Clemson University: Facility Update, First Test Campaign, and Ongoing Activities

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Clemson Energy Innovation Center

**7.5 MW Test Bench**

![Image of 7.5 MW Test Bench]

**15 MW Test Bench**

![Image of 15 MW Test Bench]

**15 MW HIL Grid Simulator**

![Image of 15 MW HIL Grid Simulator]

**Virtual Test Bench Test Capability**

![Diagram of Virtual Test Bench Test Capability]
| I             | Test Bench Only (non-loading) | • All Systems Operations  
• Overall Controllability  
• Hydraulics Operations  
• Systems Safety  
• Maximum Speed |
|---------------|------------------------------|------------------------------------------------------------------------|
| II            | Test Bench with Rigid Commissioning Stand (non-rotating) | • Load Application Unit Controllability & Accuracy  
• Reduce Nacelle Damage Risk for Phase III  
• Long Term Operations Calibration (PM) |
| III           | Test Bench with Nacelle (full system) | • Dynamometer Operational Characteristics coupled with GE 1.6-100 Nacelle  
• System Level Behavior  
• Measurement Data Verification  
• Take Over Certificate |
Rigid Commissioning Stand (RCS)

**Measurement Uncertainties**

<table>
<thead>
<tr>
<th>Description</th>
<th>Accuracy Max Error</th>
<th>Max Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCS friction (LAU force control mode)</td>
<td>0.2kN</td>
<td>0.04%</td>
</tr>
<tr>
<td>RCS friction (LAU displacement control mode)</td>
<td>9kN</td>
<td>1.6%</td>
</tr>
<tr>
<td>Estimated friction of the TB drivetrain &amp; supporting structure</td>
<td>11-13kN</td>
<td>2.0-2.4%</td>
</tr>
<tr>
<td>LAU hydraulic cylinders friction</td>
<td>15kN</td>
<td>2.7%</td>
</tr>
<tr>
<td>Estimated friction of the LAU</td>
<td>±2.6kN</td>
<td>±2.6kN</td>
</tr>
<tr>
<td>LAU hydraulic cylinders friction</td>
<td>≈1kN</td>
<td>≈1kN</td>
</tr>
</tbody>
</table>

**Description**

<table>
<thead>
<tr>
<th>Description</th>
<th>LAU Control Mode</th>
<th>Accuracy Max Error</th>
<th>Accuracy Max Load Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAU load set point tracking (calculated)</td>
<td>Force</td>
<td>0.2kN</td>
<td>0.04%</td>
</tr>
<tr>
<td>LAU vs. RCS measurement (static)</td>
<td>Disp.</td>
<td>9kN</td>
<td>1.6%</td>
</tr>
<tr>
<td>LAU vs. RCS measurement (dynamic @ 0.1Hz)</td>
<td>Disp.</td>
<td>11-13kN</td>
<td>2.0-2.4%</td>
</tr>
<tr>
<td>LAU vs. RCS measurement (static)</td>
<td>Force</td>
<td>15kN</td>
<td>2.7%</td>
</tr>
</tbody>
</table>

**Location**

<table>
<thead>
<tr>
<th>Location</th>
<th>Sensor Type</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAU Hydraulic Cylinders</td>
<td>Disp.</td>
<td>±1μm</td>
</tr>
<tr>
<td></td>
<td>Pressure</td>
<td>±0.5% FS</td>
</tr>
<tr>
<td>HSS Torque Flange</td>
<td>Strain</td>
<td>0.08%</td>
</tr>
<tr>
<td>RCS Load Cell</td>
<td>Strain</td>
<td>0.12%</td>
</tr>
<tr>
<td>Hub Point</td>
<td>Calculated</td>
<td>N/A</td>
</tr>
<tr>
<td>6-Axis Flange</td>
<td>Strain</td>
<td>0.2-5.0%</td>
</tr>
</tbody>
</table>
Electrical Interface

## Methods | Uses | Status
--- | --- | ---
**AC Recirculation** | System checkout and/or Nacelle not synchronizing with the DC method | Commissioned and operational
**DC Recirculation** | Nacelle normal operations | Commissioned and operational
**Grid Simulator** | Grid fault ride-through testing and other grid integration | Q3,2015

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**AC Power Recirculation**

7.5 MW Test Rig

**DC Power Recirculation**

Main Utility Bus (23.9 kV 60 Hz)
Recent Test Campaigns

- Test campaign 1 completed in November 2014
- Test campaign 2 completed in December 2014
- Internal Characterization tests taking place now
- Test campaign 3 to begin Q2 2015

### Test Set-up

<table>
<thead>
<tr>
<th>Test Set-up</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Article</td>
<td>GE 1.6-100 Nacelle</td>
</tr>
<tr>
<td>Grid</td>
<td>Direct Connection</td>
</tr>
<tr>
<td>Nacelle DAS</td>
<td>GE</td>
</tr>
<tr>
<td>Total Test Sequences</td>
<td>Over 150</td>
</tr>
<tr>
<td>Operational Mode</td>
<td>Double shifts</td>
</tr>
<tr>
<td>TB Utilization</td>
<td>37% (based on 24/7 operations)</td>
</tr>
<tr>
<td>Safety Incidents</td>
<td>None</td>
</tr>
<tr>
<td>Quality Incidents</td>
<td>None</td>
</tr>
</tbody>
</table>
Next Steps

- Establish **detailed dynamic** characterization map of the 7.5MW test bench
- Release **certification report** on accuracy and repeatability (complete by independent 3rd party)
- Using **modeling and simulation** to establish best test practices (dynamic, accuracy, test sequences, etc...)
- Continued **collaborative work with NREL** (CRADA)
**Modeling and Simulation**

**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.

**Hardware In the Loop Simulation**
- Model reduction for realtime
- Integrate actual HMI hardware
- Virtual test bay

**Test Bench Operation**
- Increased utilization
- Advanced test profile execution
- Confident performance
Modeling and Simulation

1. Uncertainty analysis
2. Hardware In the Loop (HIL) testing strategy
3. Control tuning/development
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

\[ p_j = p_{aj} + \mathcal{W}\mathcal{N}(0, 0.115 \text{ bar}) + \mathcal{U}(-2 \text{ bar}, 2 \text{ bar}) \]

Force Model

\[ F_j = F_{aj} + \mathcal{W}\mathcal{N}(0, \sigma^2_{ran}) + \mathcal{U}(-b, b) \]

Assumed Load Model

\[ y = Tp \]

\[ y = [F_x \ F_y \ F_z \ M_y \ M_z]' \]

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

More Comprehensive Load Model

\[ Y_i = Y_{op} \]

\[ + \sum_{j=1}^{24} \frac{\partial Y_i}{\partial F_j} (F_{aj} + \mathcal{W}\mathcal{N}(0, \sigma^2_{ran}) + \mathcal{U}(-b, b) - F_{op}) \]

Measurement Uncertainty

Expected value

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

\[
= E[Y_{op}] + \sum_{j=1}^{24} E[c_{ij} \mathcal{W}_j(0, \sigma_{ran}^2)] + \sum_{j=1}^{24} E[\mathcal{U}(-b, b)]
\]

Variance

\[
\text{Var}(Y_i) = \sum_{j=1}^{24} c_{ij}^2 \mathcal{W}_j^2 + \sum_{j=1}^{24} c_{ij}^2 \mathcal{U}_j^2
\]

\[
+ 2 \sum_{j,k:j<k} c_{ij} \mathcal{W}_j c_{ik} \mathcal{W}_k
\]

\[
+ 2 \sum_{j,k:j<k} c_{ij} \mathcal{U}_j c_{ik} \mathcal{U}_k
\]

\[
+ 2 \sum_{j=1}^{24} \sum_{k=1}^{24} c_{ij} \mathcal{W}_j c_{ik} \mathcal{U}_k
\]

\[
\text{Var}(Y_i) = \sum_{j=1}^{24} c_{ij}^2 \sigma_j^2 + \sum_{j=1}^{24} c_{ij}^2 \sigma_U^2
\]

Distribution

Pressure Uncertainty Summary

<table>
<thead>
<tr>
<th>Variance of Component</th>
<th>Aleatoric (statistical)</th>
<th>Epistemic (systematic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_x ) kN</td>
<td>44.37e6</td>
<td>514.2e6</td>
</tr>
<tr>
<td>( F_y ) kN</td>
<td>11.09e6</td>
<td>128.6e6</td>
</tr>
<tr>
<td>( F_z ) kN</td>
<td>11.09e6</td>
<td>128.6e6</td>
</tr>
<tr>
<td>( M_x ) kNm</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( M_y ) kNm</td>
<td>113.80e6</td>
<td>1,319.0e6</td>
</tr>
<tr>
<td>( M_z ) kNm</td>
<td>113.80e6</td>
<td>1,319.0e6</td>
</tr>
</tbody>
</table>

Displacement Uncertainty Summary

<table>
<thead>
<tr>
<th>( x ) mm</th>
<th>( y ) mm</th>
<th>( z ) mm</th>
<th>( \alpha ) deg</th>
<th>( \beta ) deg</th>
<th>( \gamma ) deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>±20</td>
<td>±20</td>
<td>±20</td>
<td>±0.8 deg</td>
<td>±0.8 deg</td>
<td>±0.8 deg</td>
</tr>
</tbody>
</table>

Conclusions

- Displacement based uncertainty depends heavily on the test profile.
- Statistical uncertainty can be helped with averaging but the systematic error remains
Hardware In the Loop (HIL) Nacelle Testing

Non-Simulation
- System Input
  - Wind
- Simulation
  - $\omega$
  - $F_x, F_y, F_z, M_y, M_z$
  - Yaw Command
  - Pitch Command

Simulation
- Power Amplifier
- RDN

System Input
- Grid Transient

Diagram elements:
- MB & GBX
- Generator
- Torque Command
- Nacelle Controller
- Fuse
- Triac
- LMA31
- $V_e$
- $R_1$
- $R_2$
Hardware In the Loop (HIL) Nacelle Testing

Non-Simulation

Speed Command

LAU Command

MB & GBX

Generator

Torque Command
Hardware In the Loop (HIL)
Nacelle Testing

Simulation

Speed Command
LAU Command
MB & GBX
Generator
Power Amplifier
RDN
Torque Command

LAU Command
Hardware In the Loop (HIL) Nacelle Testing

Simulation

Power Amplifier

Nacelle Controller

MB & GBX

Generator

Torque Command

ω

Fx, Fy, Fz, My, Mz

RDN

Simulation

Hardware In the Loop (HIL) Nacelle Testing
Hardware In the Loop (HIL) Nacelle Testing

System Input
Wind

Simulation

Nacelle Controller

Power Amplifier

RDN

Torque Command

Grid

Transient

System Input

Grid Transient

Wind

ω

F_x, F_y, F_z, M_y, M_z

Pitch Command

Yaw Command

Hardware In the Loop (HIL) Nacelle Testing

Simulation

Simulation

System Input

Wind

Simulation

Nacelle Controller

Power Amplifier

RDN

Torque Command

Grid

Transient
Hardware In the Loop (HIL) Nacelle Testing

Non-Simulation

- System Input
- Wind

Simulation

- Simulation
- Ω
- \( F_x, F_y, F_z, M_y, M_z \)
- Yaw Command
- Pitch Command

Power Amplifier

- Nacelle Controller

Simulation

- System Input
- Grid Transient

Wind

\( \omega \)

Grid
• The LAU poses a legitimate control challenge
  – MIMO
  – Non-linear
  – No direct feedback
• Main shaft loads produced by turbulent wind can change rapidly
• Large scale industrial equipment is not meant to change that rapidly
• Simulation results of the profile shown on the previous slide

• Values shown against full scale of the 7.5MW test bench LAU
• Blue curve shows the effects of rate limitation
• Red curves show the system output
Requested vs Actual Error Plot
Low Ramp Rates

F_x Compare

F_y Compare

F_z Compare

M_y Compare

M_z Compare
• Linear forces are experiencing -30kN of error
• Bending moments are experiencing 40-60kN-m of error
Fourier Series Expansion
Low Ramp Rates

- Not a PSD
- Series expansion of original signal
- Series expansion of rate limited signal
- Series expansion of output signal
• Expect attenuation of input signal
• Did not expect amplification in the output signal
20 m/s Wind Profile Resulting Loads - High Ramp Rates

- Simulation results of the profile shown on the previous slide
- Values shown against full scale of the 7.5MW test bench LAU
- Now with higher allowable ramp rates
20 m/s Wind Profile Resulting Loads - High Ramp Rates

- Superior tracking in for the bending moments
Requested vs Actual Error Plot
High Ramp Rates
Requested vs Actual Error Plot
High Ramp Rates

- Similar error behavior at higher ramp rates
- Indicates that the controller is still functioning well
- Still experiencing amplification
- Much better performance for the bending moment directions
Fourier Series Expansion
High Ramp Rates
Thank you