Transient Unbalance of a Turbo-Compressor Rotor due to Thermal-Gradient Induced Bow from a Seal Gas Heater

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Introduction - Pearl GTL
GTL unit, Hydrocracker and Hydrogen Recycle Compressor

High Vibration during Process Gas Start-Up
It always happens at night or on the weekend – troubled starts
Initial reaction and assessment

Comparison to Inert Gas Start-Up
"It didn’t do this before" – What’s the same, What’s different
What could it be?

Root Cause Assessment – Process Correlation
Behavior summary and Problem statement

Conclusion

Acknowledgements
PEARL GTL – HIGH LEVEL PROCESS FLOW

**Simplified Process Integration Scheme**

- **Platforms**
  - Sour gas
- **Feed Gas Processing**
  - Sweet gas
- **ASU**
  - Air
  - O2
  - Steam
- **GTL**
  - Water
  - Utilities (Power, water, steam, fuel gas, H2)
- **Reﬁnery & Storage**
  - N2
  - Liquid Processing Unit
  - Syn crude
  - Naphtha
  - Kero
  - Gas oil
  - n-Paraffin
  - Base oils
  - Sulphur
  - Condensate, LPG & Ethane

LPU = Liquid Processing Unit

Pearl GTL
GTL Department
Training Presentation
1/16/2009
PEARD GTL – LPU – HYDROCRACKER
3 Stage Centrifugal Compressor – “Recycle Gas Compressor”

92 Bar (~1500 psi)
3.6 MW
Tilt Pad Journal Bearings and Tandem Dry Gas Seal with intermediate Laby

NC1 = 6 800 RPM    MCOS = 11 718 RPM    TRIP = 12 887 RPM
Flawless Start-Up
Compressor had been run on N₂ (March) and completed H₂ loop dry out (early Apr)

Initial Start on Process Gas (H₂)
Compressor could not pass NC1 (6800 rpm) - Trip on High High Bearing Vibration

Start-Up Engineer and Operations implemented a “soft start” including a hold near 3500 rpm (What would have happened if this was not a VSDS?)

Vibration level steadily dropped during hold, compressor was able to pass NC1

On subsequent days, effectiveness of soft start was repeated, and with minor tweaking, became the “normal” start-up procedure

Engineering Team Assembled to Understand Why
Same OEM had a similar compressor in H₂ service that does not have VSDS
Pearl GTL has fully configured Bently Nevada System1®

Pearl GTL staff spent many hours setting up and verifying plot sessions

Primary Characteristics of Vibration

- Compressor had been run on N2 (March)
- Completed H₂ loop dry out (early April)
- Low vibration levels and consistent behavior

First run on process gas showed high level through NC1 (6 800 rpm)
- Primarily 1x vibration (GREEN)

Subsequent attempts to start also primarily 1x vibration

(In plots that follow, Solid Line is Start-Up, Dashed Line is Shut-Down)
1K-4001 – HIGH VIBRATION DIAGNOSIS
1K-4001 – HIGH VIBRATION DIAGNOSIS
Primary Characteristics of Vibration
Attempts to start could not pass NC1, primarily 1x vibration

High Vibration through NC1 suggests
   Excess unbalance or high Amplification Factor (AF)
   Possibly a rub (think how to break in seals on a steam turbine)
   – typically not only 1x

Previous runs and Factory Test do not show high AF (lack of damping)

Bode plot, amplitude is consistent, phase is highly irregular
   Phase: What are PURPLE and PINK doing?

Behavior at Start-up (Solid Line) and Shut-down (Dashed Line) appears different
Pearl GTL has fully configured Bently Nevada System1
Tony Soby spent many hours setting up and verifying plot sessions on all equipment.

- Primary Characteristics of Vibration
- Compressor had been run on N2 (March) and completed H2 loop dry out (early Apr), with very low vibration levels and consistent behavior
- First run on process gas showed high level through NC1, primarily 1x vibration (GREEN)
- Subsequent attempts to start could not get through NC1, primarily 1x vibration
- Looking at Bode plot – amplitude appears consistent, phase is highly irregular
- What are PURPLE and PINK doing?
Primary Characteristics of Vibration
Looking at Bode plot – amplitude appears consistent, phase is highly irregular
Phase: What are PURPLE and PINK doing?
Behavior at Start-up (Solid Line) and Shut-down (Dashed Line) appears different

Our Goal is to tie Vibration Response to a Physical State or Behavior:
High Vibration through NC1 suggests excess unbalance or high AF
Previous runs do not show high AF => Excess Unbalance
What is causing the unbalance?
Where did it come from? (Why did it not appear in N\textsubscript{2} runs?)

Is there another way of looking at the data? Yes: Polar Plot
Shows same data (rpm, amplitude and phase), different graphical format
Polar Plot makes it clear the rotor starts and returns to same slow roll
POLAR AND BODE PLOTS

Polar and Bode plots show similar data

Natural Frequency or Resonance = peaking of amplitude and 180 phase shift

Bode – “Slide and Mountain”
Offers clear amplitude and AF comparison

Polar – “Loop”
Offers intuitive slow roll compensation

Unbalance Location
Initial direction of phase (compensated)
“High Spot follow Heavy Spot”

Bode – Need to properly 1x compensate for slow roll

Polar – Unbalance Location and 1x compensation can be done intuitively

1K-4001 – HIGH VIBRATION DIAGNOSIS
1K-4001 – HIGH VIBRATION DIAGNOSIS

Slow Roll Vector (8μ @ 10°)
Pearl GTL has fully configured Bently Nevada System:

Tony Soby spent many hours setting up and verifying plot sessions on all equipment.

Primary Characteristics of Vibration:

The Compressor had been run on N2 (March) and completed H2 loop dry out (early Apr), with very low vibration levels and consistent behavior.

First run on process gas showed high level through NC1, primarily 1x vibration (GREEN).

Subsequent attempts to start could not get through NC1, primarily 1x vibration.

Looking at Bode plot, amplitude appears consistent, phase is highly irregular.

What are PURPLE and PINK doing?

- **Unbalance** (High Spot initial direction)
  - **Green** – 0 degrees
  - **Pink** – 100 degrees
  - **Purple** – 120 degrees
  - **Blue** – 195 degrees
  - **Orange** – 275 degrees
Polar Plot

Behavior during start-up and shut-down is consistent, except Phase Angle of initial Unbalance seems to Change with each start.

Unbalance – *Center of Mass offset from Centerline of Bearings*

Mechanical or Residual Unbalance (fixed over speed, temp, starts)

Bow - *deformation of the rotor shaft that causes centerline of rotor to shift off centerline of bearings (CoM assumed to be at center of rotor)*

  Mechanical Bow – “permanently” bowed due to initial processing, plastic deformation during handling (fixed over speed, temp, starts)

  Thermal Bow – *bowing of rotor due to heat-> temperature (fixed or random)*

  Gravity Sag Bow – *rotor takes a “set” when not rotating (random orientation)*
**Thermal Bow of rotor due to heat-> temperature (mixed)**

Variety of sources:
- Differential growth on opposite sides due to temperature difference
  - e.g. rub on high spot
- Axial binding – lack of thermal axial gap between added components
  - e.g. seal rings and impellers
- Internal, residual stresses or abnormality that result in non-isotropic growth

All repeatable: same circumferential location, phase angle, unbalance location

**Gravity Sag Bow, rotor takes a “set” when stationary (random orientation!)**
- This is temporary – rotor will straighten as it rotates
- Typically associated with heavy, long bearing span rotors
- Worse with hot rotors, which is why Gas and Steam Turbines have turning gear

*However - This rotor is too short, too light, too cold…*

**Similar Behavior was Described in:**
*Modeling of Rotor Bow During Hot Restart in Centrifugal Compressors*
Baldassarre and Fontana, 39th Turbosymposium
**1K-4001 – HIGH VIBRATION DIAGNOSIS**

- **Light Green** is start – on similar trajectory, but hold at 3500 rpm
- **Blue** is hold, vibration drops – very close to slow roll values
- **Dark Green** is “normal” critical speed – now less than 5 microns peak
After multiple runs and attempts to start, team was able to establish:

If rotor sits for a moderate time, it establishes a bow – *not sure why*

With 5 minutes of roll-out, bow is relaxed and unbalance eliminated

This is effective method of dealing with the *symptom*

Strong motivation to identify root cause:

There is a narrow window between NC1 and TNF – delicate balance

Project has two other Hydrogen Compressors from same OEM, without VSDS

Will not be able to hold and allow rotor to relax if same issue occurs

Look for Process Correlation:

- Inlet Pressure
- Inlet Temperature (\(T_{\text{in}}\))
- Discharge Pressure
- Discharge Temperature (\(T_{\text{out}}\))

\(T_{\text{in}}\) *(Blue Line)* Rises when unit stops, normal running is 30°C, stop is 80°C
Process Correlation =

$T_{in}$ (Blue Line) Rises when unit stops

- normal running is 30°C, stop is 80°C
- Temperature falls rapidly when RPM rises
- appears to be locally trapped heat

Build Spread Sheet with various inputs and parameters

Engineering Team found correlation with Seal Gas Heater

- Had not been used during $N_2$ runs
- Was only needed when drawing Seal Gas from Process (dew point)
- During start-up, Seal Gas supplied by Plant $N_2$, no risk of liquids

Perform Test Run: Confirm when seal gas heater Off

- Hold is not necessary (no bow present)
## 1K-4001 – PROCESS CORRELATIONS

### 1K-4001 LPU Start-up Problem Timeline

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td><strong>Purpose</strong></td>
<td>Mech Run³</td>
<td>Dry Out</td>
<td>Process Run</td>
<td>Process Run</td>
<td>Process Run</td>
<td>Process Run</td>
<td>Process Run</td>
<td>Process Run</td>
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<tr>
<td><strong>Run time</strong></td>
<td>5hrs</td>
<td>5 days</td>
<td>2 days</td>
<td>HH trip on Start</td>
<td>HH trip on Start</td>
<td>1 hour</td>
<td>HH trip on Start</td>
<td>Running</td>
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<tr>
<td><strong>Line up</strong></td>
<td>Long Loop</td>
<td>Long Loop</td>
<td>Long Loop</td>
<td>Long Loop</td>
<td>Long Loop</td>
<td>Long Loop</td>
<td>Long Loop</td>
<td>Long Loop</td>
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<tr>
<td><strong>Previous start (before)</strong></td>
<td>First</td>
<td>13 days</td>
<td>5 days</td>
<td>2 hours</td>
<td>2 hours</td>
<td>4 hours</td>
<td>30 min.</td>
<td>3.5 days running</td>
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### Compressor:

<table>
<thead>
<tr>
<th>Ts, degC</th>
<th>20</th>
<th>24,31,24</th>
<th>85 initial, 24 normal</th>
<th>85</th>
<th>85</th>
<th>85 initial, 24 normal</th>
<th>45</th>
<th>85</th>
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<tbody>
<tr>
<td>Td, degC</td>
<td>66-103</td>
<td>110³,73,63</td>
<td>55 initial, 31 normal</td>
<td>39</td>
<td>43</td>
<td>55 initial, 31 normal</td>
<td>41</td>
<td>46</td>
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<tr>
<td>rpm</td>
<td>8022-8067</td>
<td>7934- 8900</td>
<td></td>
<td>8534</td>
<td>11700⁹</td>
<td></td>
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### Start Type:

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<tr>
<th>Fast</th>
<th>Yes⁴</th>
<th>Yes</th>
<th>Yes</th>
<th>Yes</th>
<th>Yes</th>
<th>Yes</th>
<th>Yes⁶</th>
<th>Yes to 4000rpm</th>
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<tbody>
<tr>
<td>Slow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8min yes,23um</td>
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</table>

### SU Vibration:

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<thead>
<tr>
<th>Initial &quot;Bump&quot;</th>
<th>yes, 28um</th>
<th>Yes, 20um</th>
<th>Yes, 23um</th>
<th>Yes, 22um</th>
<th>Yes, 24um</th>
<th>Yes, 25um</th>
<th>Yes, 26um</th>
<th>Yes, 25um</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nc (6500rpm)</td>
<td>Very Low</td>
<td>Low but chng²</td>
<td>Yes 48um</td>
<td>yes, 80um</td>
<td>Yes, 79um</td>
<td>Uneventful⁵</td>
<td>Yes, 70um</td>
<td>Uneventful</td>
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<tr>
<td>H or HH alarms&quot;</td>
<td>No</td>
<td>No</td>
<td>H alarm</td>
<td>HH trip on Start</td>
<td>HH trip on Start</td>
<td>No</td>
<td>HH trip on Start</td>
<td>No</td>
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<tr>
<td>Vib &quot;Relax&quot;</td>
<td>Yes</td>
<td>Yes, very low</td>
<td>Yes</td>
<td>Trip no data</td>
<td>Trip no data</td>
<td>yes &quot;slow roll&quot;</td>
<td>3471</td>
<td>Trip no data</td>
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<tr>
<td>&quot;Relax rpm&quot;</td>
<td>7876</td>
<td>7876</td>
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### Primary Seal Gas:

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<tr>
<th>Type Gas</th>
<th>N2</th>
<th>N2</th>
<th>H2</th>
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<tbody>
<tr>
<td>T, deg C</td>
<td>19</td>
<td>28</td>
<td>105</td>
<td>105</td>
<td>105</td>
<td>?</td>
<td>105</td>
<td>55</td>
</tr>
<tr>
<td>P, barg</td>
<td>3barg&gt;Ps</td>
<td>3barg&gt;Ps</td>
<td>3barg&gt;Ps</td>
<td>3barg&gt;Ps</td>
<td>3barg&gt;Ps</td>
<td>3barg&gt;Ps</td>
<td>3barg&gt;Ps</td>
<td>3barg&gt;Ps</td>
</tr>
<tr>
<td>Heater</td>
<td>off</td>
<td>off</td>
<td>On</td>
<td>On</td>
<td>On</td>
<td>Off</td>
<td>On</td>
<td>off</td>
</tr>
</tbody>
</table>

### Lube Oil:

<table>
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<tr>
<th>P, barg</th>
<th>1.6</th>
<th>1.6</th>
<th>1.6</th>
<th>1.6</th>
<th>1.6</th>
<th>1.6</th>
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<tbody>
<tr>
<td>T, deg C</td>
<td>42</td>
<td>42</td>
<td>42</td>
<td>42</td>
<td>42</td>
<td>42</td>
<td>42</td>
<td>39</td>
</tr>
</tbody>
</table>
Seal Gas Heater – Injects a Large Volume of Hot Gas ⇒

Larger gap at Top of Inner Seal ⇒ more heat and Temperature Rise on Top Top vs Bottom Differential Temperature causes a *Temporary Thermal Bow*

As shaft rotates, heat becomes distributed, temperature equalizes, bow straightens, eventually **Unbalance is Eliminated** and **Vibration Decreases**
CONCLUSION

- Significant Value in Categorizing Vibration
- Use a variety of plots
- Establish Slow Roll vector and Repeatability
- Determine if vibration change on sequential runs
- Find correlation to Process or other Environmental Variables

- Get Help!
  - Others at Facility or within Company
  - Industry Experts (like those you meet at METS!)
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We appreciate the State of Qatar and Texas A&M for sponsoring METS and the opportunity to share knowledge and learning with our colleagues.