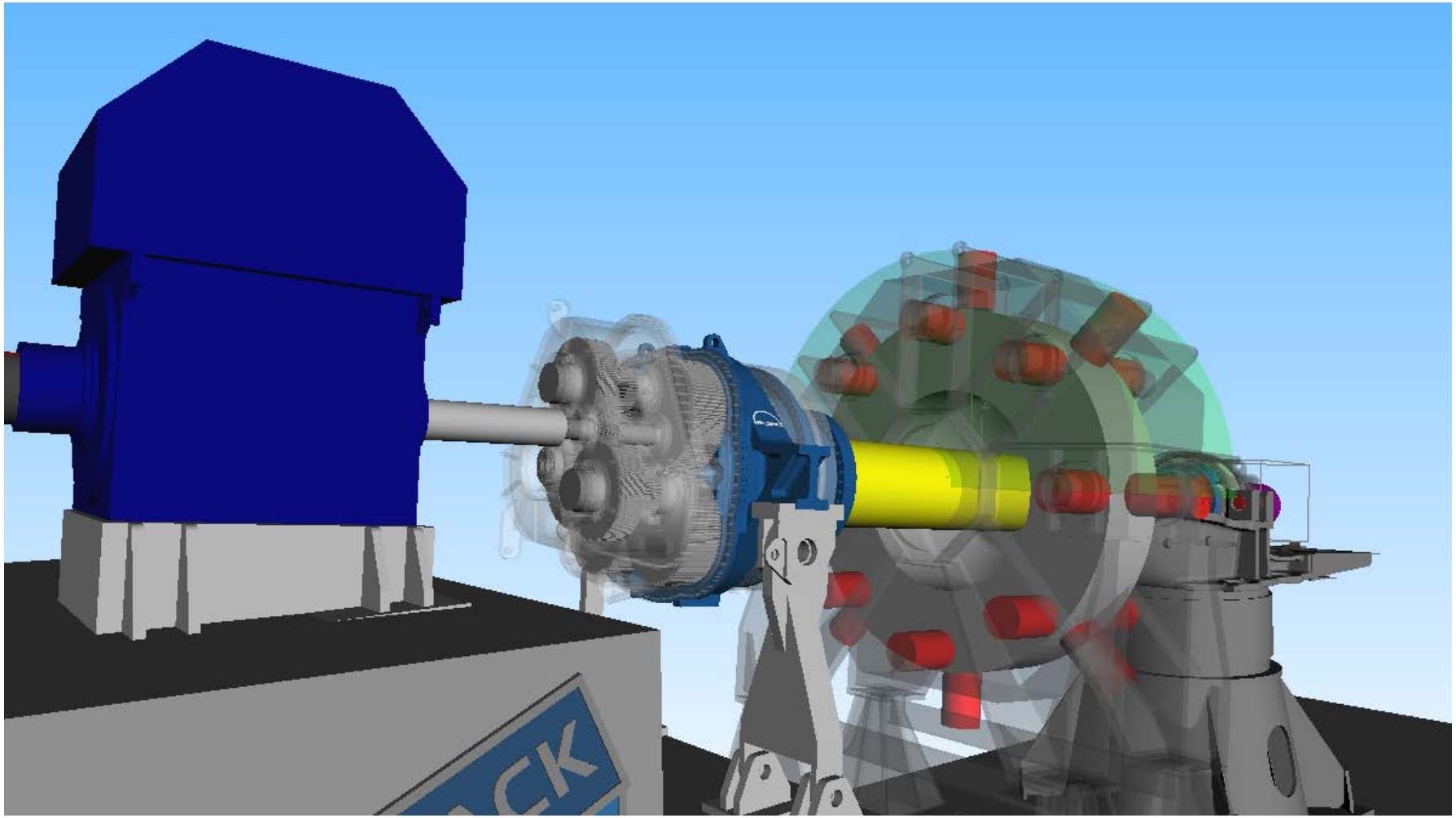
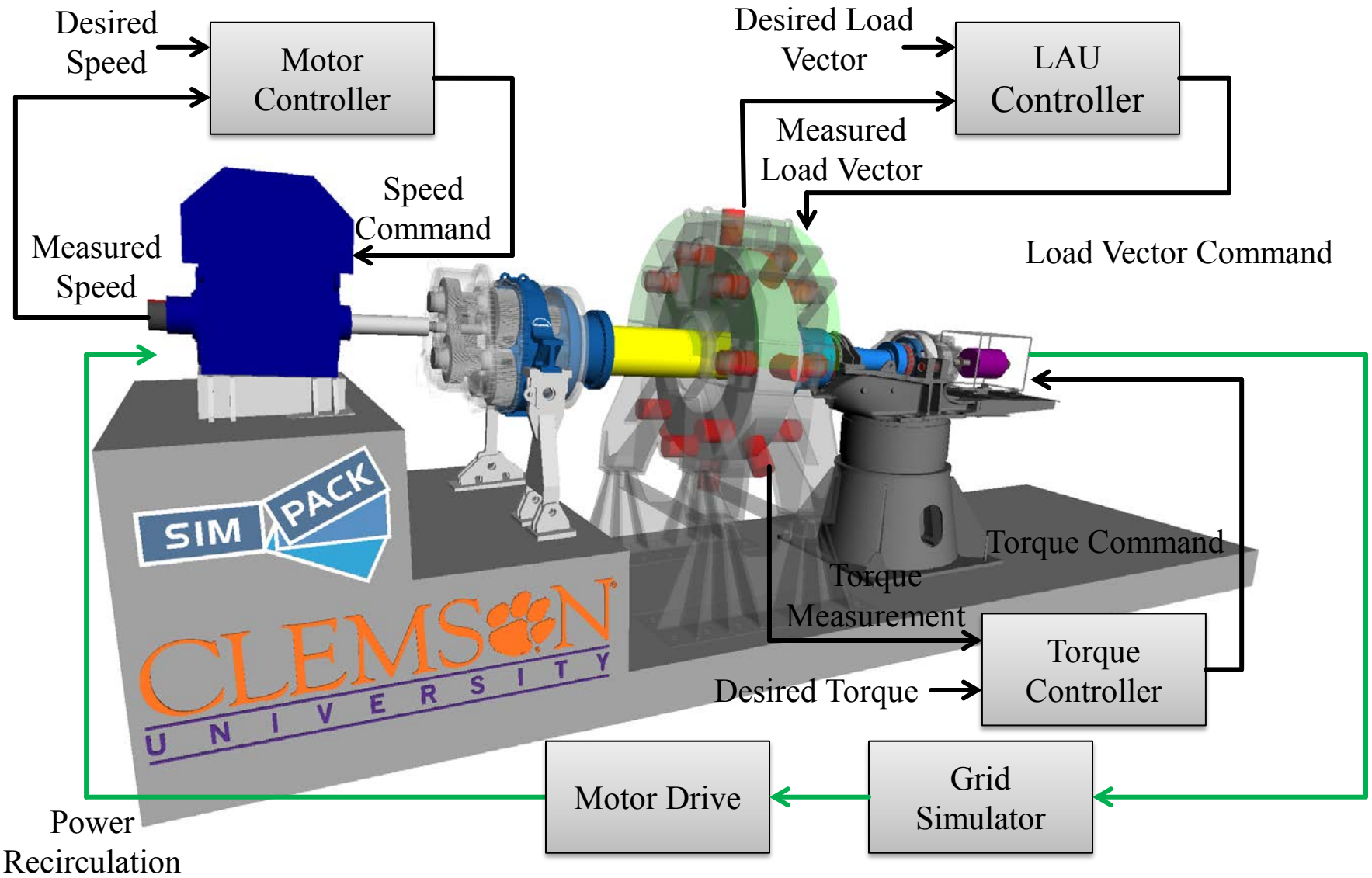


Integrated Model Topology



Topics

- What we have modeled
- How we have validated
- How we are validating
- What these models facilitate

Measurement Uncertainty

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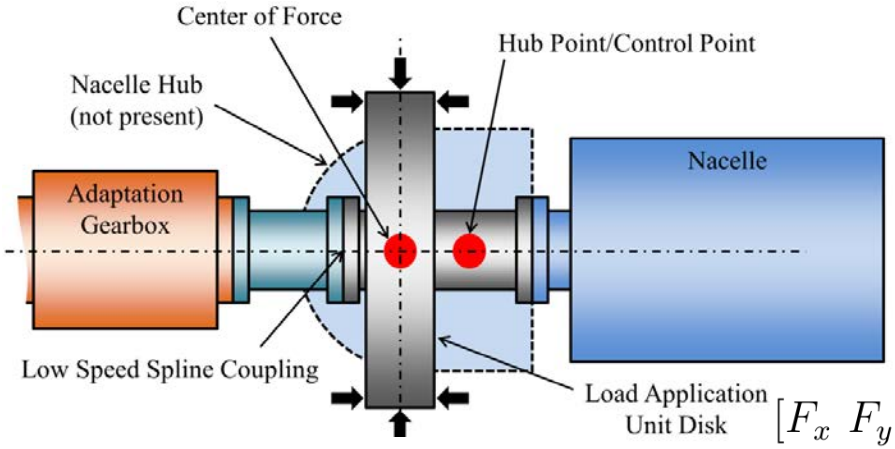
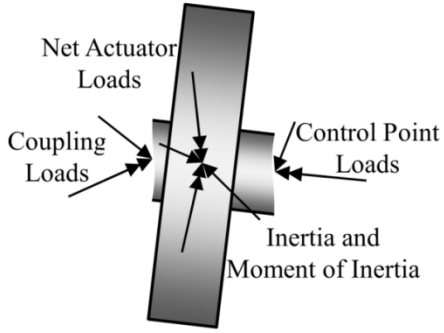
Sources of Uncertainty

- Uncertainty in the pressure measurements
- Changing geometry caused by displacement of the disk
- ~~Frictional losses~~
- Inertial effects
- ~~Spline effects at the low speed coupling~~





Pressure Model

$$p_j = p_{a_j} + \mathcal{WN}(0, 0.115 \text{ bar}) + \mathcal{U}(-2 \text{ bar}, 2 \text{ bar})$$

Force Model

$$F_j = F_{a_j} + \mathcal{WN}(0, \sigma_{ran}^2) + \mathcal{U}(-b, b)$$

Assumed Load Model

$$\mathbf{y} = \mathbf{T}\mathbf{p}$$

$$\mathbf{y} = [F_x \;\; F_y \;\; F_z \;\; M_y \;\; M_z]'$$

$$\mathbf{p} = [p_1 \;\; p_2 \;\; \cdots \;\; p_{24}]'$$

More Comprehensive Load Model

$$[F_x \;\; F_y \;\; F_z \;\; M_y \;\; M_z]' = f\left(\mathbf{F}, x, y, z, \alpha, \beta, \gamma, \dot{x}, \dot{y}, \dot{z}, \omega_x, \omega_y, \omega_z\right)$$

$$Y_i = Y_{op} + \sum_{j=1}^{24} \frac{\partial Y_i}{\partial F_j}\left(F_{a_j} + \mathcal{WN}(0, \sigma_{ran}^2) + \mathcal{U}(-b, b) - F_{op}\right)$$

R. F. Schkoda, “Static Uncertainty Analysis of a Wind Turbine Test Bench’s Load Application Unit,” in *2015 American Controls Conference*, Chicago, IL, July 1-3, 2015

Measurement Uncertainty

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Expected value

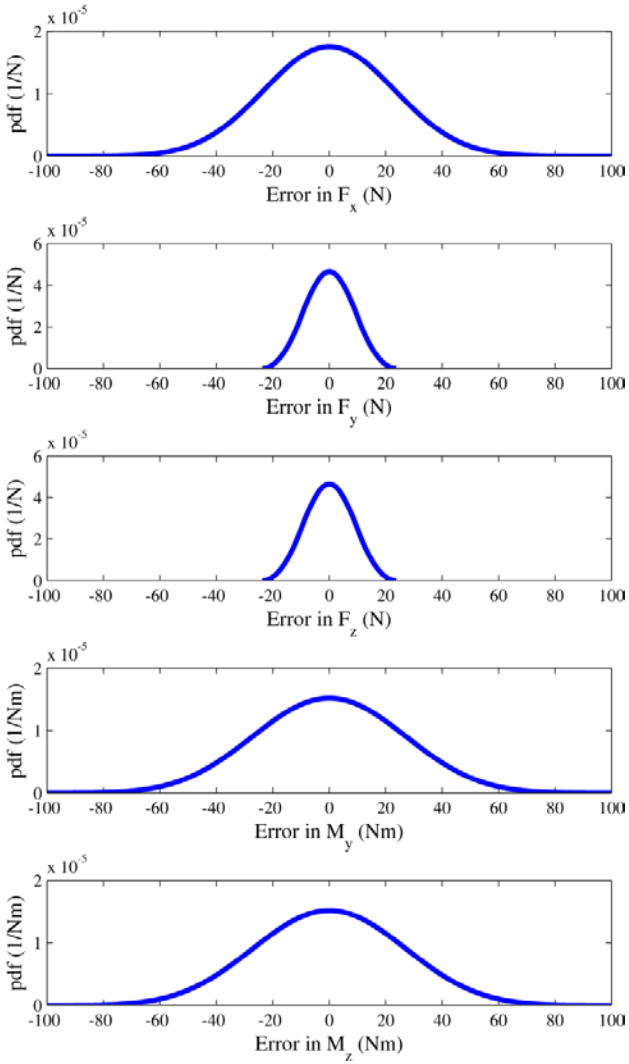
$$\mathbf{E}\left[Y_i\right] = \mathbf{E}\left[Y_{op} + \sum_{j=1}^{24} c_{ij}\left(\mathcal{WN}(0,\sigma_{ran}^2) + \mathcal{U}(-b,b)\right)\right]$$
$$= \mathbf{E}\left[Y_{op}\right] + \mathbf{E}\left[\sum_{j=1}^{24} c_{ij}\mathcal{WN}(0,\sigma_{ran}^2)\right]$$
$$+ \mathbf{E}\left[\sum_{j=1}^{24} c_{ij}\mathcal{U}(-b,b)\right]$$

Variance

$$\mathrm{Var}\left(Y_i\right) = \mathbf{E}\left[\sum_{j=1}^{24} c_{ij}^2\mathcal{WN}_j^2 + \sum_{j=1}^{24} c_{ij}^2\mathcal{U}_j^2 + 2\sum_{j,k:j<k} c_{ij}\mathcal{WN}_j c_{ik}\mathcal{WN}_k + 2\sum_{j,k:j<k} c_{ij}\mathcal{U}_j c_{ik}\mathcal{U}_k + 2\sum_{j=1}^{24}\sum_{k=1}^{24} c_{ij}\mathcal{WN}_j c_{ik}\mathcal{U}_k\right]$$

$$\mathrm{Var}\left(Y_i\right) = \sum_{j=1}^{24} c_{ij}^2\sigma^2 + \sum_{j=1}^{24} c_{ij}^2\sigma_U^2$$

Distribution



Pressure Uncertainty Summary

	Variance of Component	
	Aleatoric (statistical)	Epistemic (systematic)
F_x	44.37e6	514.2e6
F_y	11.09e6	128.6e6
F_z	11.09e6	128.6e6
M_x	0	0
M_y	113.80e6	1,319.0e6
M_z	113.80e6	1,319.0e6

Displacement Uncertainty Summary

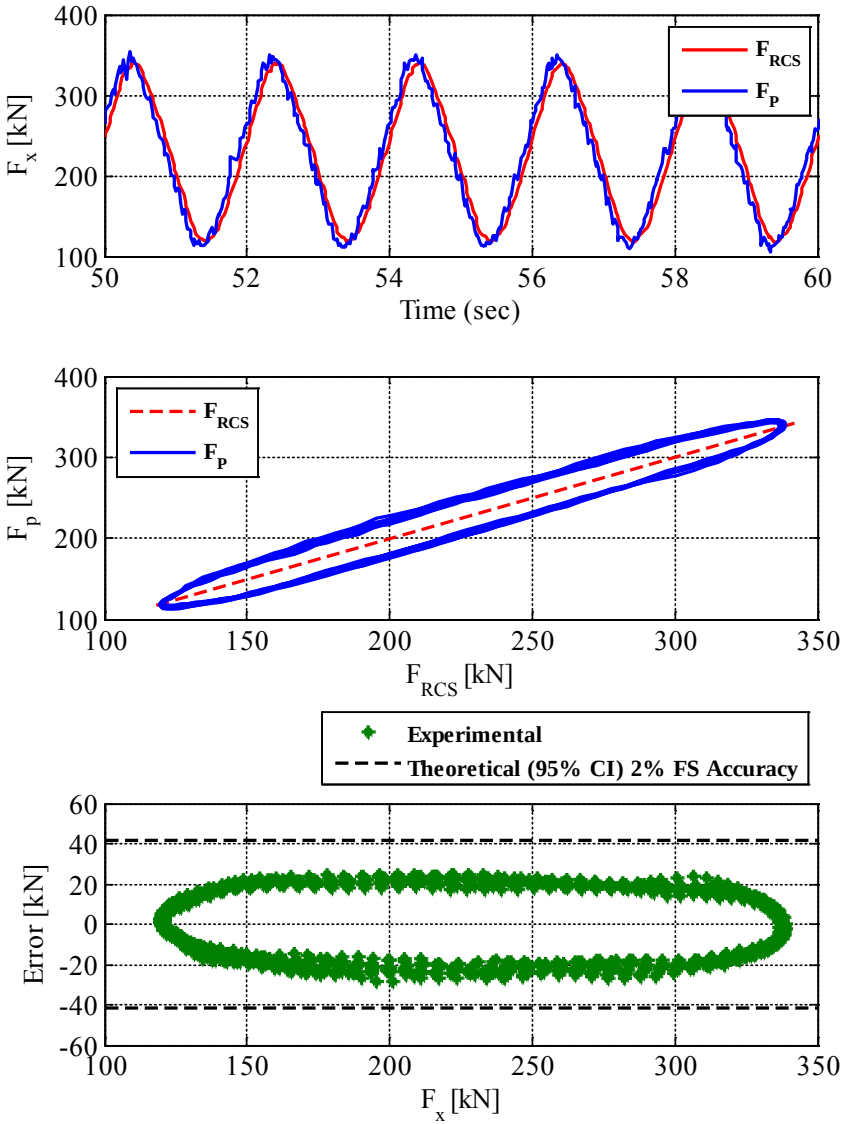
	x	y	z	α	β	γ
	±20 mm			±0.8 deg		
F_x kN	0	0	0	0	0	0
F_y kN	0	25.1	0	0	0	0
F_z kN	0	0	25.1	0	0	0
M_x kNm	0	0	0	0	0	0
M_y kNm	0	0	30.1	0	-174.8	0
M_z kNm	0	-30.1	0	0	0	-174.8

Conclusions

- Displacement based uncertainty depends heavily on the test profile.
- Statistical uncertainly can be helped with averaging but the systematic error remains

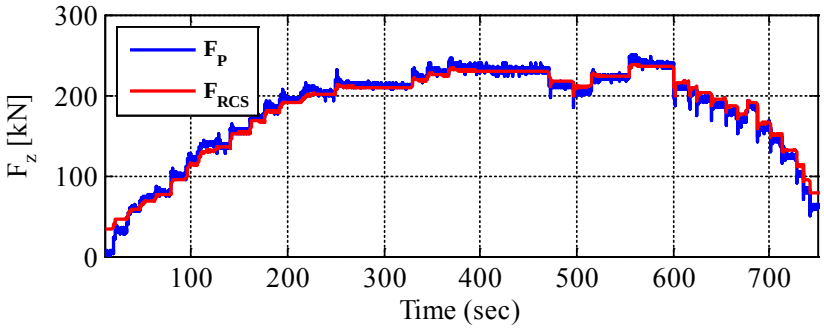
Thrust Force (Fx) Evaluation

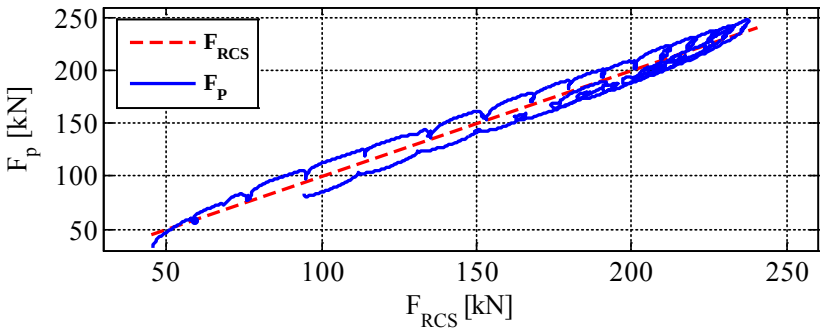
- Theoretical analysis based on the systematic error of the pressure measurement uncertainty
- 95% confidence interval ±42kN which suggests a 2% full scale error
- This interval is supported by data from the slow oscillation repeatability test
- Observed interval is 28.75kN which suggests a full scale error of 1.44%

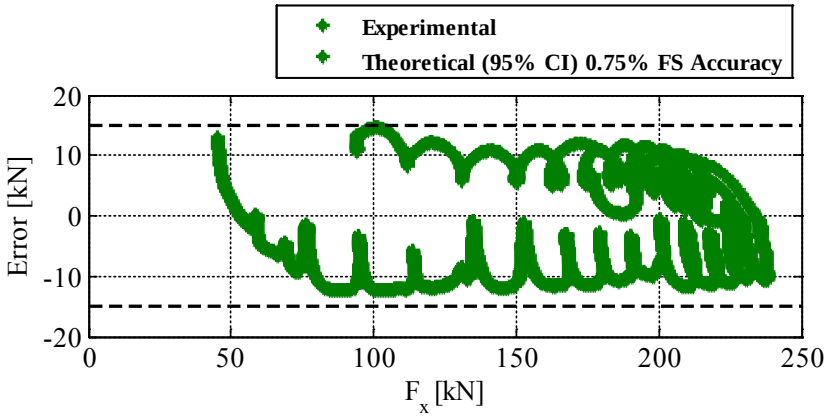


Vertical Force (Fz) Evaluation

- Theoretical analysis based on the systematic error of the pressure measurement uncertainty
- 95% confidence interval ±15kN which suggests a 0.75% full scale error
- This interval is supported by data from the step-up-step-down repeatability test
- Observed interval is 14.35kN which suggests a full scale error of 0.72%

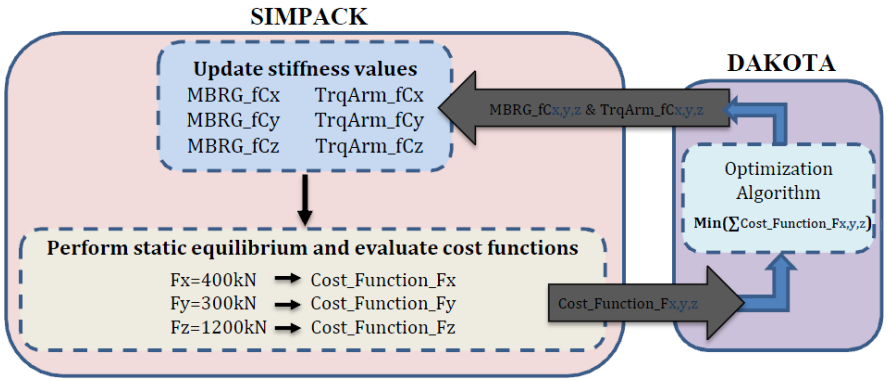


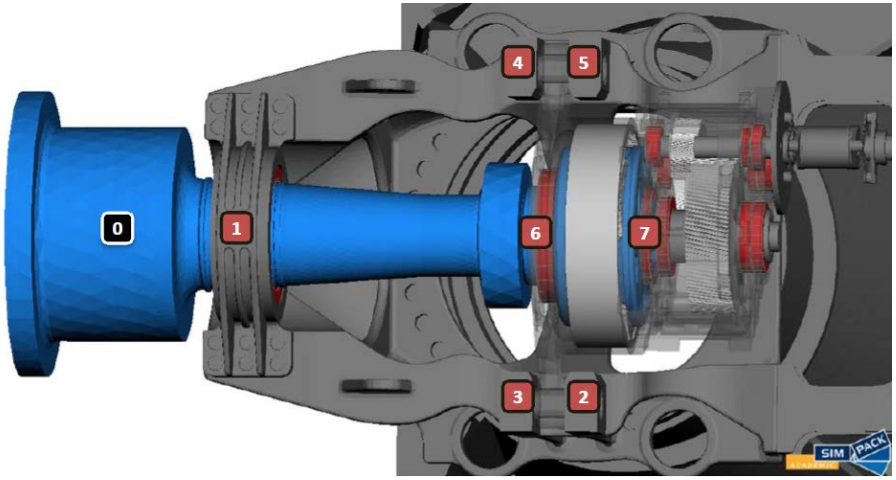


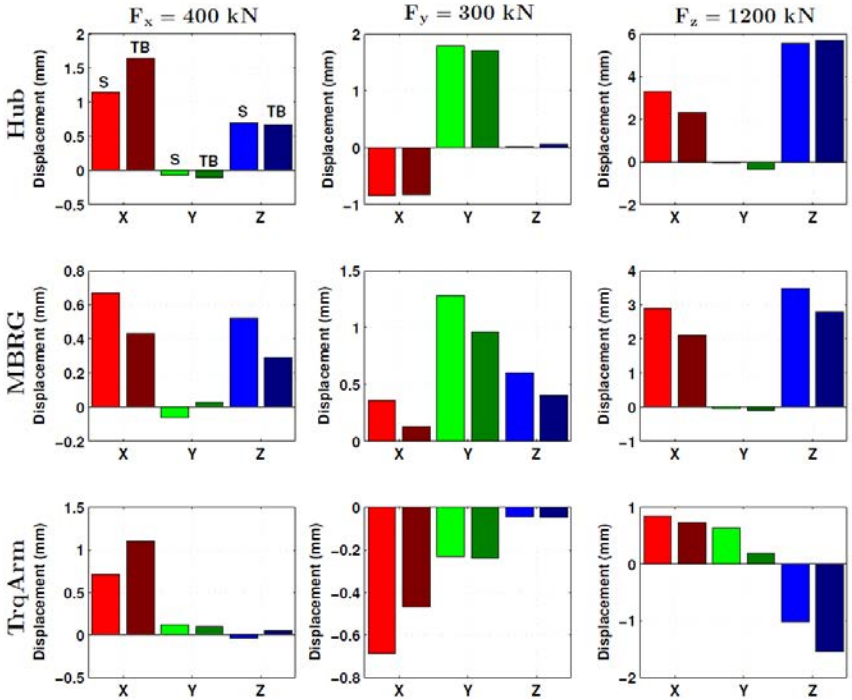


Static Deflection

- Static load profiles were used to validate force deflection behavior of the DUT model
- Main bearing and gearbox trunnion deflections were studied
- Model showed similar magnitude and trends

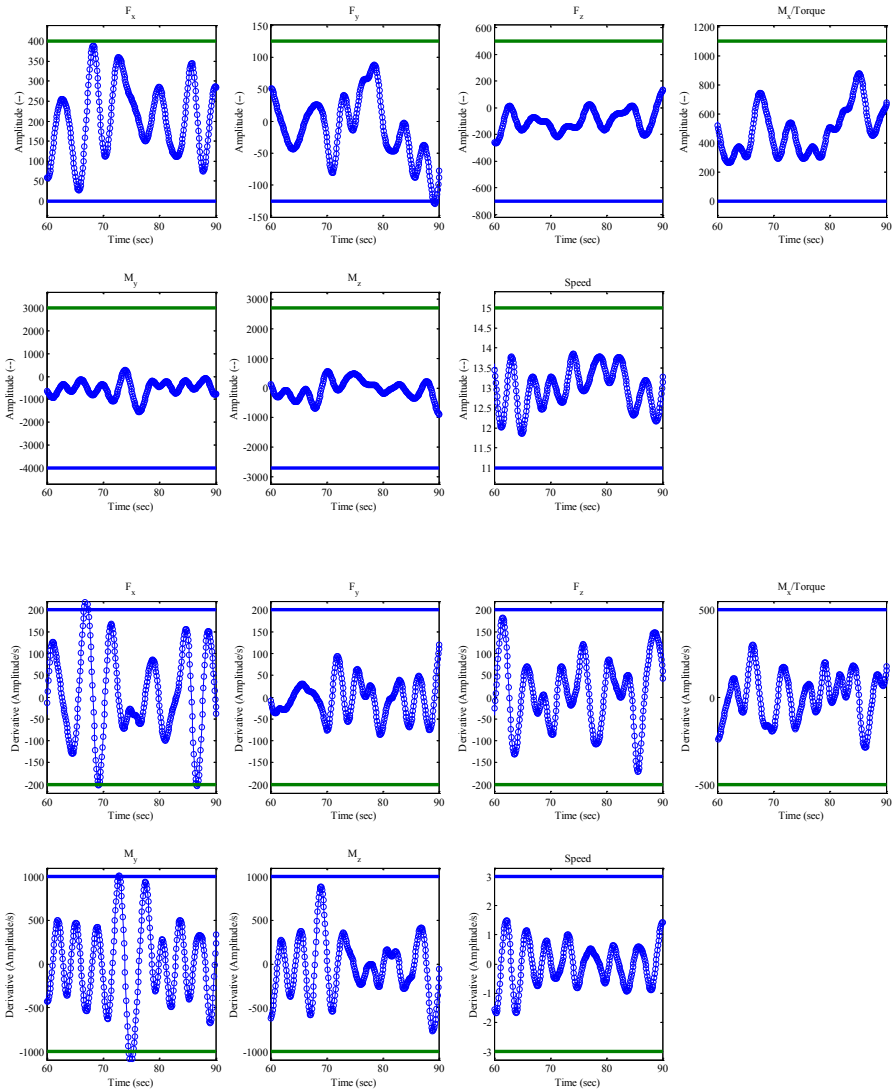






System Level Validation

- A series of filtered white noise profiles are proposed
- The goal is to study the input-output relationship of the test bench across a frequency range
- Profile generation procedure
  - Simulate a white noise series
  - Filter this series to the desired cutoff frequency (used a 4th order Chebyshev filter with 0.5dB ripple)
  - Scale the series so that its magnitude is within amplitude bounds 99% of the time (see slide 2)
  - Further scale the signal so that its derivative is within bounds 99% of the time
- The resulting signals may be applied one at a time or in combinations (i.e. actuating the tilt and yaw directions simultaneously and actuating the tilt, yaw, and thrust directions simultaneously)



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Model Capabilities

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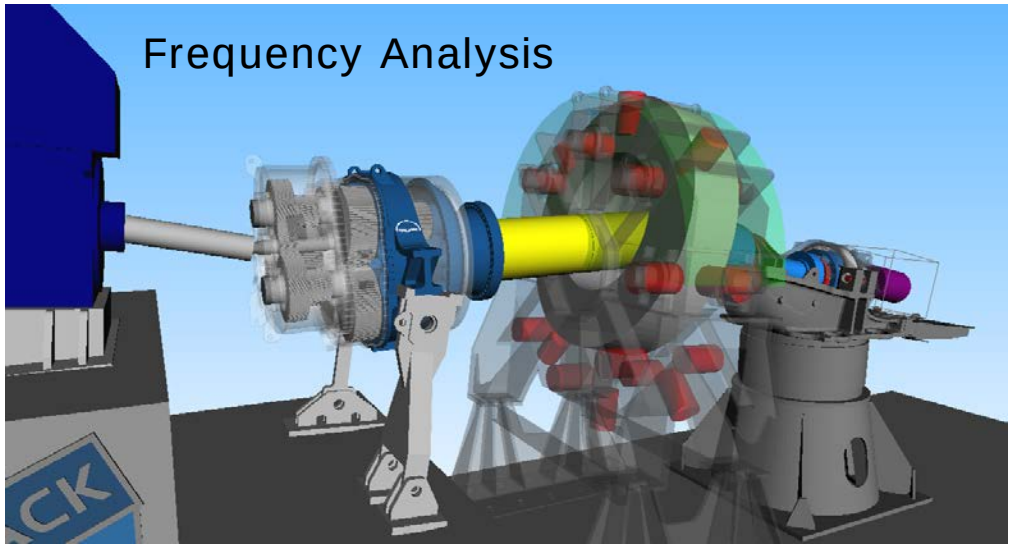
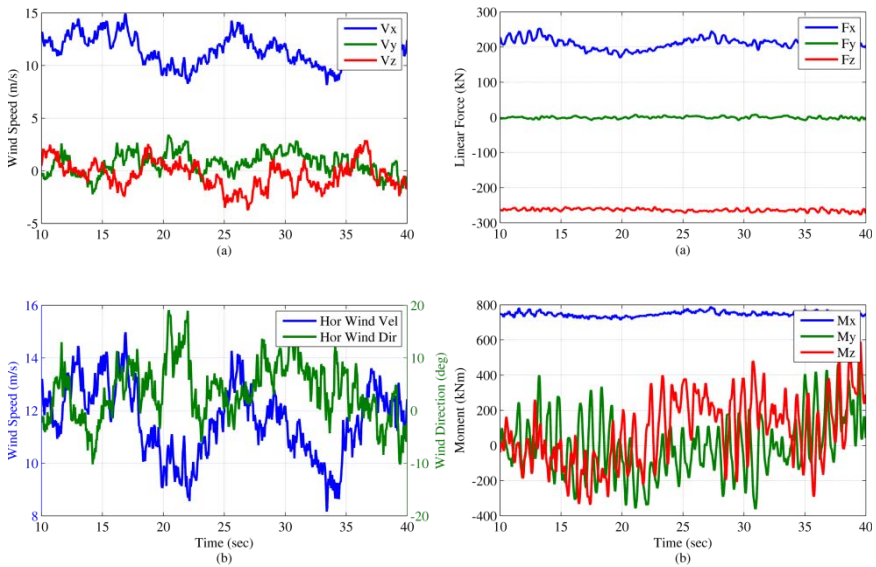
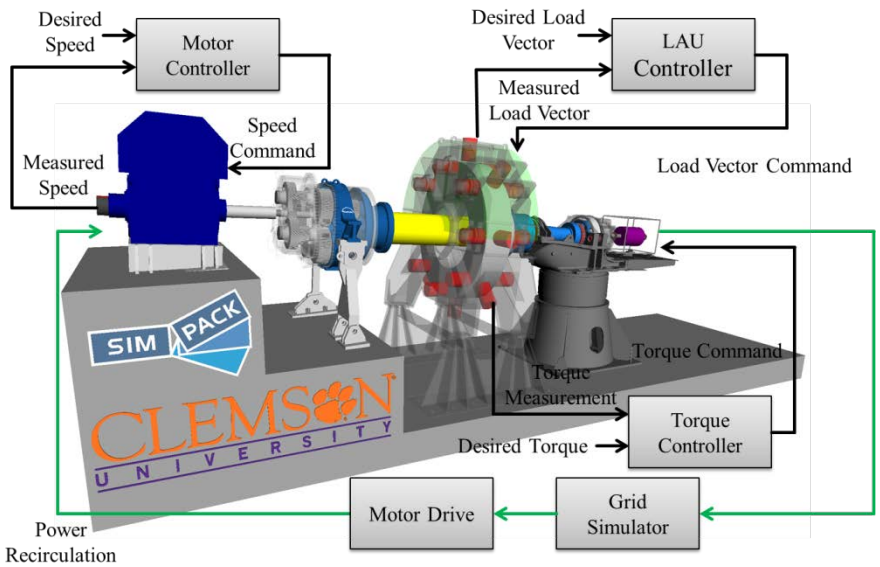
- Multi-body dynamics
- Control systems
- Electrical/power systems
- Real-time execution
- Wind load simulation
- Test profile development and evaluation
- Third party tool integration



Wind and Main Shaft Load Simulation





Time Domain Simulation

Simulation and Analysis Projects

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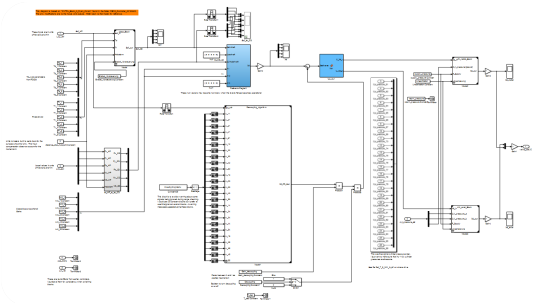
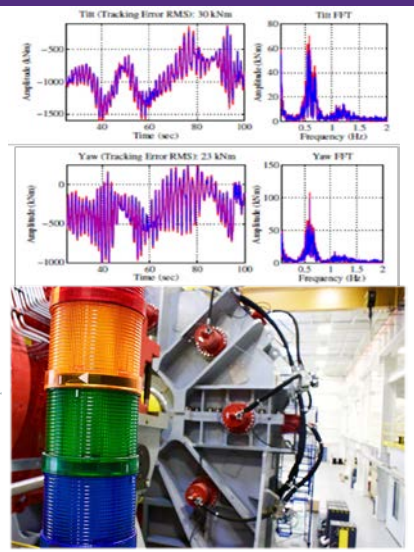
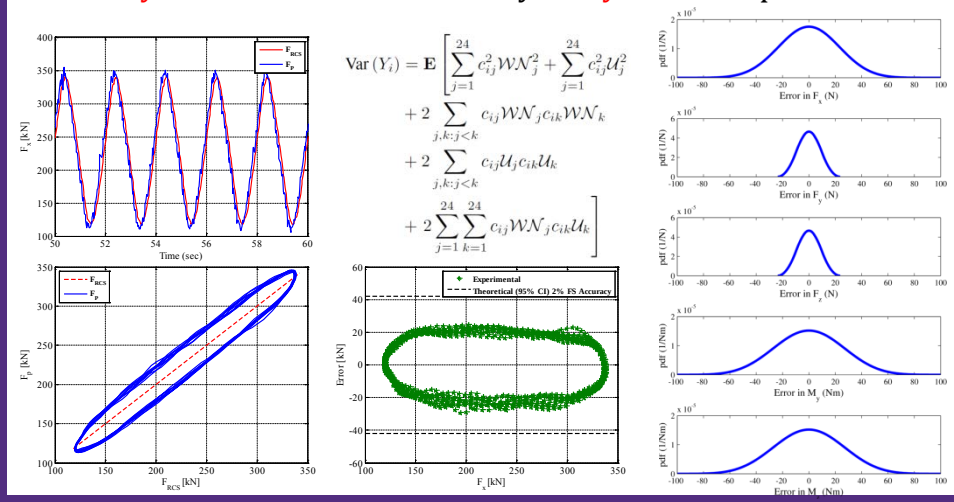
Re-design LAU Controller for improved Test Bench dynamic performance.



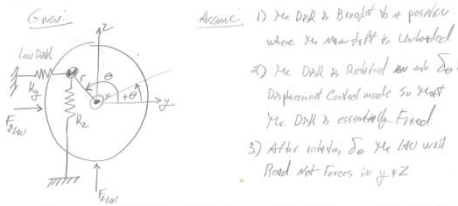


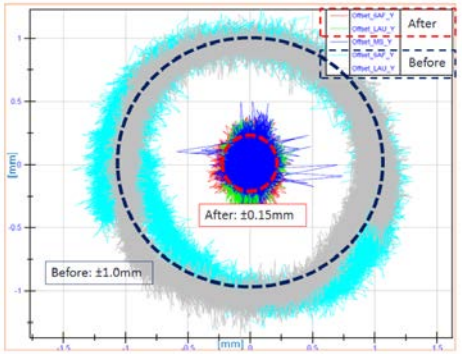
Accuracy evaluation and Uncertainty Analysis of LAU performance

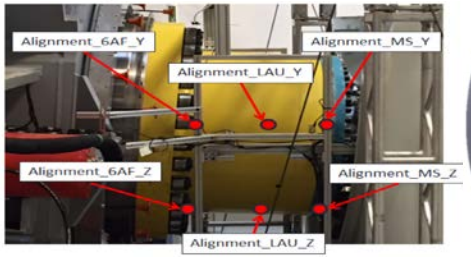


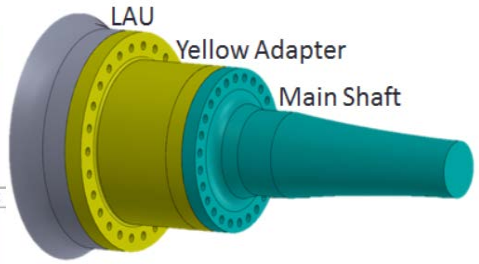
$$\mathrm{Var}(Y_i) = \mathbf{E}\left[\sum_{j=1}^{24} c_{ij}^2 \mathcal{WN}_j^2 + \sum_{j=1}^{24} c_{ij}^2 \mathcal{U}_j^2 + 2\sum_{j,k:j<k} c_{ij}\mathcal{WN}_j c_{ik}\mathcal{WN}_k + 2\sum_{j,k:j<k} c_{ij}\mathcal{U}_j c_{ik}\mathcal{U}_k + 2\sum_{j=1}^{24}\sum_{k=1}^{24} c_{ij}\mathcal{WN}_j c_{ik}\mathcal{U}_k\right]$$

Developing a procedure for Main shaft-to-LAU alignment within 0.1 mm accuracy.

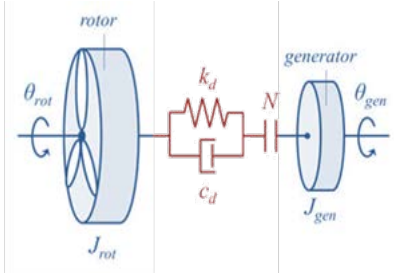


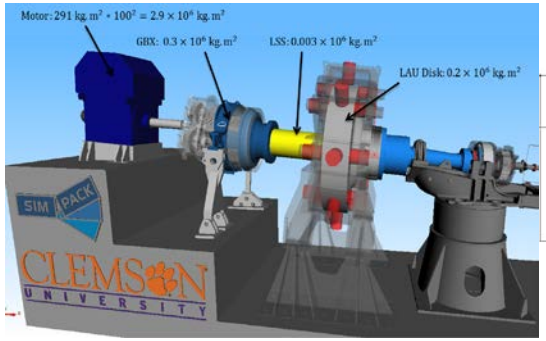


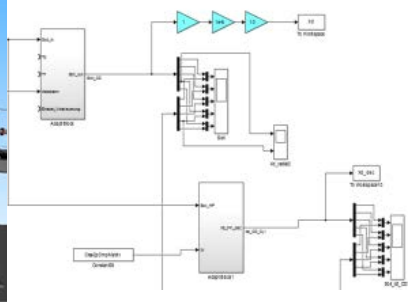




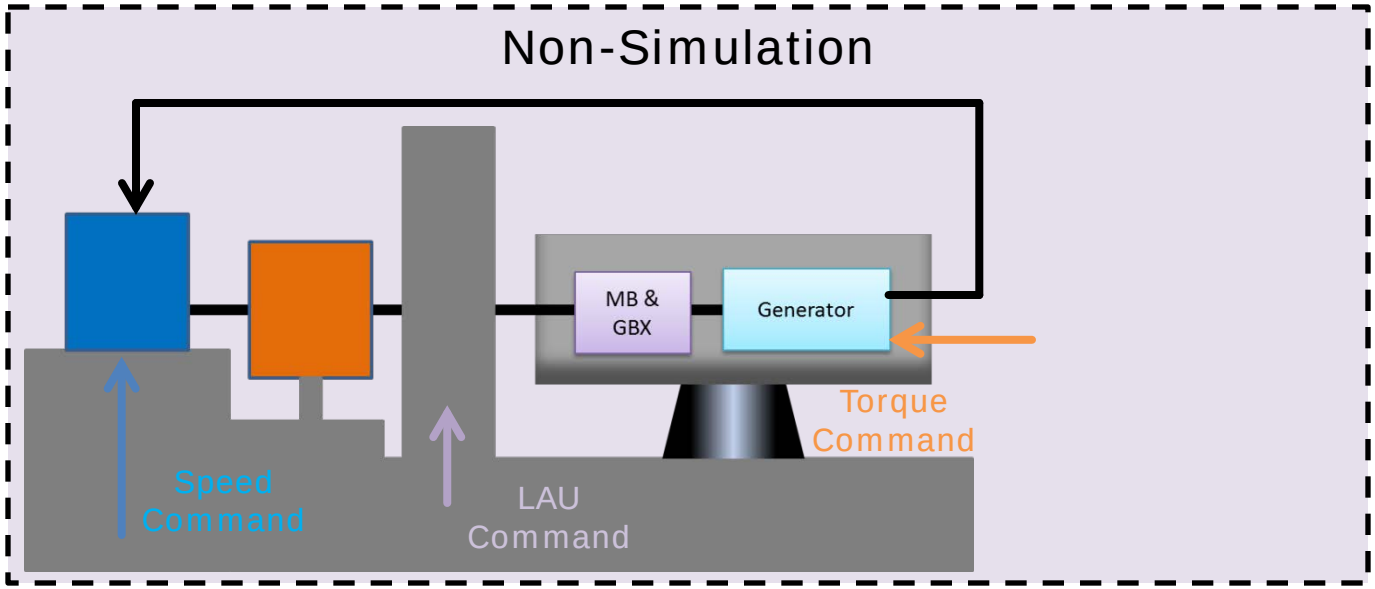
Rotor Inertia Compensation through Motor drive controller (on-going).







Hardware In the Loop (HIL) Nacelle Testing



Hardware In the Loop (HIL) Nacelle Testing

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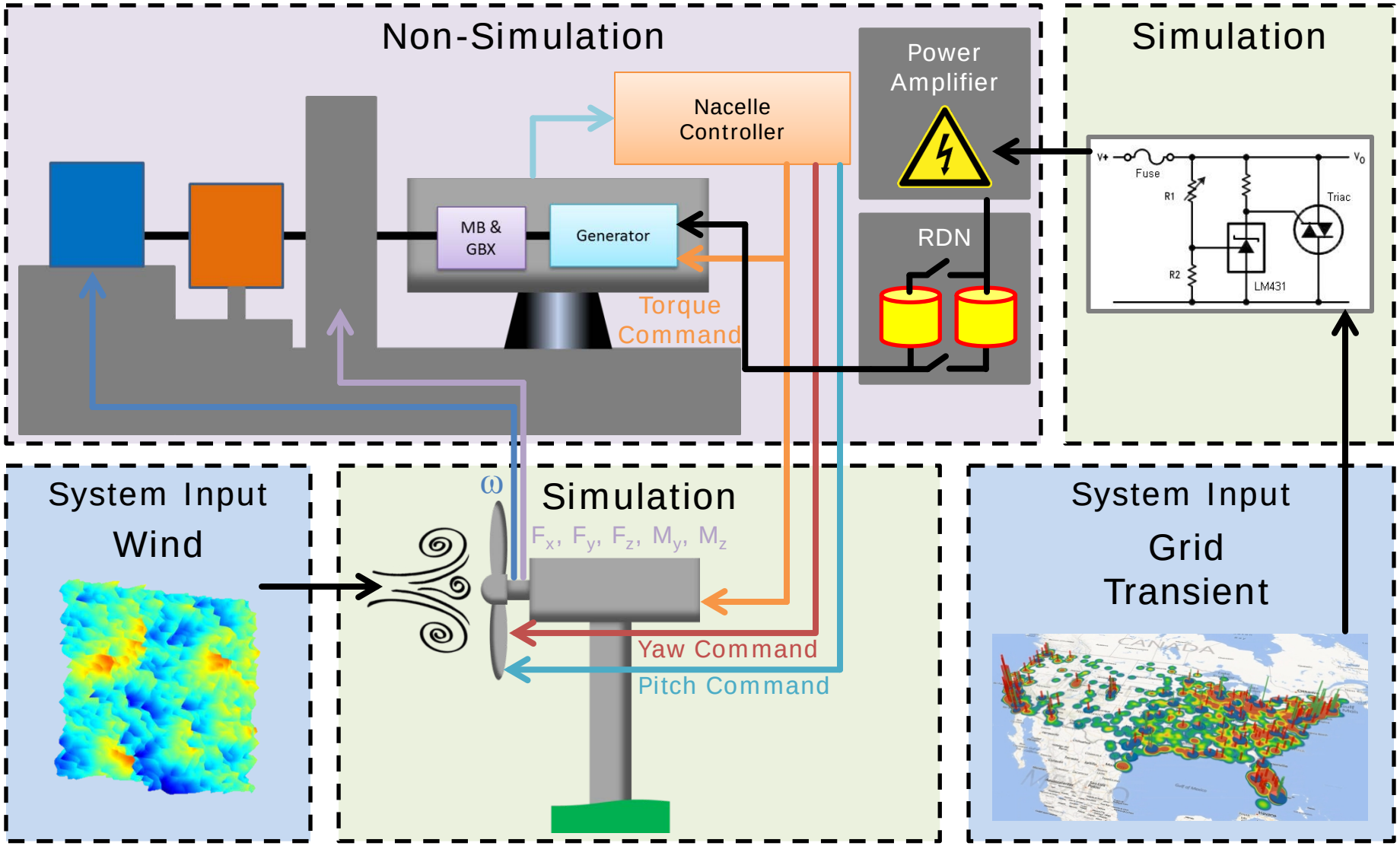

Hardware In the Loop (HIL) Nacelle Testing

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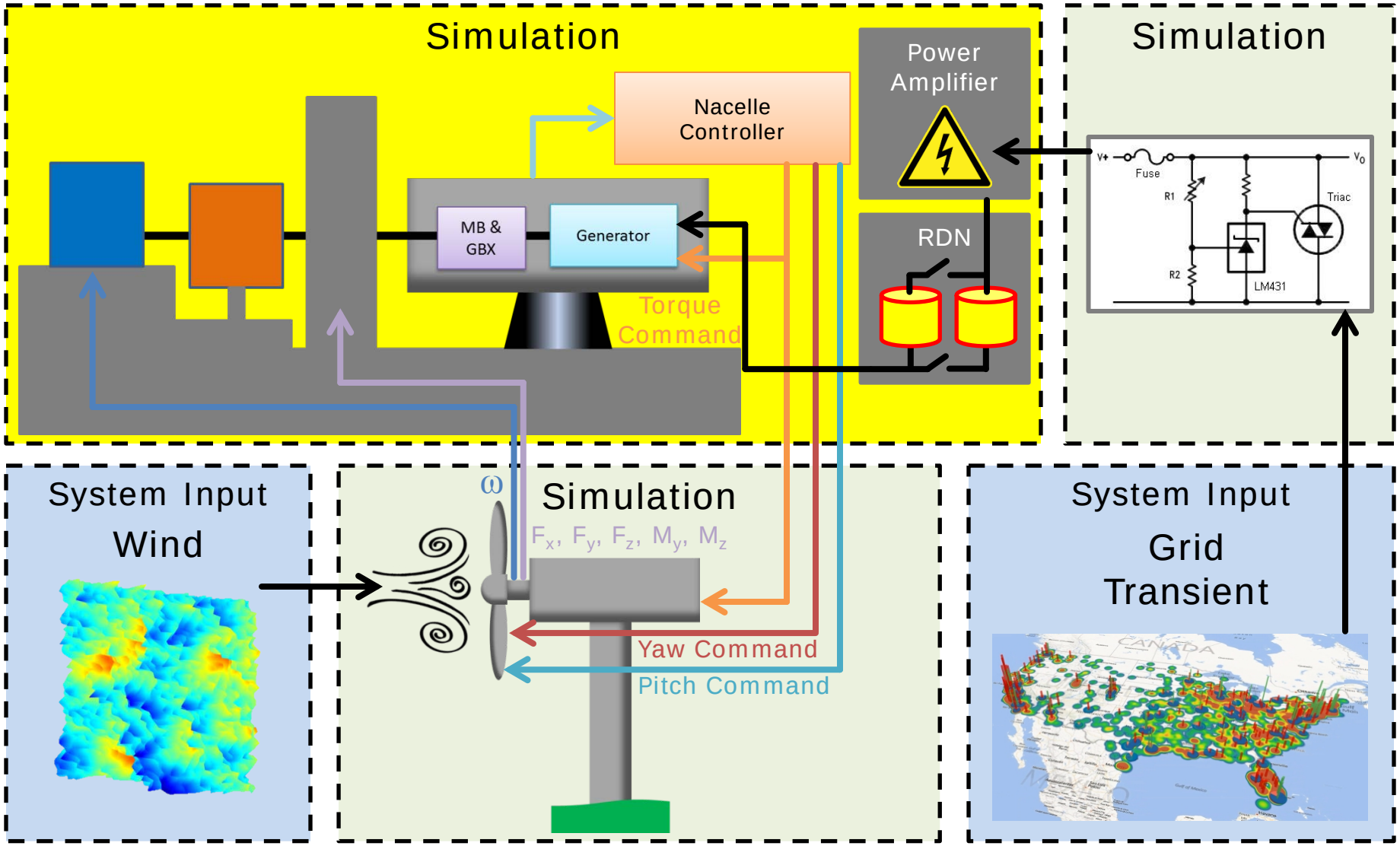
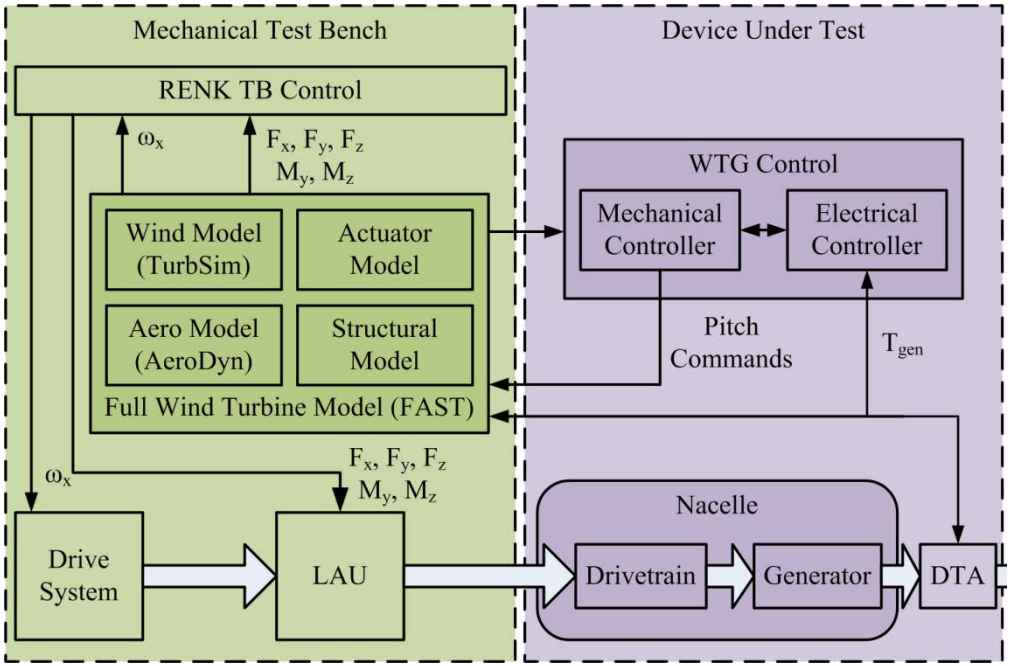


HIL Strategy

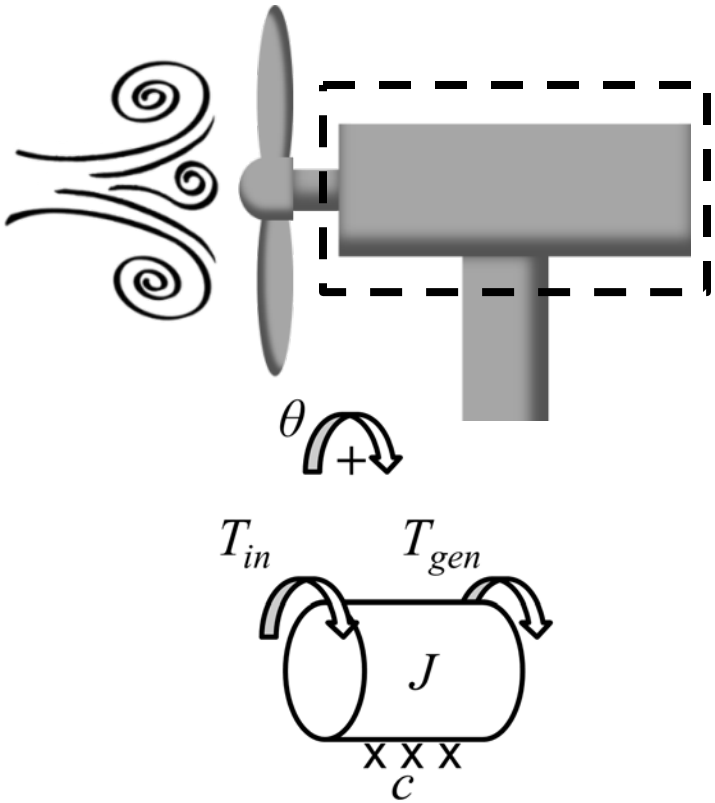
- Objective of the Hil strategy is to have a controllable and repeatable environment that the nacelle/DUT can interact with.
- The abstraction of the test bench is a key barrier to this goal.
  - absence of blades and a tower
  - negligence of pitch and yaw dynamics
  - differing inertia between the test bench drivetrain and the nacelle hub assembly
- The result is dissimilar boundary conditions

- Complete wind turbine model running in parallel with test bench
- Wind profile is predefined
- Pitch commands sent to model
- Torque commands sent to model and generator
- Speed reference is sent to drive motor



HIL Strategy

Drivetrain with no tower or blades



$$T_{in} + T_{gen} - c\omega = J\dot{\omega}$$

If T_{gen} is known, then T_{in} and ω are dependent

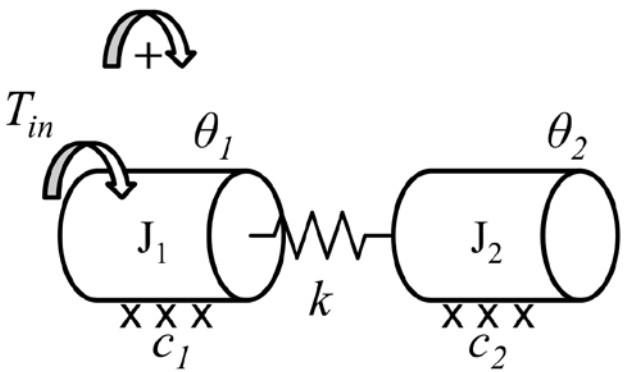
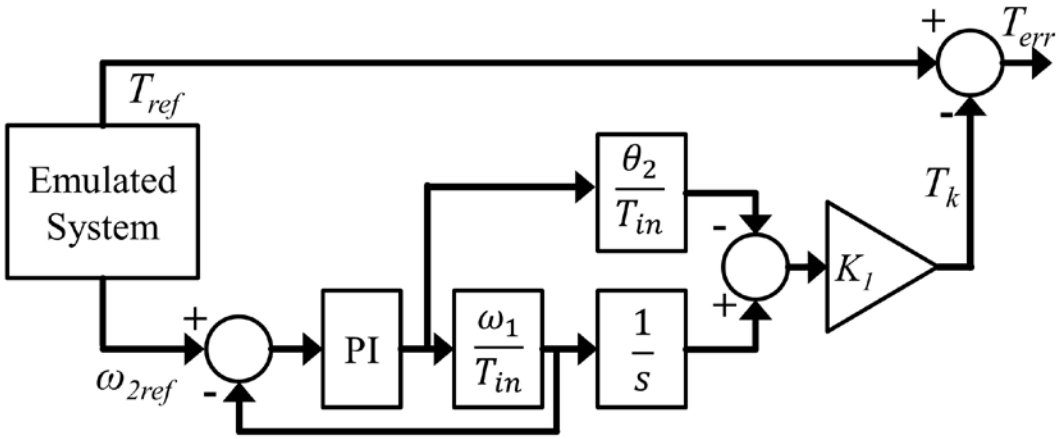


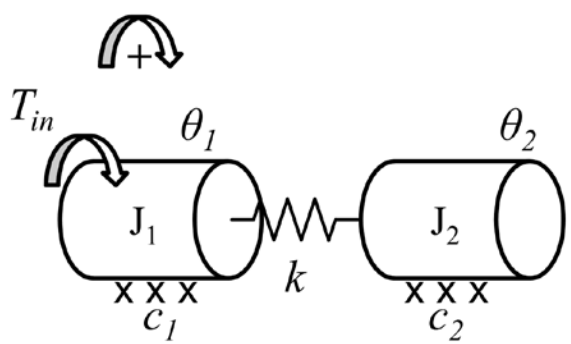
TABLE 1. MODEL PARAMETERS

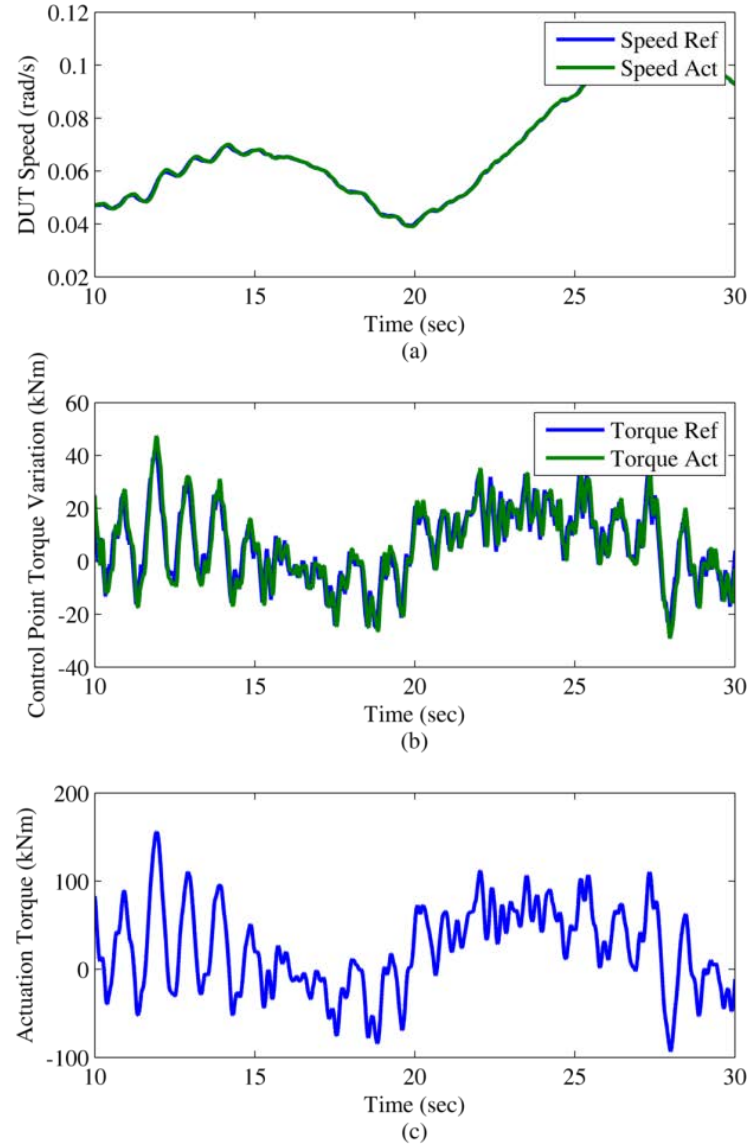
Parameter	value
J_1	3.4e6 kgm^2
J_2	1.2e6 kgm^2
c_1	117e3 Nms/rad
c_2	65e3 Nms/rad
k	2e9 Nm/rad



HIL Proof of Concept

- shows that the actual speed of mass two followed the reference signal rather well.
- This result is not trivial because it relies on the assumption that the measured speed of mass one may be substituted for the measured speed of mass two.
- Compare this to the attempt at assuming that the torque measured at the motor is equal to the torque experienced at the control point





HIL Simulated Results

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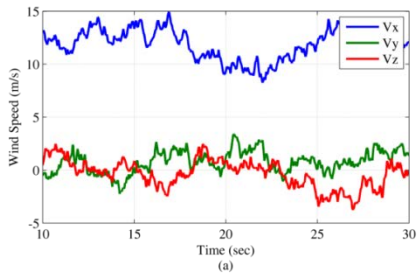
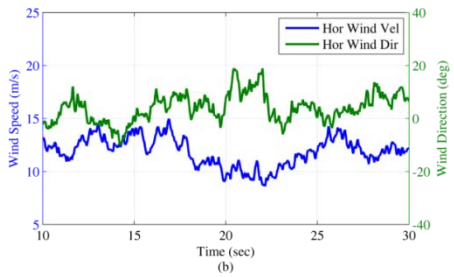
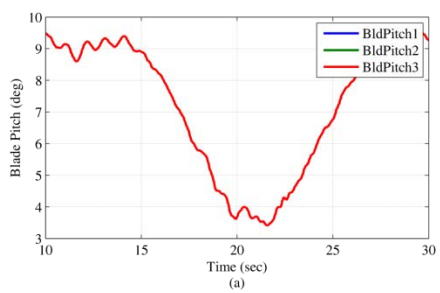


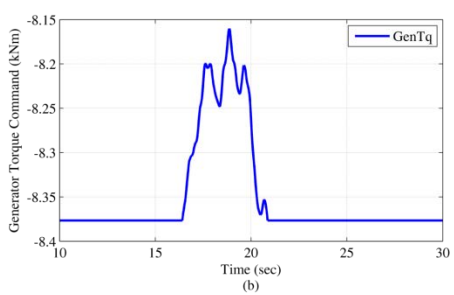
Wind Profile



- Predefined wind profile drives the test bench
- Overall response is based on interaction between controller and test bench

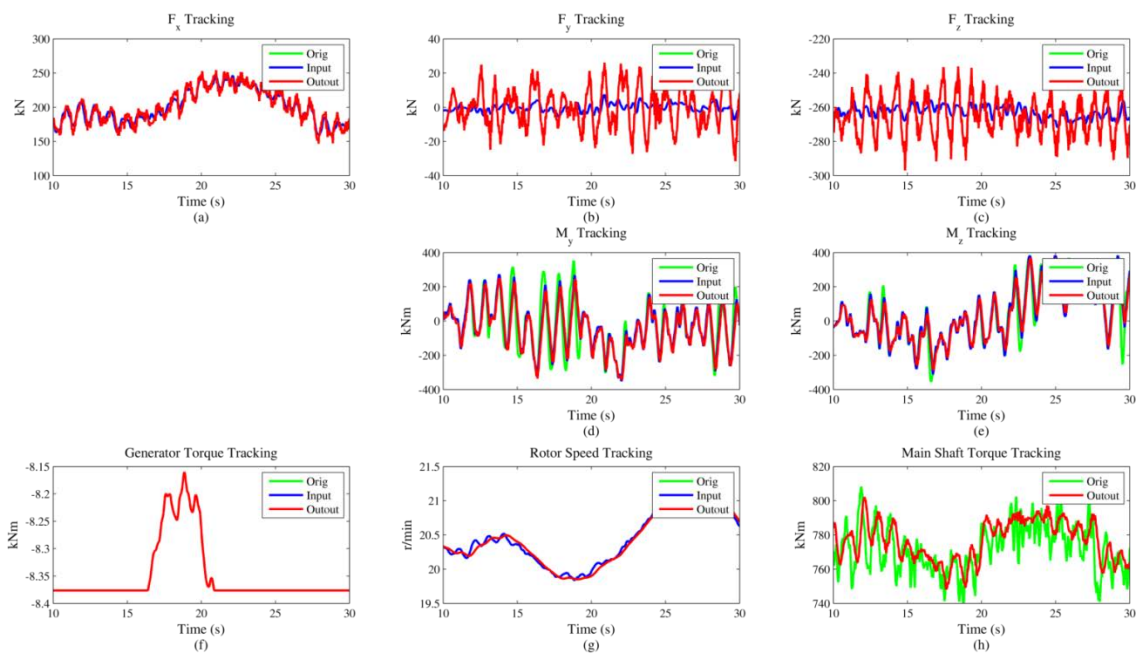


Controller Response



Feedback

Test Bench Response



HIL Simulated Results

- Main shaft torque error is comparable to errors in other directions
- No significant difficulty with trying to control speed

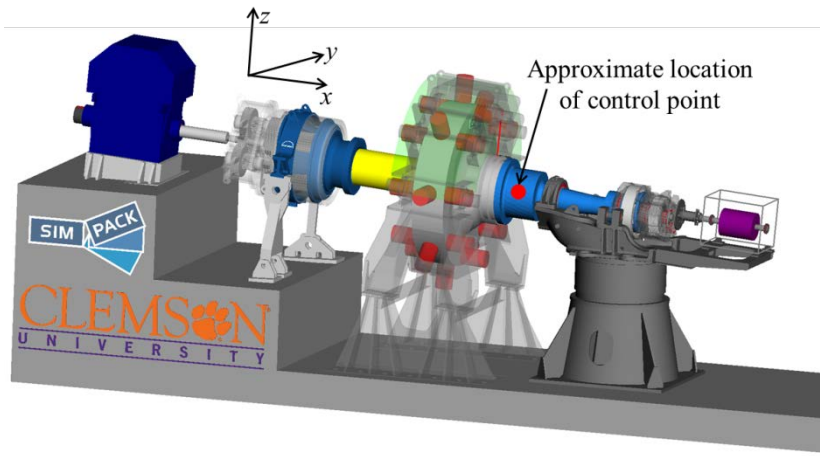
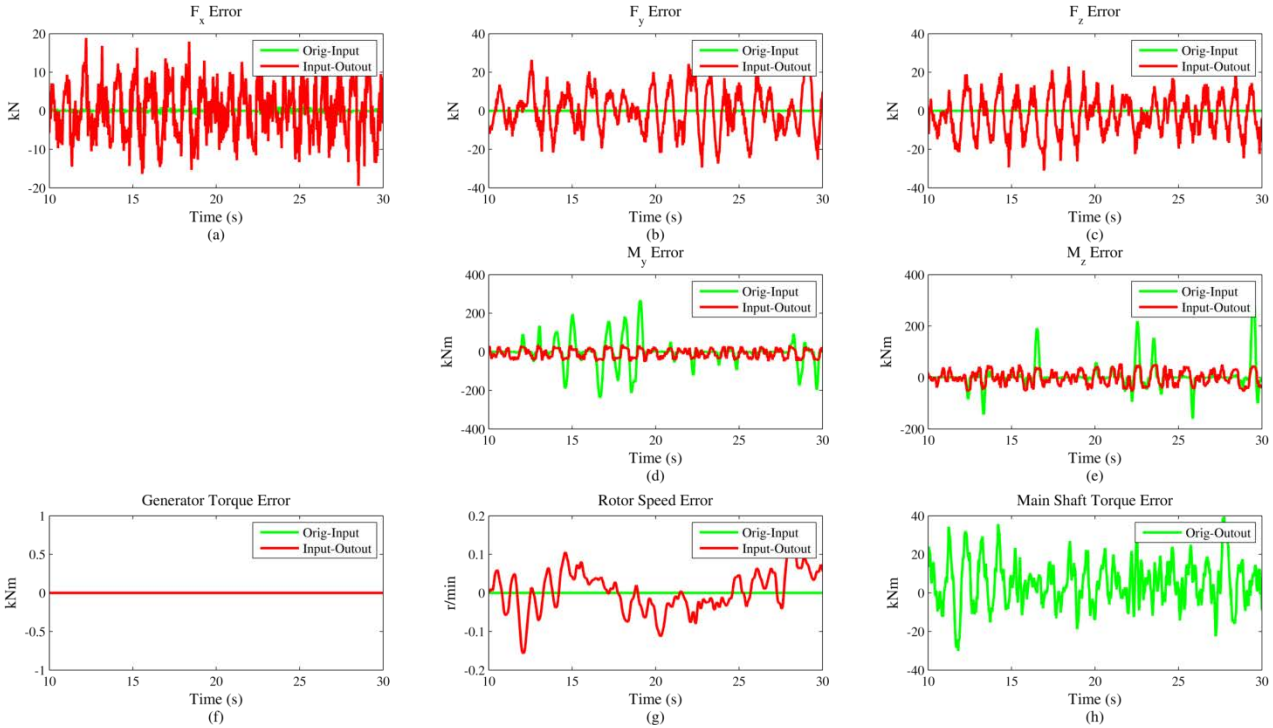


TABLE 2. TRACKING ERROR RMS

Direction	Orig-Input	Input-Output
F_x	0.22	6.33
F_y	0.00	11.32
F_z	0.04	9.51
M_y	76.92	24.85
M_z	65.84	29.81
GenTorque	0.00	0.00
RotorSpeed	0.00	0.05
M_x	–	10.56

Units are appropriate for each quantity (kN, kNm, RPM)



Real Time Resources

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Duplicate RDDS
- Identical hardware and software
- Test profile evaluation
- Operation troubleshooting

RDDS

Concurrent Real-Time System
- Detailed component simulation
- Collaborative multidomain modeling
- Involve faculty, students, etc.

concurrent REAL-TIME

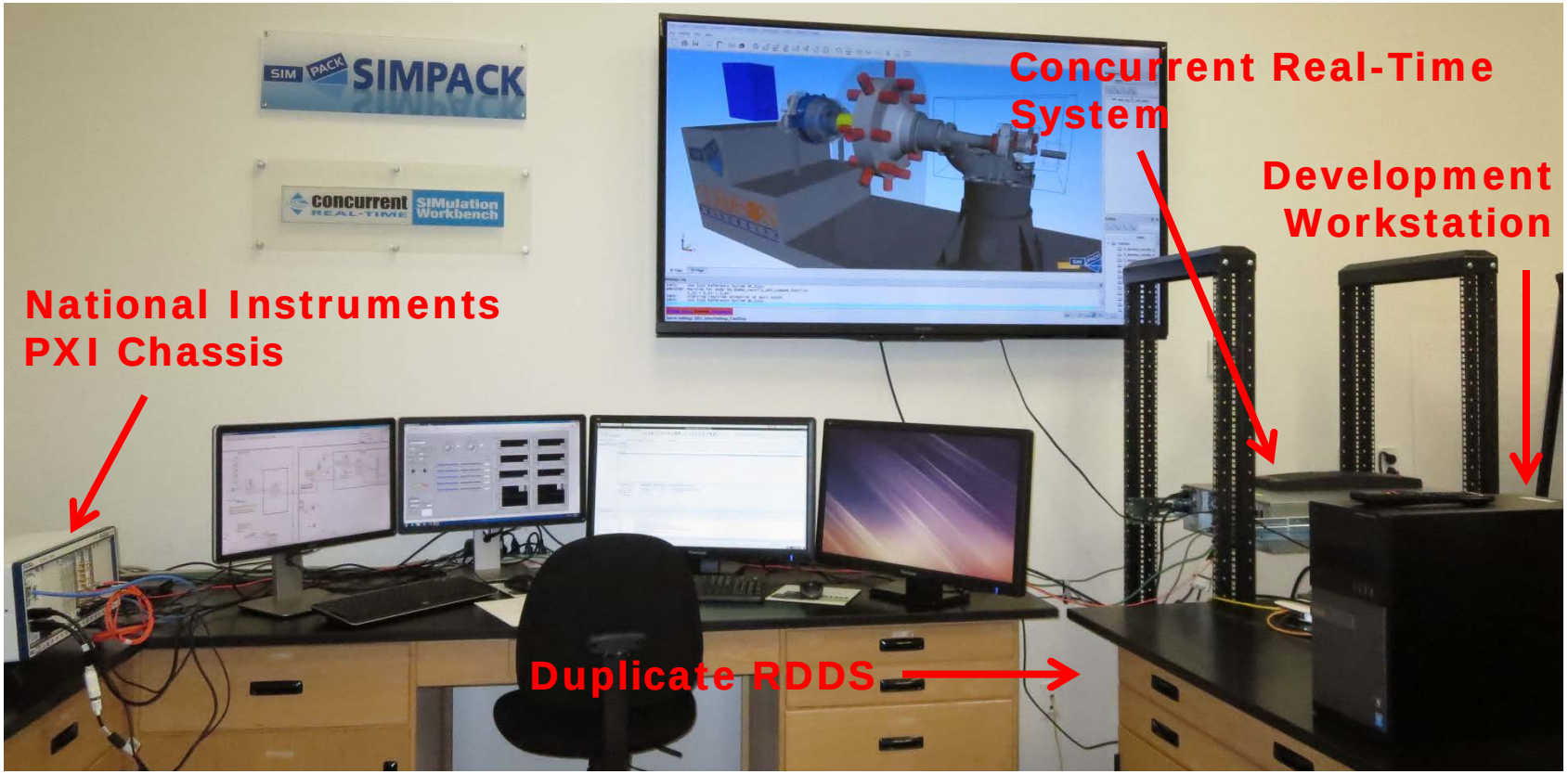
Speedgoat Real-Time System
- Nacelle controller implementation
- Mechanical and electrical control
- Flexible real-time simulation

speedgoat
real-time simulation and testing

National Instruments PXI
- Flexible simulation and DAQ
- Execute NREL FAST code
- Integrates with facility DAQ

NATIONAL INSTRUMENTS™

Current Simulation Lab Setup



- Concurrent system runs SIMPACK, MATLAB and Simulink models in real time
- NI PXI Chassis runs LabVIEW code and NREL's FAST in real-time
- Duplicate RDDS
- Communication via EtherCAT or reflective memory

Conclusion

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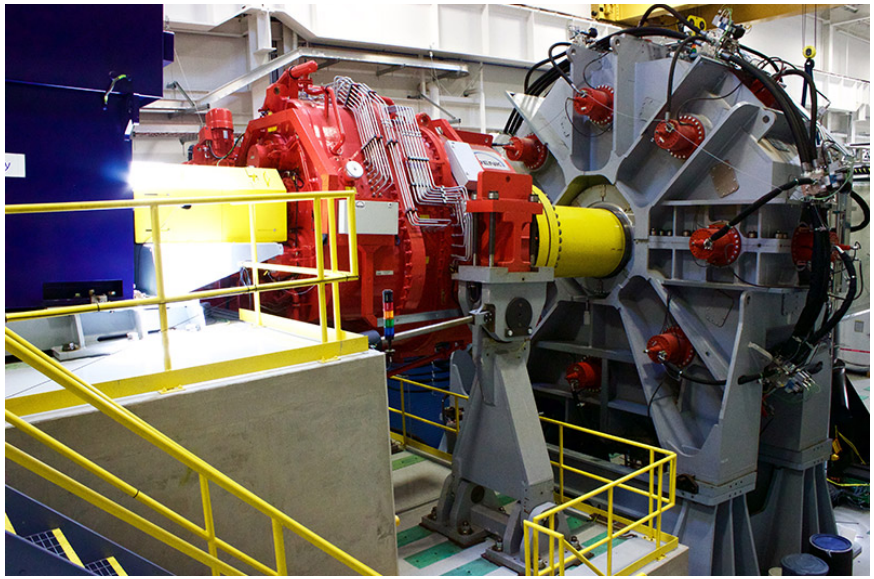
- What we have modeled ✓

- How we have validated
- How we are validating ✓

- What these models facilitate ✓

Understanding of the dynamic systems allows the equipment to be used Safely, Efficiently, and Competitively.



Thank you