Case Study – Load Dependent Critical Spee

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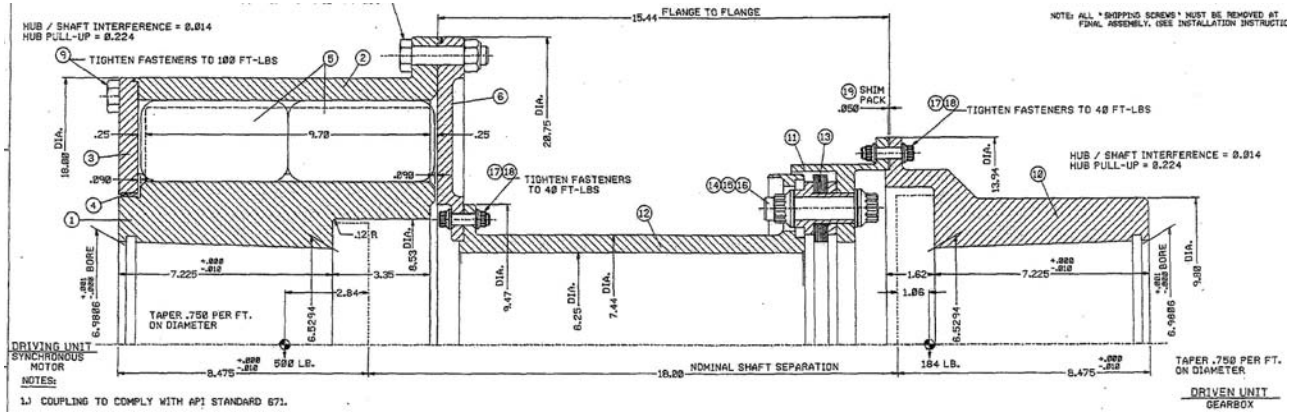
Problem Statement

- Machinery train in natural gas processing facility
  - 5750 HP (4287 kW) synchronous motor at 1800 RPM.
  - Speed increasing gear drive.
  - Centrifugal compressor at 14620 RPM.
- Over-torque event after fifteen years of operation
  - Sheared bolts in LSP coupling.
  - Raised questions about gear rotating elements.
- Gearbox refurbishment and shop test
  - Time was critical.
  - Spare rotating elements used.
  - Unrelated HS bearing issue – replacement required.
  - Changed HS bearing design due to long delivery time of original design.
- After refurb, tripped on HS pinion vibration at startup.

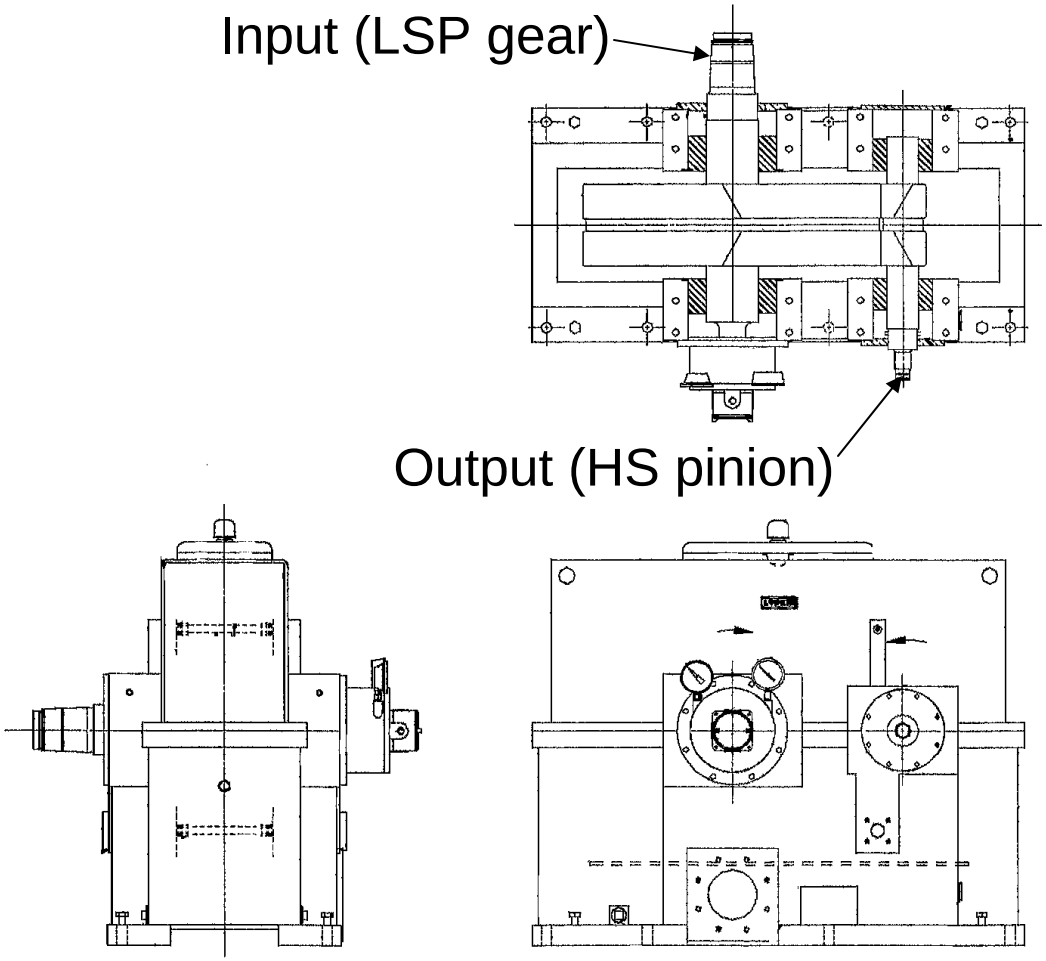
Low Speed Coupling With Elastomer Inserts

- Coupling bolts sheared; most likely cause improper restart.
- Gearbox refurbishment requested.



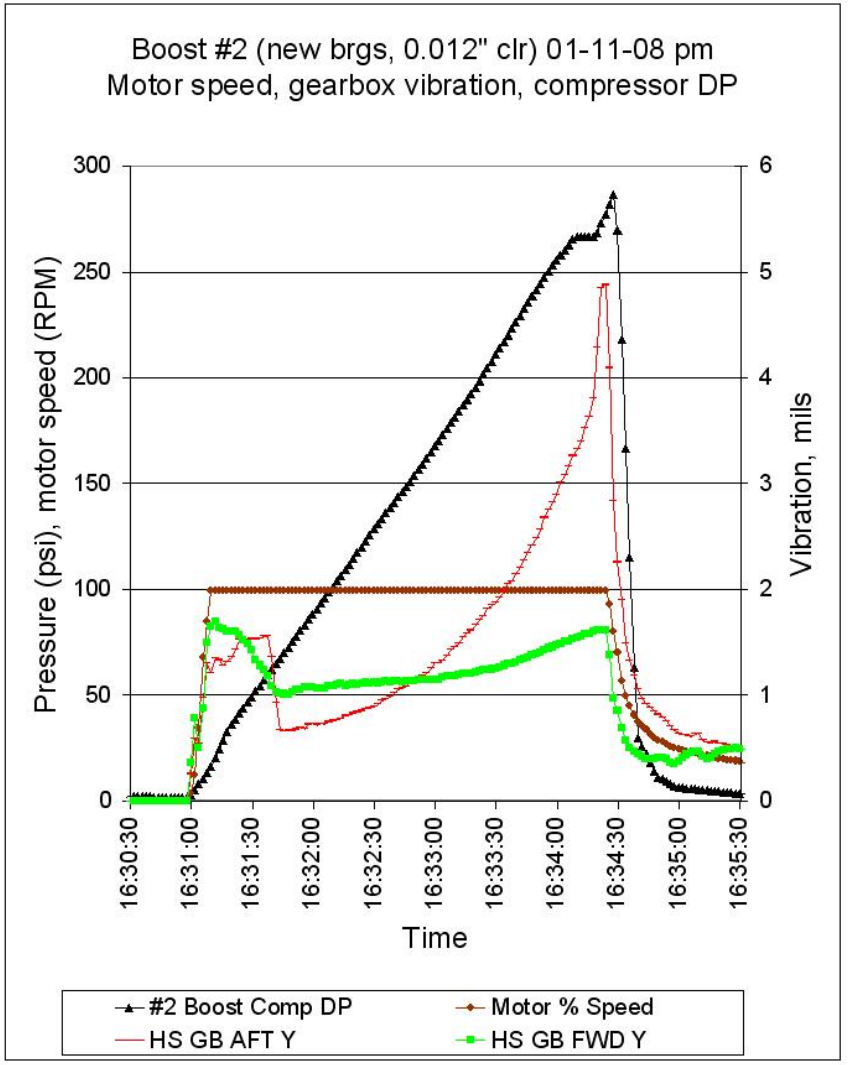
Gearbox Description

- Single stage, 8.1:1 ratio speed increaser
- Shaft center distance 24 inches (610 mm)
- Double helical gearing
- Fabricated steel casing
- Tilting pad HS pinion radial bearings



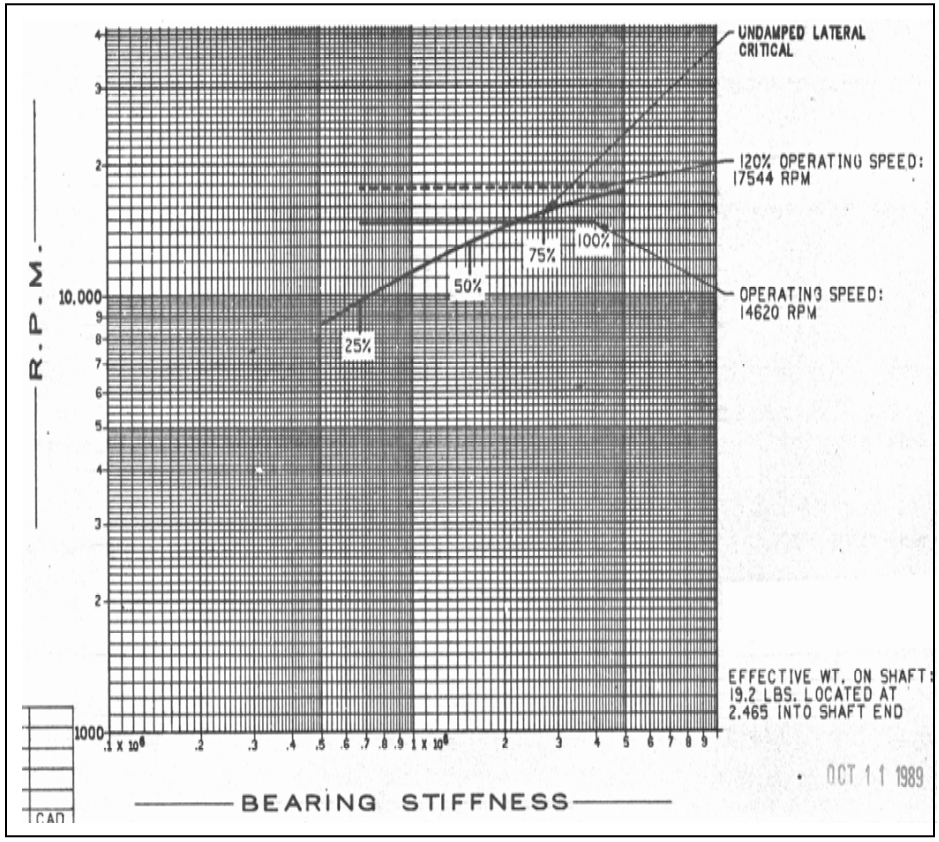
Vibration After Gearbox Refurbishment

- Could get up to speed (initially, no load).
- HS pinion vibration increased with compressor discharge pressure.
- Tripped on HS pinion shaft radial displacement before reaching full load.
- Parallel solution process:
  - Review original design.
  - Simulate analytically.
  - Implement changes in gearbox.



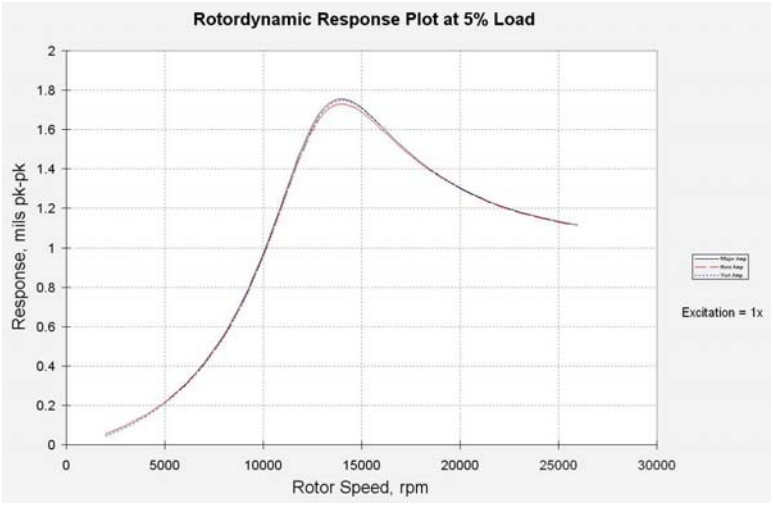
Review of Original Design and Operation

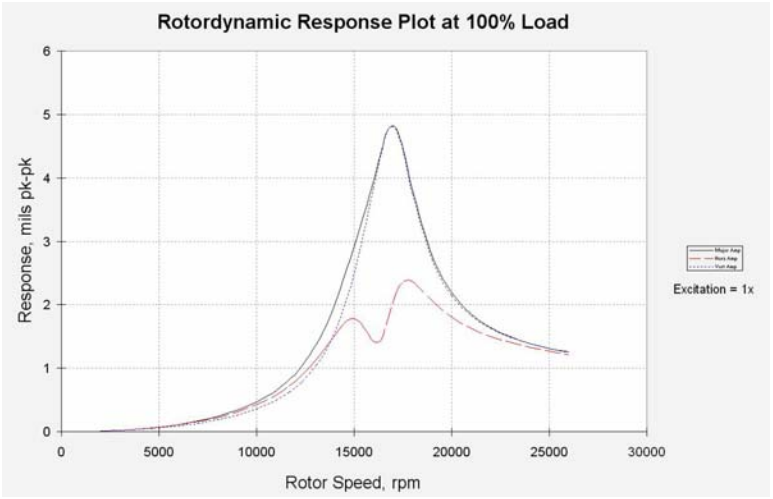
- Condition existed in original design:
  - Calculated natural freq. below running speed at low load.
  - Above running speed at full load.
- Operating data showed pinion vibration problem before refurbishment.
- Amplitude before refurb lower than after refurb; reasons not fully understood.



Effect of Load on HS Pinion Bearings

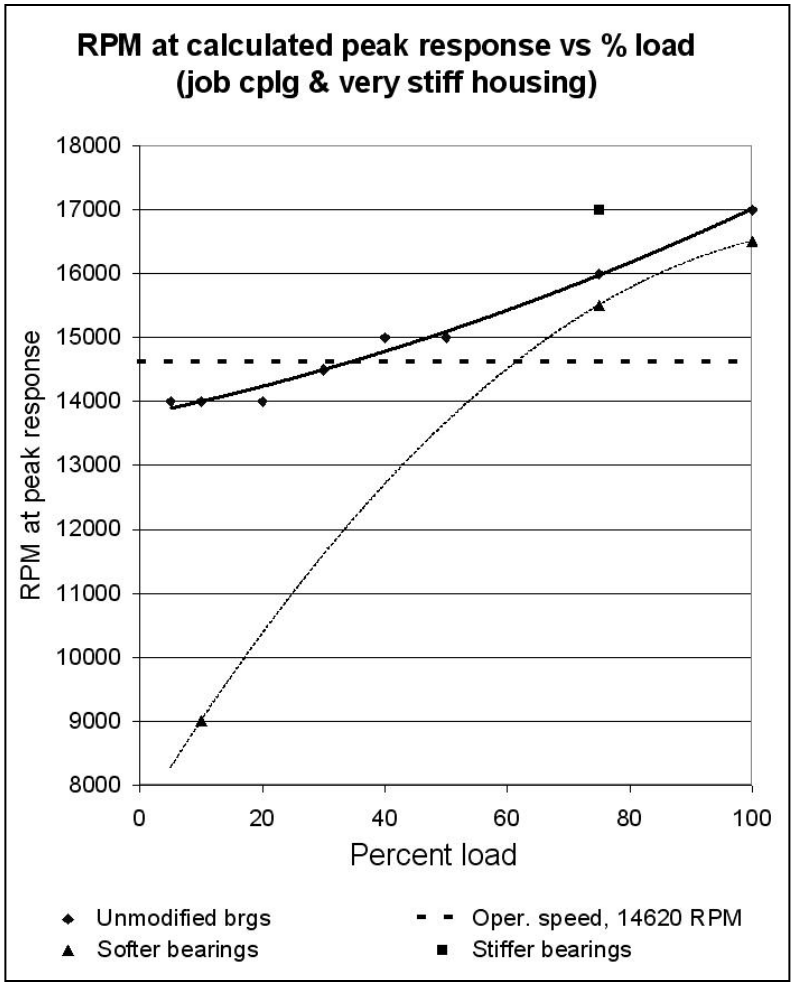
- Gear mesh force proportional to torque
  - Mesh is main bearing load.
  - Low torque = soft bearings.
  - High torque = stiff bearings.
- Operating speed 14620 RPM.
- Calculated critical speed changes with load
  - 13800 RPM at low load.
  - 17100 RPM at full load.
- As machine is loaded critical speed moves from below to above operating speed.





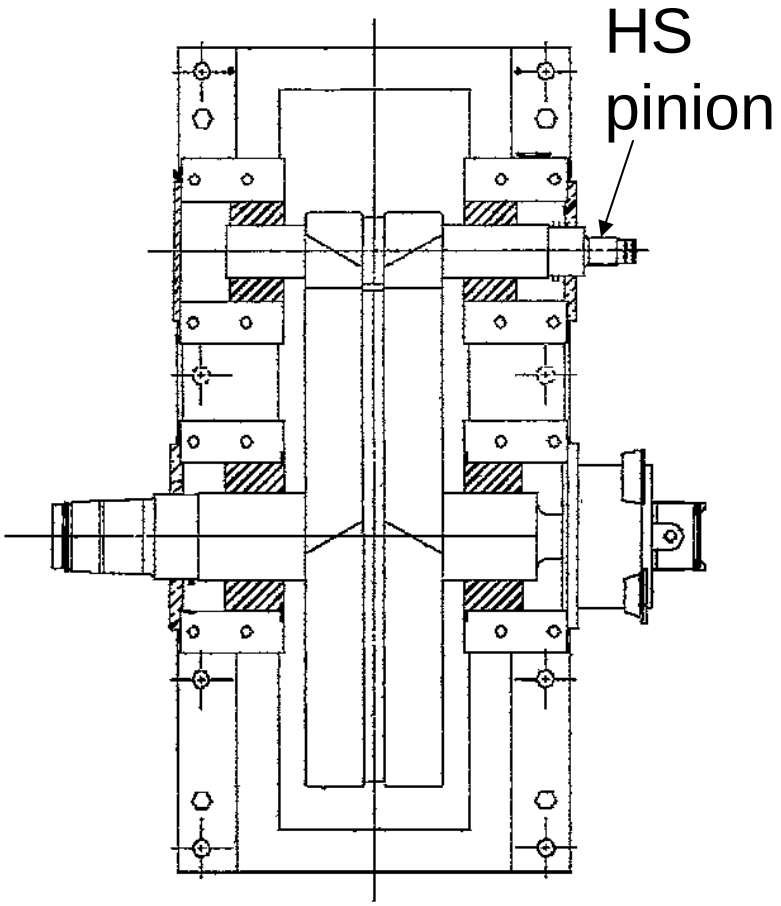
Evaluated Load and Bearing Clearance

- Possibly other system issues, but focus was on gearbox.
- Changed bearing clearance
  - Relatively quick and easy to do (removable pad seats).
  - Affected bearing stiffness at low to medium load.
- Machine still tripped; during loading with medium & loose bearings; at motor start with tight bearings (higher stiffness).
- Field & analytical results were generally consistent.
- Changing bearing clearance was not the solution.



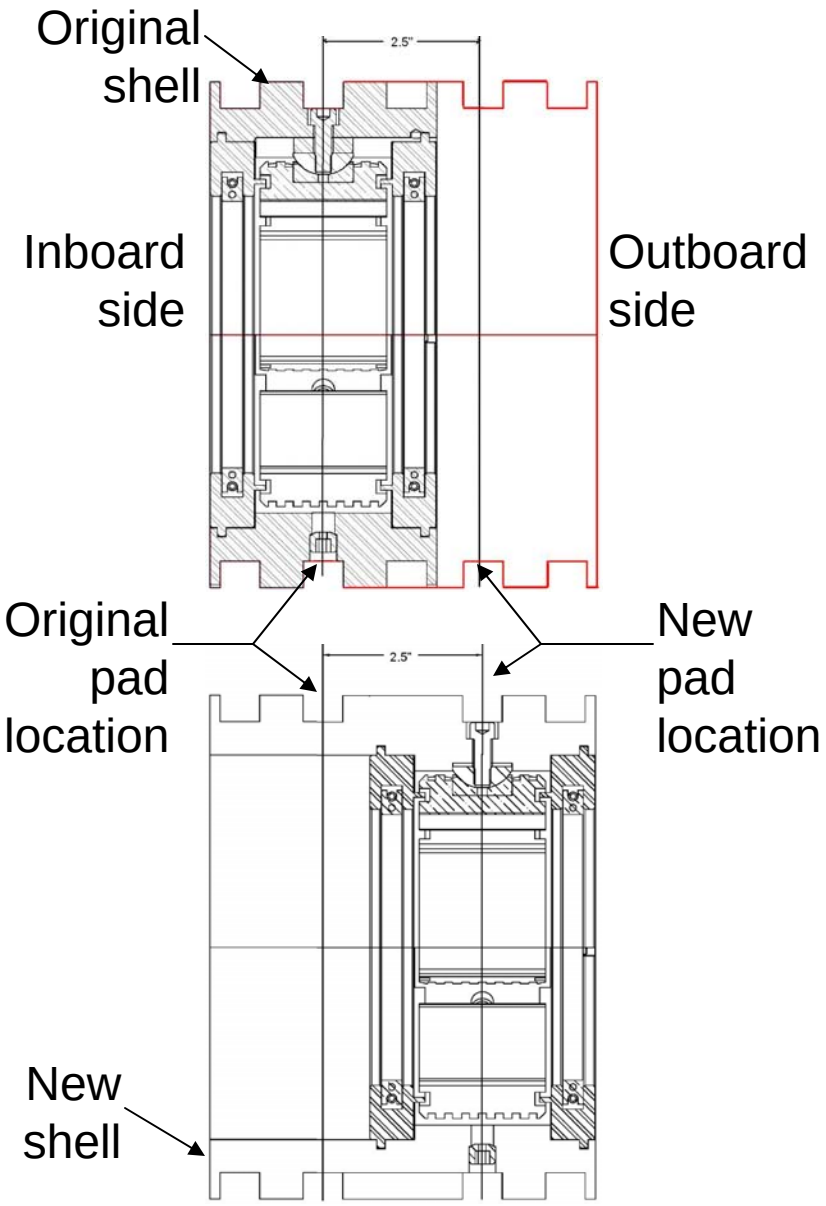
Reviewed Rotor-Bearing Layout

- Substantial change was needed
- HS coupling half CG location was relatively far from the drive end bearing.
- Moving the drive end bearing toward the shaft end should make a significant improvement in the rotor-bearing system behavior. For example, the critical speed should move up in frequency.
- Oil supply passages in gear housing could not be moved without machining housing – not a good option.



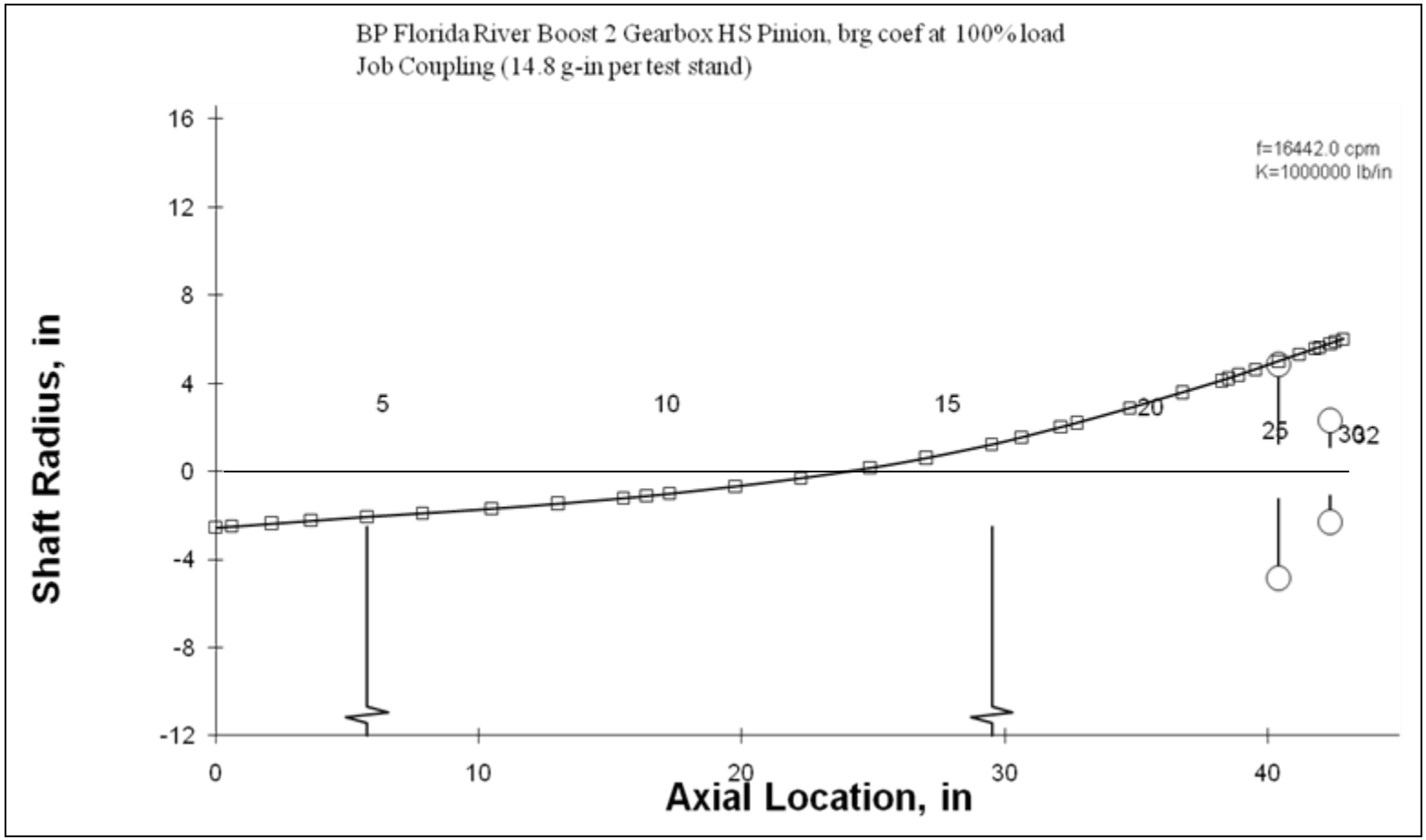
Relocating HS Pinion Bearing Pads

- Extended bearing shell toward the shaft end as shown in red.
- New shell moves the bearing pad centerline outward while using the original gear housing oil passages.
- New shell could be produced quickly.
- Pinion drive end bearing only.
- Moved bearing centerline 2.5 inches (63 mm) closer to HS pinion shaft end.
- Improved rotordynamics.



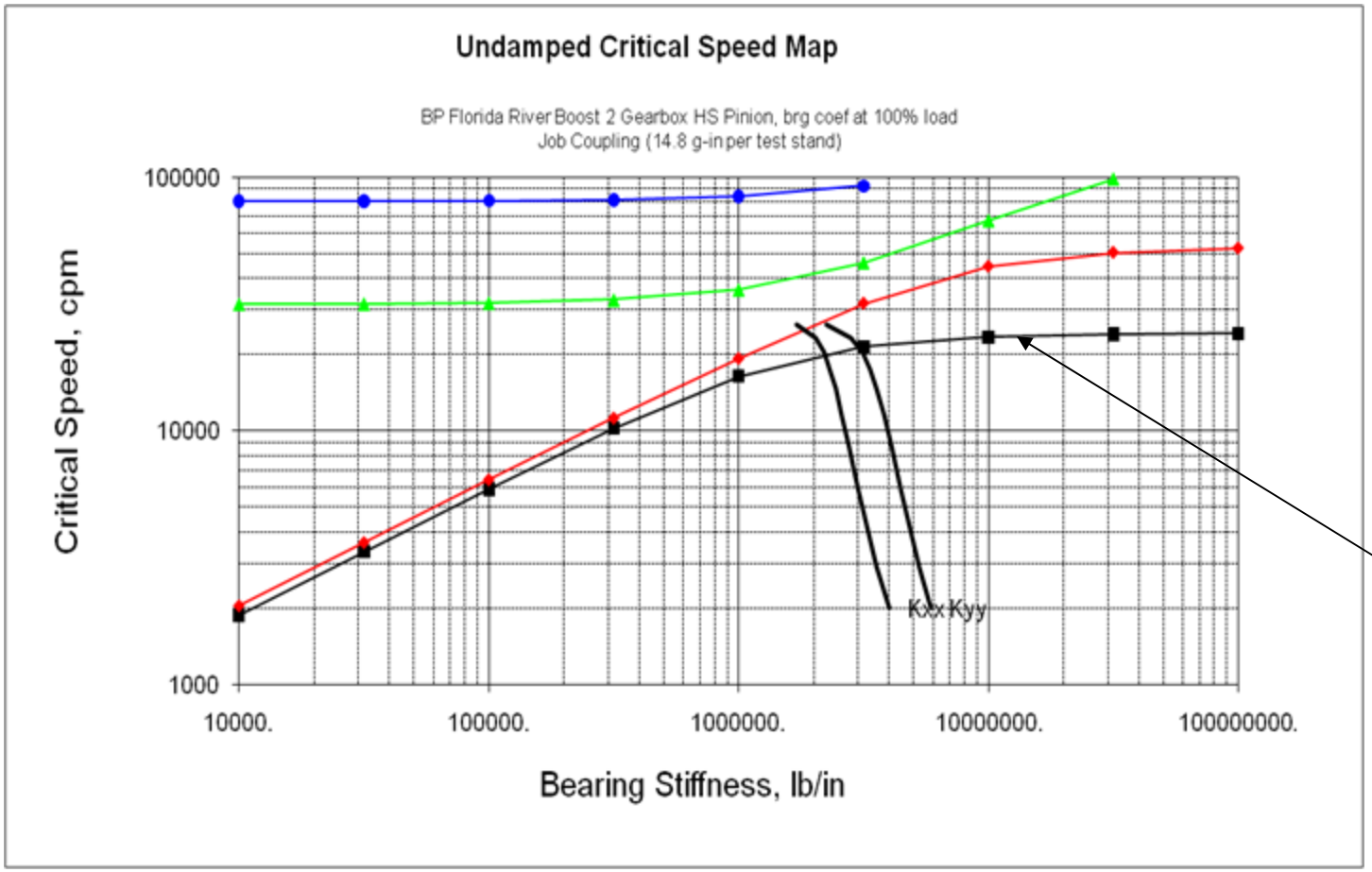
Undamped Mode Shape

- Overhung coupling weight at shaft end has strong effect.
- Moving drive end bearing closer to shaft end is beneficial.



Critical Speed Map

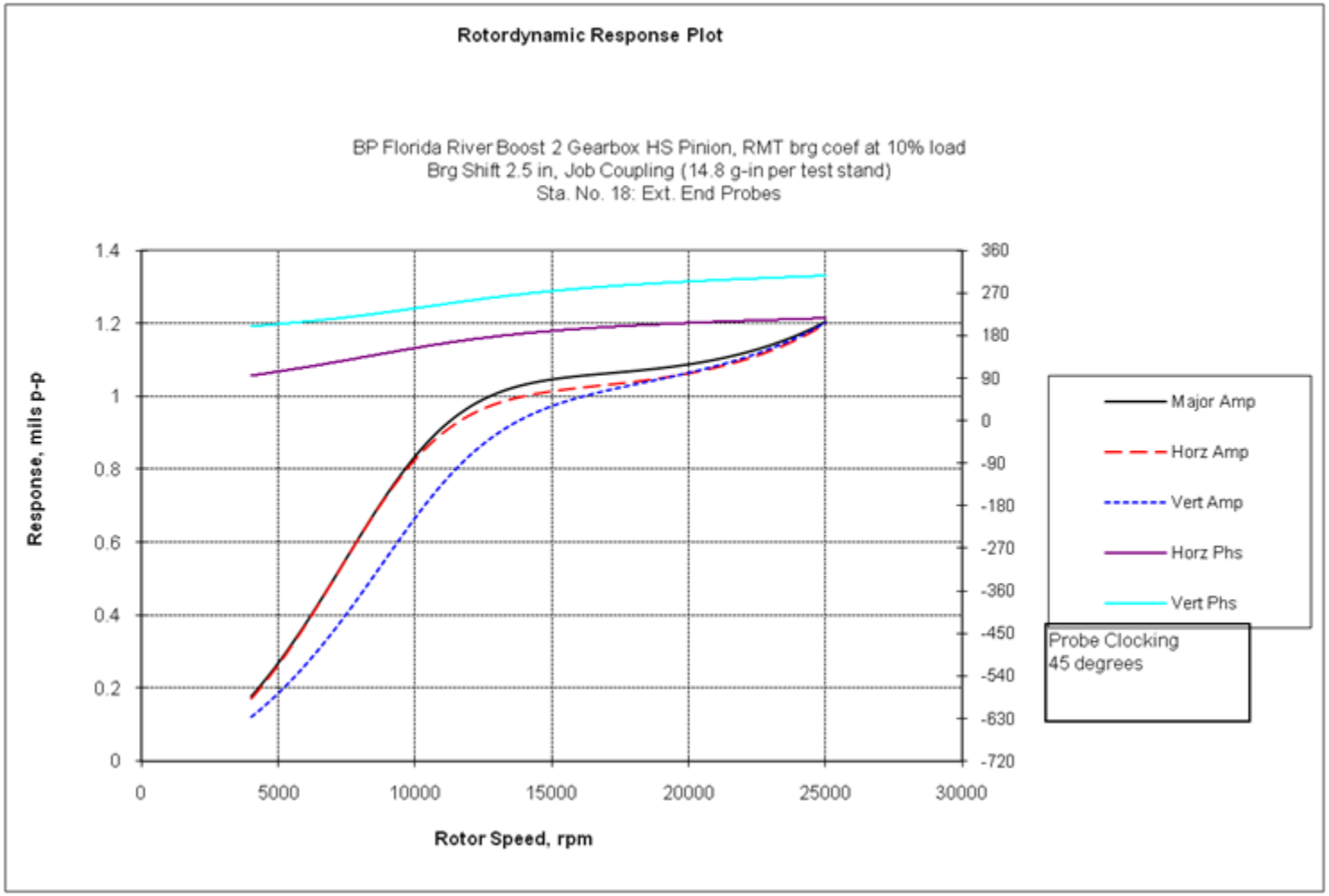
Undamped critical speeds are higher with bearing moved nearer to overhung weight at shaft end



Re: mode shape plot

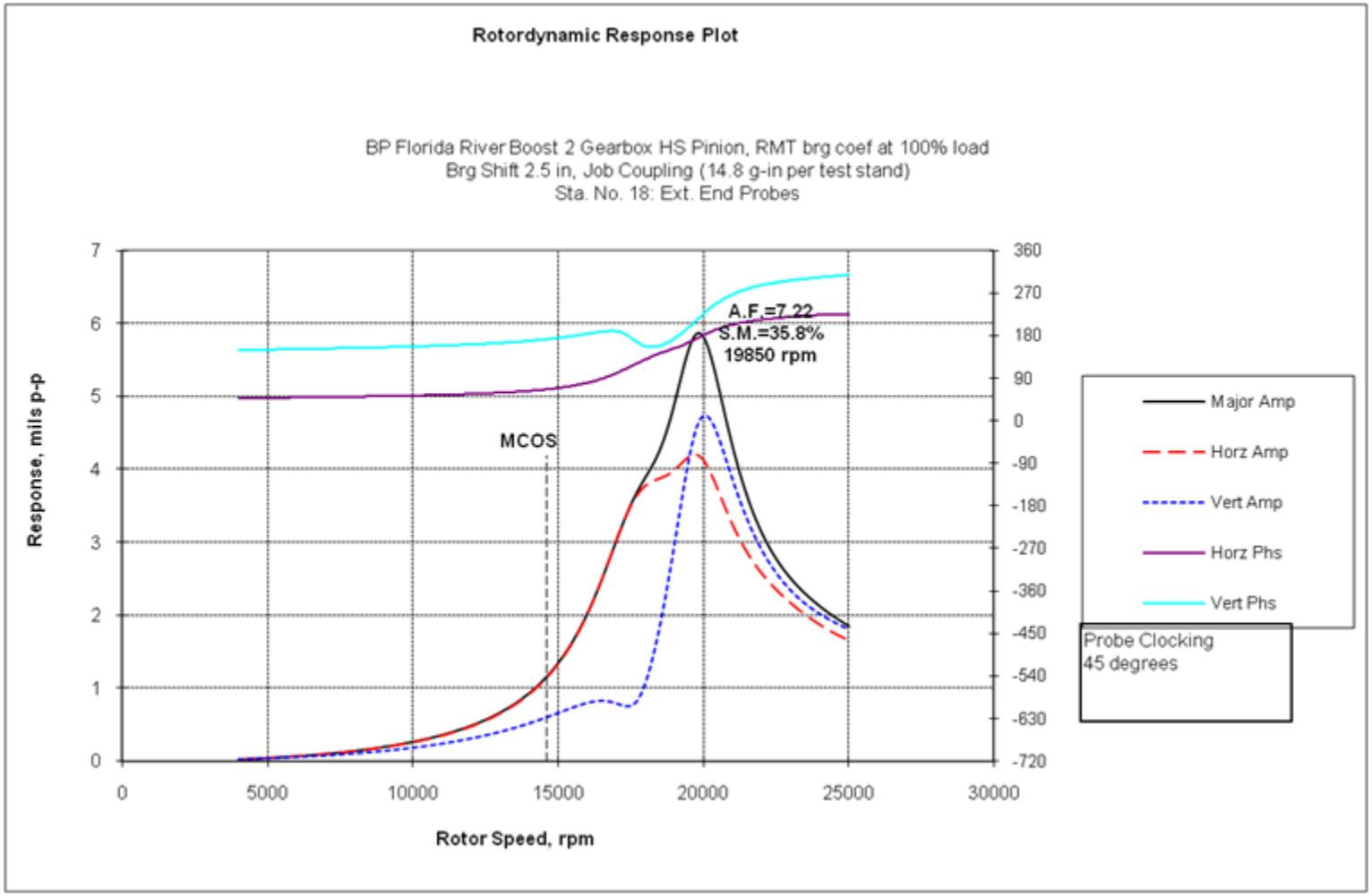
Predicted Effect of Moving Pinion Bearing – Low Load

Natural frequency still low at low load – but now well damped.



Predicted Effect of Moving Pinion Bearing – Full Load

Critical speed moved up at full load, 17100 to 19850 CPM.



Field Results of Moving Pinion Bearing

- No problem during startup, about 0.001” (0.025 mm) shaft radial displacement was worst HS pinion vibration observed.
- Pinion running about 0.0003-0.0004” (0.008-0.010 mm) at load.
- Gearbox robust enough to resist possible alignment or compressor problems.
- The machine now runs better than it did before the refurbishment.
- Good performance in more than two years operation since fix.

Conclusions

- HS pinion lateral critical speed with frequency varying with load, crossed operating speed as load increased, resulting in a trip as the machine was loaded.
- Vibration already present before refurbishment increased due to slight change in bearing properties, rotor balance, alignment, or behavior of a connected machine; otherwise behavior was similar before bearing was relocated.
- Adjusting bearing clearance to change rotor-bearing system behavior was insufficient to solve the problem.
- Relocating the HS pinion drive end bearing closer to the shaft end significantly improved rotordynamics and solved the problem.
- As a result of the changes the machine was more robust than it was as originally designed and built.

Lessons Learned

- “Simple” refurbishments may not be as simple as they seem
  - There may be an existing problem that was worked around in previous operation.
  - Unknown unbalance, temperature, alignment, or other system conditions can be enough to trigger unexpected results.
  - Original design and operating data should be reviewed.
- A time will come when it’s necessary to do what it takes to get on with life
  - Operators understandably don’t like “research projects” that interfere with production.
  - Something that normally should work may have to be abandoned.
  - To use a basketball analogy, one must go for the slam dunk.
  - In this case the slam dunk was to move a bearing.

Questions?