Rotor Retrofits Improve Pump Station Vibration

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By:
Jeffrey R. West P. E.
Udelhoven International Inc.
Two nearly identical crude oil pump stations on a world-scale pipeline encountered significant vibration on initial startup.

Each station equipped with five each, 5 MW centrifugal Main Oil Line (MOL) pumps driven by variable speed, gas fuelled, spark ignited reciprocating engines.

Station throughput is achievable with four-pump operation with one spare.
Background - 2

- MOL Pumps in parallel configuration
- Nominal driver speed is 700 RPM with speed increaser gear resulting in pump speed to approximately 3400 RPM
- MOL Pumps are identical, two-stage, horizontally split, double volute designs with double flow stage impellers
History - 1

- At startup heavy vibrations appeared on Small Bore Connection (SBC) piping attachments: instrument, drain and vent connections to the pumps and throughout station.

- Vibrations also evident on elbows and piping supports as a high-frequency “buzz” continuously and throughout operating speed range.

- Surprisingly, pump case vibrations, as well as shaft movement measured by proximity devices, were within recognized industry standards and OEM specifications.

- With concurrence of station designer and pump OEM, pipeline ramp-up continued to rated capacity.
History - 2

- Within months the annoying vibrations developed into a major system integrity problem due to failures at SBC welds
- Inspections confirmed high-cycle fatigue as cause
- New and repeat failures occurred
History - 3

- Mechanical braces fitted on all SBC to limit vibrations
- Appropriate inspection and weld repair programs established to insure business continuity
- Diagnostics undertaken to determine cause of damage
Machinery / System Analysis

Analysis confirmed the following to be acceptable and NOT be causative:

• Pump rotor balance
• Machinery alignment
• Bearing stability
• Rotor stability
• Machinery and piping support
• Engine and gear operation
• Machinery train torsional resonance
• Piping acoustic resonance
Damage Continues

- Header subsidence discovered in buried headers outside pumphouse
- SBC weld failures continue, now numbering >100 causing huge integrity and availability issues
Pulsation Study - 1

Suction pulsation spectrum

- High intensity pulsations discovered within pumped fluid column
Pulsation Study - 2

Discharge pulsation spectrum

- Discrete frequency spikes found “locked” to rotor speed
Problem Definition

- Dynamic pressure pulsations at damaging levels exist throughout the pumping systems that result in cyclic stress driven fatigue (high cycle fatigue) to SBC welds.

- Consequential damage occurs to instrumentation and support systems including buried headers outside pumping stations.
Root Cause Analysis

_root Cause Investigation:
- System integrity compromised
- Weld failures
- High-cyclic stress fatigue
- Excessive vibration
- Excessive pulsation energy
- Rotor / impeller design suspect

Preliminary Conclusion: System vibrations are driven by dynamic pressure pulsations from impeller design and resulting behavior
Impeller / Rotor Inspections

- OEM discussions proved inconclusive
- Vane count: 4 and 6 (double volute case) promotes “phase resonance” or “constructive reinforcement” due to jet-wake / casing interactions: pulsations
- Concern that stage one inlet eye geometry promotes inlet recirculation
- Basic design – orthogonal vane features, no central rib / stagger on first stage etc.
Impeller / Rotor Inspections

➢ Basic Design
Disassembly Case Inspection

- Hydraulic gap “B-Gap” smaller than industry standard and not consistent
- Cutwater locations / profiles not as expected for high-energy pump
- Volute has “tight fit” relative to impeller width – limits redesign options
Root Cause

- Poor pump behavior due to high-energy dynamic pulsations resulting from several facets of pump design

- Secondary causes include:
  - Poor SBC design – susceptible to vibration damage
  - Inappropriate recycle throttling device selection
Investigation Conclusion

- Four major factors contribute to excessive dynamic pressure pulsation including:
  - Constructive pulsation reinforcement resulting from impeller vane count
  - Unusually small stator / rotor tip clearance
  - Pump operation near or at inlet recirculation
  - Likely interaction with vane encounter, inlet backflow and system response frequency
New Rotor Design Requirements

- Mechanical interchangeability
- Hydraulic duplication (or better)
- Pulsation levels reduced to acceptance (4%?)
- System compatibility – seals, bearings, vibration monitors etc.
- Shaft material upgrade
- Minimal case alterations (if needed) – no spare case
New Design – Stage One Impeller

- Vane count from 4 to 5
- Vane skew from orthogonal
- Inlet hydraulic enhancements
- Casting technology improvements
- Double entry partition rib plus “stagger”
New Design – Stage Two Impeller

- Vane count from 6 to 7
- Vane skew from orthogonal
- Inlet hydraulic enhancements
- Casting technology improvements
New Design – Case Alterations

- Increased impeller tip-to-cutwater hydraulic gap
- Improved cutwater profile and location on both cutwaters – both stages & skewed stage two
The Solution?
Test Program

- Duplicate test “Before” and “After” prototype installation
- Test with “single pump” operation
- Test 12 operating conditions from recycle to 100% flow and speed at 14 pumphouse locations
- Collect performance data including:
  - Dynamic pressure
  - Dynamic stress at historically troubled locations
  - Hydraulic performance; flow and head
  - Vibration
- Develop “factory” performance curve
Test Results

➤ Before and After Dynamic Pressure Levels

Pump Performance Test #1 - Dynamic Pressure Measurements on MOL Pump E Discharge Line

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>0.0</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
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<tbody>
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<td>Dynamic Pressure, bar (pk-pk)</td>
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</tbody>
</table>

Recovery Test Point 1
Test Point 1
Test Point 2
Test Point 3
Test Point 4
Test Point 5
Test Point 6
Test Point 7
Test Point 8
Test Point 9
Test Point 10
Test Point 11
Test Point 12

Pump Performance Test #2 - Dynamic Pressure Measurements on MOL Pump E Discharge Line

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<th>Frequency, Hz</th>
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Recovery Test Point 1
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Test Point 8
Test Point 9
Test Point 10
Test Point 11
Test Point 12

Graphs showing dynamic pressure measurements at various points in the discharge line for two pump performance tests. The graphs display pressure at different frequencies, with various test points indicated.
### Test Results - 2

- **Before and After Stress Levels**

<table>
<thead>
<tr>
<th>Test Point</th>
<th>Number of Measurement Points with Excessive Dynamic Stress Levels</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Pump Performance Test #1</td>
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<tr>
<td>Recycle</td>
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<td>4</td>
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<tr>
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</table>
Test Results - 3

Single and Multi-Pump Flow Rates

Pump Performance Test #2 - MOL Pumps Flowrate Measurements from Ultrasonic Flowmeters

Flowrate, m³/hr

Date & Time

28/05/2010 14:24:00
28/05/2010 16:48:00
28/05/2010 19:12:00
28/05/2010 21:36:00
29/05/2010 00:00:00
29/05/2010 02:24:00
29/05/2010 04:48:00
Conclusions

- Dynamic stress levels reduced to “acceptable” within normal operating range at all monitored locations
- Pulsation levels reduced > 50% with most locations >70%
  - Pulsation level at stage crossover location still borderline high at 100% speed although reduced >80% from original
  - Confirmed excitation of 7X acoustic resonance in crossover
  - Not normal operating speed
- Shaft movement (by proximity) and case vibrations reduced by approximately 50%
- Sound levels reduced 3 db in pump vicinity and 9 db at pump discharge
- Hydraulic output improved by 5% to 10% within normal operating range - correctable with 1% speed reduction
- Apparent pump efficiency improved about 1%
Project Completion

- Ten new rotors installed
- Instrument, drain and vent connections to pump cases replaced with new
- In-station suction, discharge and recycle piping plus recycle throttle replaced with new
- Outside-station headers repositioned and re-supported
Remedial Action

- Suction, discharge, recycle lines renewed
- Pump vents, drains, instrument taps renewed
**Lessons Learned**

- **Original equipment design reviews are critical**
  - Maintain “Global Vision” of system - not just flange-to-flange
  - Pump design review should consider all operating parameters including pulsation levels

- **Process / piping design reviews are important** - branch connection design is critical

- **Factory acceptance tests have major limitations:**
  - Different connected piping
  - Different fluid
  - Different support system
  - Different driver usually
  - Only looks at flange-to-flange compliance
Thank You!

Questions?