Evaluating and Correcting Subsynchronous Vibration In Vertical Pumps

Case Study #8

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Case Study Overview

- New Vertical Pumps
- Liquid Sulfur Service
- Operating Speed – 3,575 RPM
- Primary Vibration Component at 1,750 CPM
- Shaft Whirling or Whipping Suspected
- Structural Resonance near $\frac{1}{2} X$
- Solution
Pump System

6 Vertical Pumps in 3 Separate Sumps
Single Stage 81 GPM  219 Ft Head  40 HP
Molten Sulfur at 300 °F
Pump and Shaft are Steam Jacketed
4 Radial Bearings/Bushings
Top Bearing is also Thrust Bearing
Line Shaft Bushings are Carbon Graphite
History

• Hard “Sulcrete” Buildup in Sumps
• New Pump Mounting System Devised
• Initial Base Impact Test Showed Structural Natural Frequency in Excess of 5,000 CPM

• Initial Vibration Readings:
  ➢ First Installation had 0.2 IPS at 1,710 CPM
  ➢ Second Installation had 0.65 IPS at 1,750 CPM
Vibration Measurements

- High Vibration on All Units
- Virtually no 1X (Running Speed) Vibration
- Most Vibration near \( \frac{1}{2} \)X Running Speed

**Measured Spectrum on Motor**

- Route Spectrum
  - 19-Aug-09 09:19:2
  - OVERALL = 0.5879
  - PK = 0.5845
  - LOAD = 100.0
  - RPM = 3,575

- Route Waveform
  - 19-Aug-09 09:19:2
  - PK = 0.5717
  - PK(+/−) = 0.7916/0.744
  - CRESTF = 1.96
  - Freq: 1,775 CPM
### History

- **Installed Impact Test Results on Motor**

<table>
<thead>
<tr>
<th>Bump Test Location</th>
<th>East - West Direction</th>
<th>North - South Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Pump</td>
<td>1,734 CPM</td>
<td>1,887 CPM</td>
</tr>
<tr>
<td>West Pump</td>
<td>1,657 CPM</td>
<td>1,887 CPM</td>
</tr>
</tbody>
</table>
History

• Clearly there was a system natural frequency near half of operating speed

• What was the “Forcing Function”?

• Sulfur “whirl” considered
Initial Attempts

• Reduced Weight of Coupling
  ➢ No Significant Effect

• Possibly Stiffen Structure?
  ➢ Probably would be Ineffective – Not Done

• Rotordynamics Analysis
  ➢ Selected Approach
Rotordynamics Analysis

- Gather Data from Disassembled Unit
- Dimensions and Weights of all Rotating Parts
- Evaluate Bushing Dimensions
- Determine Properties of Liquid Sulfur
- Translate into Finite Element Model
- Match Model to Observed Vibrations
- Design New Components to Fix Problem
Actual System Compared to Model

**FEA Model**
- Thrust Bearing
- Top Bushing
- 2.5 Inch Diameter Shaft
- Lower Bushing
- Pump Bearing
- Imbalance

**164 Inches**

**Actual System**
- Motor
- Coupling
- Seal
- Discharge
- Bypass Lines
- Bushing
- Pump
- Suction
Center Two Rotating Sleeves

- Original Design
- Modified Design
Properties of Molten Sulfur

• Unusual Material

• Room Temperature Sulfur is a Crystalline Solid

• Fully Liquid at 235°F

• Forms Long-Chain Molecules – Gamma Sulfur

• Highy Non-Linear Viscosity

  ➢ 7.8 cP at 300°F  93,000 cP at 350°F

• Sump Temperature Control Very Important
Crystalline Solid Sulfur
Sulfur Viscosity v. Temperature

Oil Viscosity (cP)

<table>
<thead>
<tr>
<th>Oil ISO</th>
<th>120°F</th>
<th>175°F</th>
<th>250°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>18</td>
<td>6.7</td>
<td>2.8</td>
</tr>
<tr>
<td>100</td>
<td>53</td>
<td>16.5</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Sulfur Temperature, °F

Viscosity, cP
Original Bushing Design

Original Sulfur Pump Bushing

Bearing Data
L = 4.25 in
Ds = 3.375 in
Cb = 0.008 in
2Cb/D = 0.00474
Cp = 0.008 in
Preload = 0
Offset = 0
Theta1 = 0
Theta2 = 360
Load Angle = 0
Viscosity = 1.2E-06
Density = 0.06424

Diametral Clearance
16 Mils

w = 0

\( \Omega \)
First Critical Speed
Mode Shape

Calculated Frequency = 1,770 CPM
With Original Upper and Lower Bushings
Original Unbalance Response

Bode Plot - Pump Shaft Lower Middle Bushing
Station: 13, Sub-Station: 1
Probe 1 (x) 0 deg: Amp ~ 1.42 phase ~ 10 at 1785 rpm
Probe 2 (y) 90 deg: Amp ~ 1.42 phase ~ 101 at 1785 rpm

Calculated Response
At Lower Bushing

1,785 CPM
Stability with Original Bushings

Precessional Mode Shape - UNSTABLE FORWARD Precession
Shaft Rotational Speed = 357.5 rpm, Mode No. = 3
Whirl Speed (Damped Natural Freq.) = 1780 rpm, Log. Decrement = 0.3613
Stability with Original Bushings

Original Bushings with 16 mils Diametral Clearance
Station: 13, Delta Freq.= 36.62 cpm
X Spectrum - max amp = 15.804 at 1794.43 cpm
Y Spectrum - max amp = 16.125 at 1794.43 cpm

Non-Linear Time Transient Analysis
Calculated Spectrum At Lower Bushing

Frequency, CPM
Evaluation

• Shaft Critical Speed at ½ Operating Speed
• Structural Resonance at ½ Operating Speed
• Inherently Unstable Plain Circular Bushings

• Need To Control The Rotor Vibration
• Center Two Bushings Logical Items to Revise
Solution Goals

- Design New Upper and Lower Bushings
  - Increase Direct Stiffness
  - Raise Critical Speed above Operating Speed
  - Eliminate Instability
  - Assure Low Operating Speed Vibration
  - Increase Reliability and Reduce Costs
Optimized Bushing Design

Diametral Clearance
9 Mils

Bearing Data
L = 3 in
D_s = 3.375 in
C_b = 0.0045 in
2C_b/D = 0.00267
C_p = 0.015 in
Preload = 0.7
Offset = 1
Theta_1 = 100
Theta_2 = 200
Load Angle = 270
Optimized Bushing Pressure Profile

Peak Pressure
27 PSI
# Bushing Stiffness and Damping Coefficient Comparison at 3,575 RPM

<table>
<thead>
<tr>
<th>Bushing Type</th>
<th>Principal Stiffness, LB/IN</th>
<th>Principal Damping, LB-SEC/IN</th>
<th>Cross-Coupled Stiffness, LB/IN</th>
<th>Horsepower Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain Bushing</td>
<td>1,830</td>
<td>407</td>
<td>-69,400</td>
<td>0.65</td>
</tr>
<tr>
<td>3-Lobe Bushing</td>
<td>49,100 (26.8 Times Stiffer)</td>
<td>323</td>
<td>-20,700</td>
<td>0.38</td>
</tr>
</tbody>
</table>
New Design Unbalance Response

Bode Plot - Predicted Vibration at Lower Middle Bushing with 3-Lobe Bearings

Station: 13, Sub-Station: 1
Probe 1 (x) 0 deg: Amp = 0.92 phase = 118 at 4000 rpm
Probe 2 (y) 90 deg: Amp = 0.92 phase = 208 at 4000 rpm

Calculated Response
At Lower Bushing
Stability with New Design Bushings

Calculated Vibration at Lower Middle Bushing with 3-Lobe Design
Station: 13, Delta Freq: - 36.62 cpm
X Spectrum - max amp = 0.44365 at 3552.25 cpm
Y Spectrum - max amp = 0.44394 at 3552.25 cpm

Time Transient Analysis
Calculated Spectrum
At Lower Bushing

Frequency, CPM
Final Result

Measured Spectrum on Motor

Route Spectrum
25-Aug-09 16:23:26
OVERALL = .0151 V-DG
PK = .0150
LOAD = 100.0
RPM = 3581. (59.68 Hz)

Route Waveform
25-Aug-09 16:23:26
PK = .0148
PK(+/-) = .0261/.0316
CRESTF = 3.02

Freq: 3600.0
Ordr: 1.005
Spec: .01156
• Vibration Problem Eliminated

  ➢ Replaced 2 Plain Bushings with Profile Design

  ✓ Inexpensive

  ✓ Available Locally

  ➢ Eliminated Critical Speed

  ➢ No Structural Modifications Necessary

  ➢ Reliability Increased and Costs Reduced