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Innovative Design in Expander Wheel-Shaft Attachment Replaces Hirth Coupling for High Speed, High Temperature and High Power Applications

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Abstract

- Although this Case Study is focused on an Expander-Generator unit in a geothermal application, it’s findings can be used in all turbomachinery applications where other conventional shaft-wheel attachments are causing problems. This solution is a notable alternative to the Hirth coupling design for high power, high speed and high temperature applications.
- An Expander-Generator unit for a geothermal power plant application experienced ongoing failures during a 10-year period. The longest run cycle for the machine was 18 months yet with less than 10 MW power production. The average time between failures was less than six months and with each failure; the wheel was completely damaged and separated from the shaft. A complete metallurgical study on previous failures showed the Hirth coupling attachment was the first to fail in all cases.

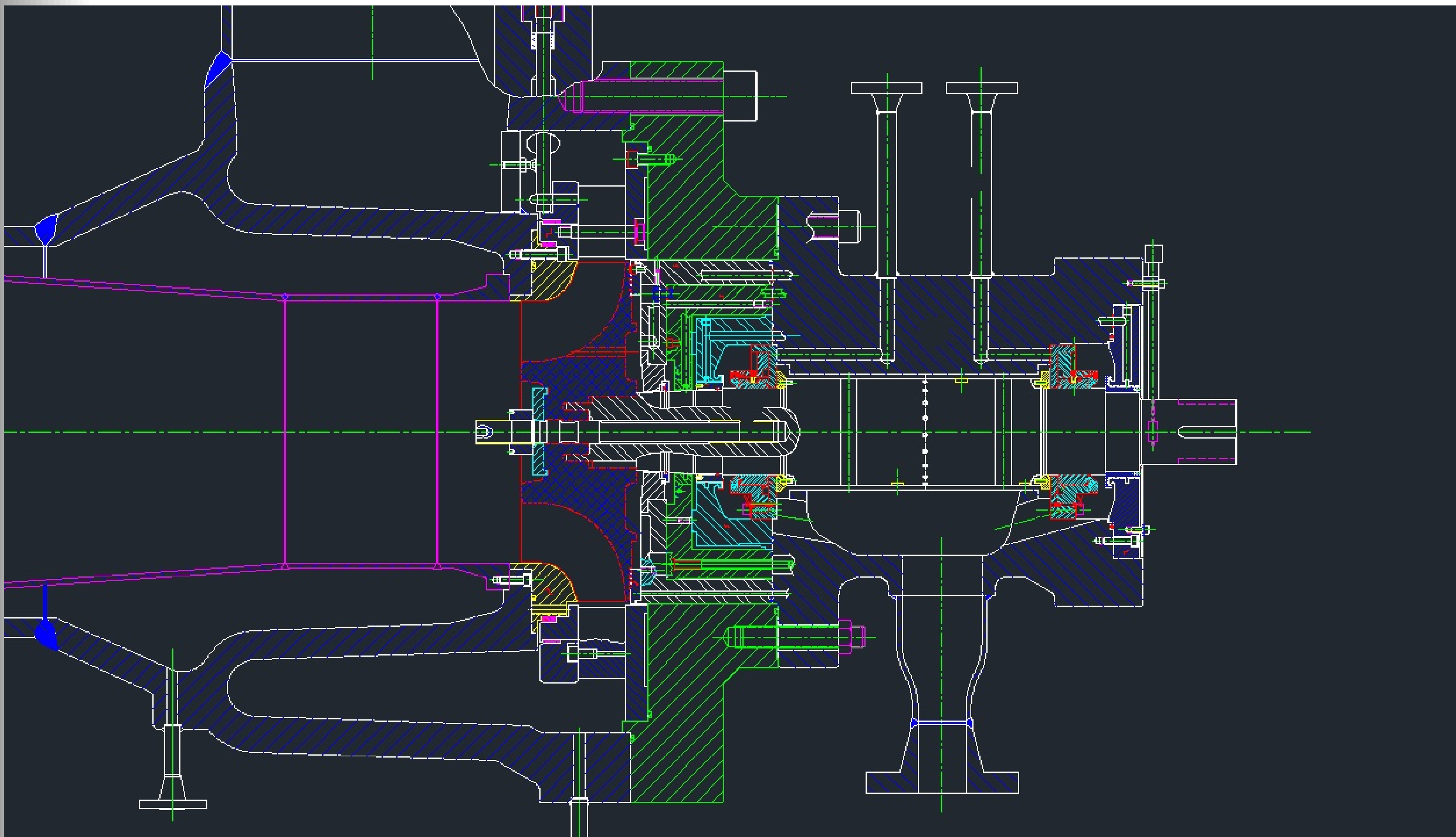
Abstract

- Using fully coupled non-linear contact point FEA analysis and benefiting from advancement in machining techniques, new four-lobe polygon shaft-wheel attachments were designed for high speed, high power and high temperature applications. The redesign reduced the hub centrifugal stress by 30 percent, allowed the shaft to be inserted inside the wheel to hold the wheel C.G. on the shaft, and increased the power transfer capacity of the rotary parts.

- By holding the wheel on the shaft, other problems like high vibration, electrical current passing through the unit, and incorrect blade resonance could be addressed and resolved. For more than two years, the redesigned machine has run continuously without failures and with constant low vibration producing up to 12 MW, at a minimum of 20% above any previous operating points.

Background

(Cross Section)

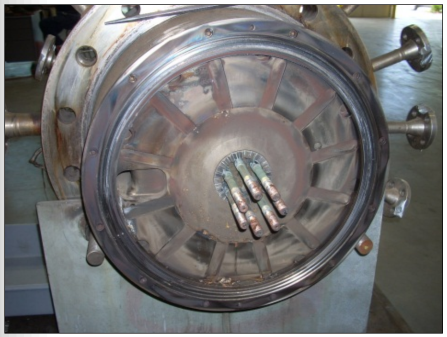


Background

- An Expander-Generator unit for geothermal application was commissioned in 2000.
- The expander wheel failed continuously since commissioning of the machine.
- Machine experienced very high vibration (0.13 mm and higher) during operation.
- During a 10-year period, the machine was redesigned several times yet the problems remained.
- When the machine operated close to the designed power (10 MW), the average time between failures was less than three months.
- On one occasion, the unit ran for 18 months but on a lower power (6 – 8 MW).

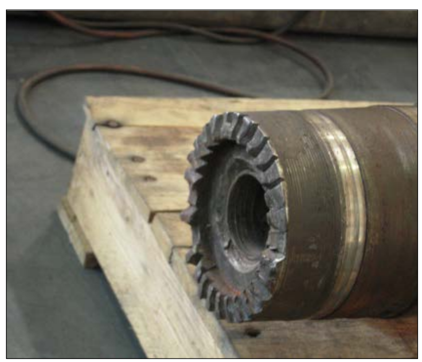
History

2007



2008

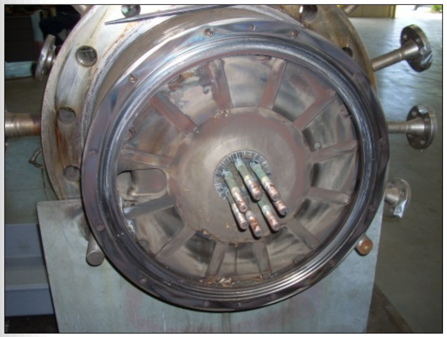
2009



- Hirth coupling attachment was failing on all previous designs.
- Inconel 718 retaining bolt was also failing-either severely bent or completely sheared.
- Because of above reasons, in all failures the expander wheel was completely separated from the shaft, and it was rubbing to the follower and the housing, thus not much evidence was left for useful metallurgical analysis.

History

2007



2008

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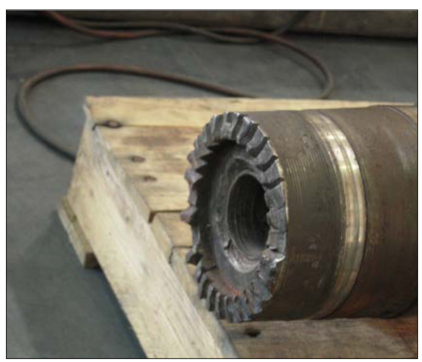


Possible causes for Hirth coupling failures:

- Wheel Weight (above 90 Kg)
- Hirth coupling size
  (Re-designed 3 times)
- Hirth coupling teeth design
  (Re-designed 4 times)
- Weak retaining bolt
  (one single bolt, 7 bolts)
- Locating the wheel on the retaining bolt

First Stage of Re-design

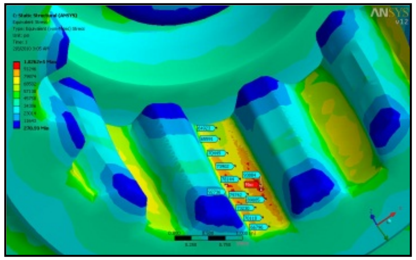
- The first goal was to find a solution to keep the wheel on the shaft.

- To achieve this goal, a decision was made to eliminate the old 7.6 cm Hirth coupling and manufacture a new shaft design to be inserted inside the wheel and enable us to hold the center of gravity (C.G.) on the shaft.

- To successfully insert the shaft inside the wheel, challenging operational factors needed to be considered:

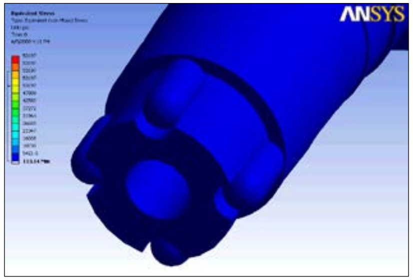
  - Weight: Very heavy wheel - 60.3 cm Titanium Wheel (86 Kg)
  - Speed: Very high operating speed - 12,500 RPM
  - Performance: High design horse power - 15 MW
  - Temperature: High operating temperature of 175C - 200C

First Stage of Re-design

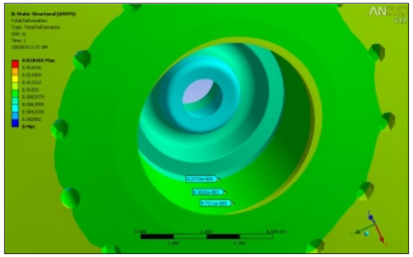


Other considerations:

- Combination of heavy wheel weight and high operating speed causing very high stress on any opening inside the wheel.



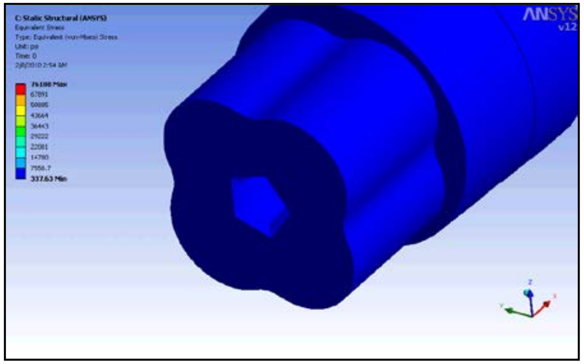
- Traditional keyway design ruled out as key’s weight would apply additional stress to the hub.
- Centrifugal force opens up the hub diameter by a minimum of 0.5 mm and reduces effective contact area to transfer the torque.



- Hub expansion for any opening inside the wheel, caused by high temperature and centrifugal force make it difficult to hold the wheel C.G. close to the center of the shaft and hold the imbalance.

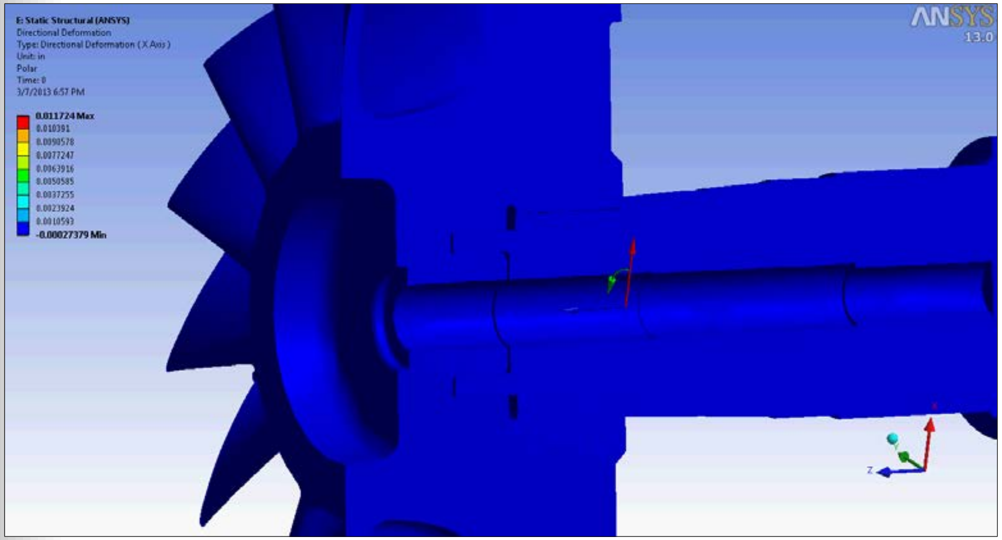
First Stage of Re-design

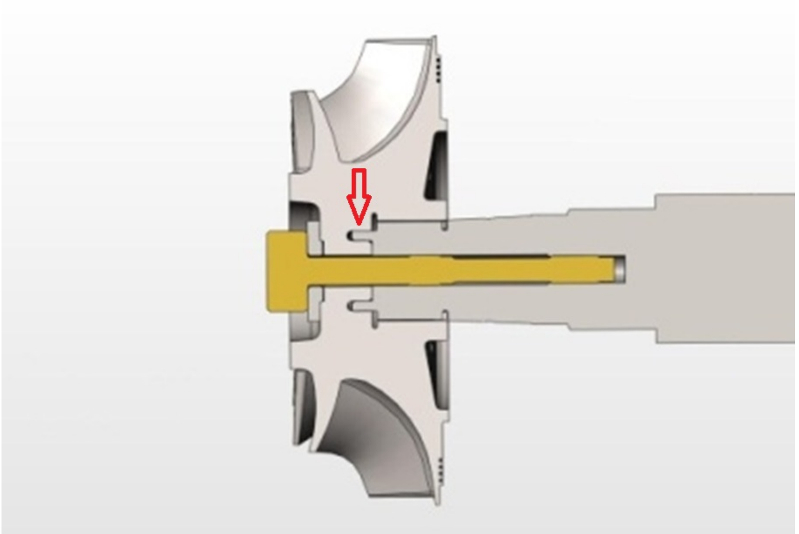
- A unique four-lobe polygon attachment was designed.
- To reduce the centrifugal stress further, shaft diameter increased by 2.5 cm and enabled us to design 10.15 cm shaft-hub attachment (versus old 7.6 cm Hirth coupling).
- With this new design, stress at the hub at no point exceeds more than 60% of expander wheel's material yield stress (with all maximum operating conditions).
- To increase the effective contact area, very tight tolerances were used. Advanced CNC technology allowed to machine shaft and hub assembly to a tight tolerance of less than 0.005 mm.



First Stage of Re-design

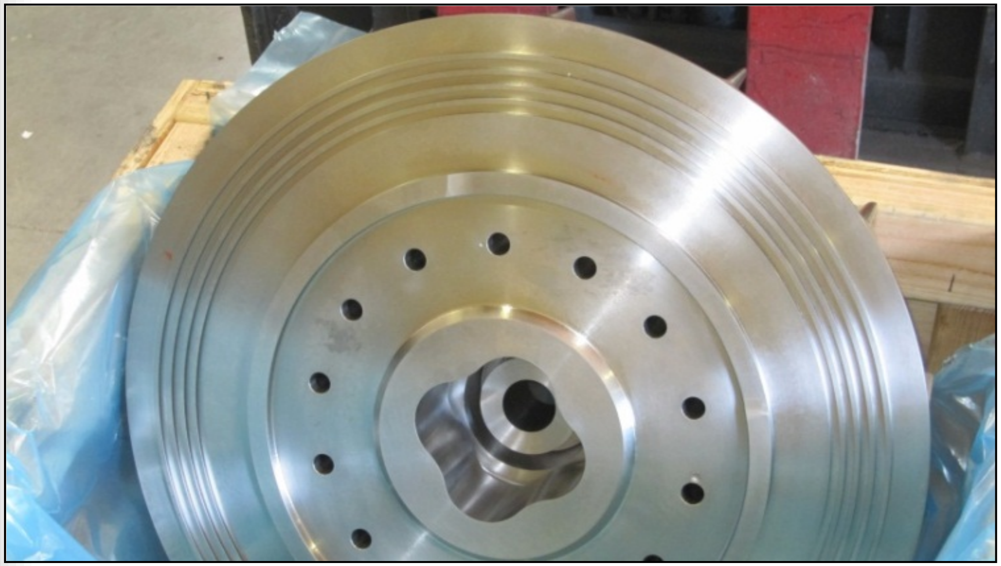
- To be able to repeat the balancing procedure by keeping the wheel centric to the shaft, a tightly-machined locator was added to the end of the shaft design.

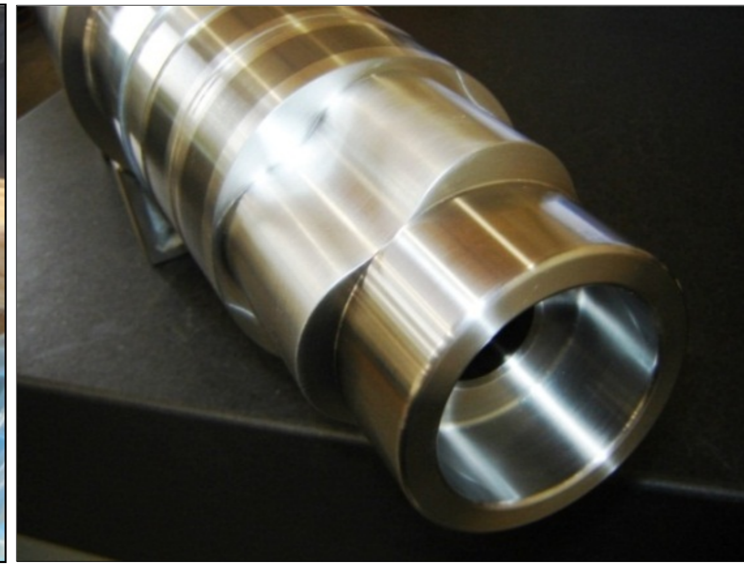




First Stage of Re-design

- New machining design applied to the shaft and wheel.

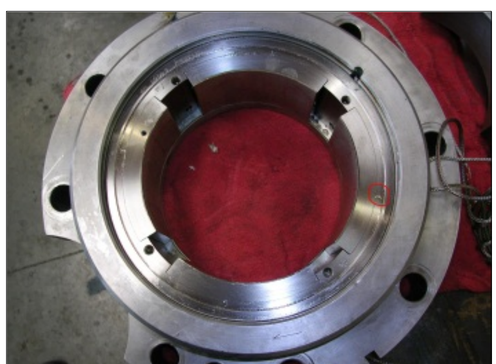




- In addition to the problems with Hirth coupling, this unit originally was suffering from high vibration and high temperature on bearings. As a result, the bearings needed to be replaced after each crash.

First Stage of Re-design

- Increased bearing size by 2.5 cm to increase stiffness and increase the shoulder area between shaft and expander wheel.
- Changed the number of pads from four to five for better bearing stability. Both lateral and torsional rotor dynamic analysis showed more stable results with this new shaft and bearing design.
- The original pivot-pin design changed to half-sphere pivot (4140 Rc52), for better strength. (Historically, following each crash, the bearings needed to be replaced because of crushed pivot pins.)


First Stage of Re-design

- Installed new unit design, ran it continuously for three months producing 11 MW of power until the wheel failed.
- Balancing procedure was repeatable on this new design.
- Vibration was much lower this time, around 0.05 mm.
- After operation, damaged wheel was still firmly connected to the shaft and was not rubbing to the housing. (Minor rub between the wheel and the follower was detected.)
- Retaining bolt remained in place with no sign of elongation.
- No signs of high stress on the shaft and wheel hub.

First Stage of Re-design

- For the first time in the history of this unit, the wheel was still attached to the shaft after the failure.
- The expander wheel maintained its integrity so it could be sent to the metallurgical lab for detailed failure root cause analysis.
- All of the following findings could be observed for the first time in the history of this unit. (On all previous failures, the wheels were severely damaged so limited material remained for further analysis.)

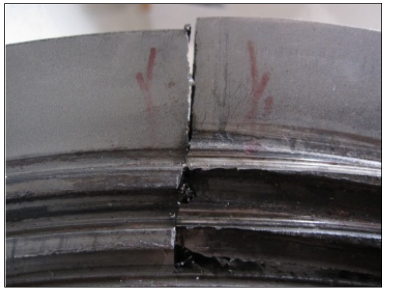
Root Cause Analysis

1. Expander wheel was attached to the shaft and retaining bolt was intact.

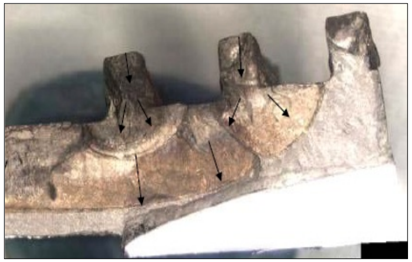
2. Build-up from the operating steam was firmly attached to the blades OD and was causing friction between the expander wheel blade and the follower.

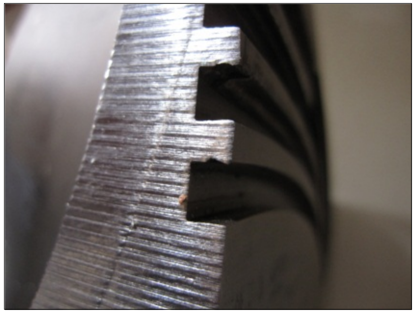
3. Expander wheel blades were cut off in several locations, signs of high cycle fatigue observed.

4. Expander wheel disc had cracks in three locations on the OD.

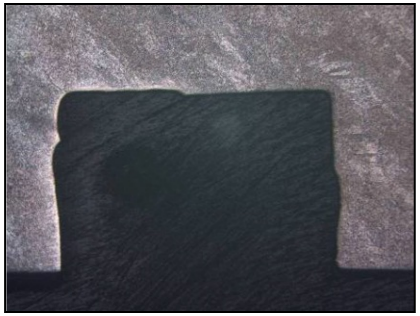


Root Cause Analysis



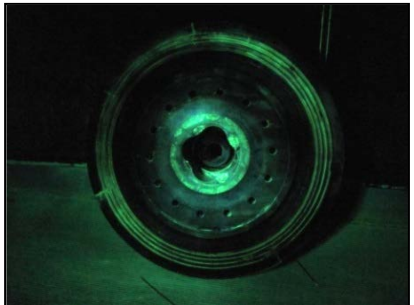


5. Disc cracks were initiating from the third stage of the back wheel seal on all three locations.



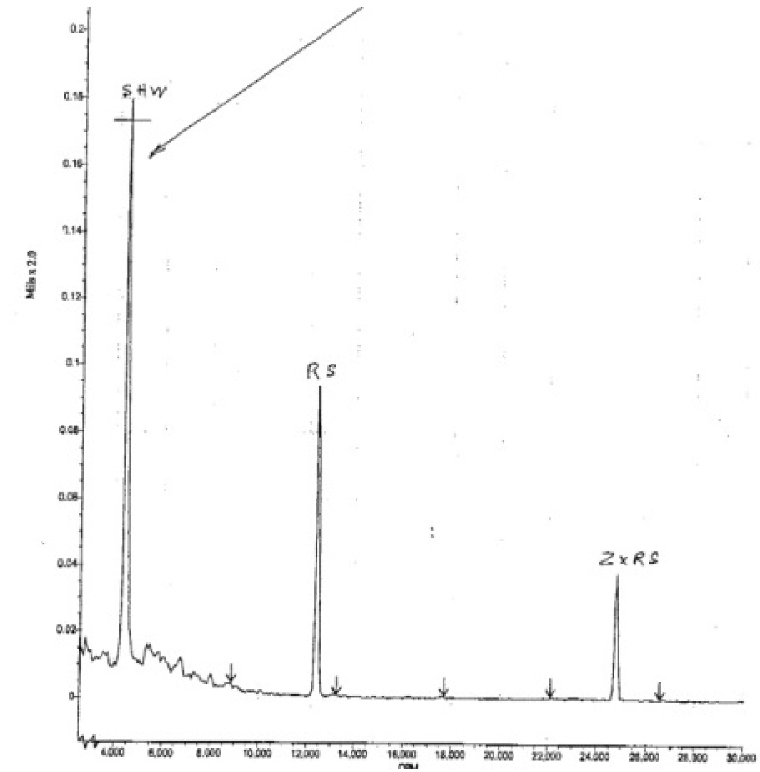
6. Signs of severe rubbing were observed between the wheel and back wheel seal inside all four stages of the back wheel seal. Material property changed locally and became brittle.

7. Discovered electrical current was passing through the unit. Signs observed on blades between each crack and between shaft and wheel shoulder surface.



Root Cause Analysis

8. Serious instability observed during operation after the start-up but the vibration limit was steady and less than 0.05 mm.



9. On both bearings, journal pads and thrust faces were showing signs of high temperature exposure.

Second Stage of Re-design

- No change made to shaft-wheel attachment.
- Increased the clearance between the expander wheel and the follower to avoid rubbing on blade’s outer edges.
- Wheel resonance re-evaluated on complete rotor assembly and with the maximum stretch on the retaining stud. Few blade frequencies observed to be close to the operating speed. By cutting blades in front and on the OD, safety margin increased on these frequencies.
- Back wheel seal design changed to increase the clearances and consider the wheel expansion by centrifugal forces and temperature.

Second Stage of Re-design

- New grounding system implemented on all casings on four different locations, and on two places on the shaft with higher capacity brushes to eliminate current migration through the unit.
- Moved sphere pivot to 55% position under each pad to improve the bearing stability based on the data collected during three months of operation and new rotor dynamic analysis.
- Used new Cr-Cu material for bearing casings to transfer heat faster to the bearing housing.
- Study on high temperature marks on both bearings with no thrust force indicated that oil pumps were failing to provide sufficient oil to keep these bearings cold. Repaired both oil pumps to ensure the maximum capacity of oil flow is reachable.
- Changed oil and cleaned oil piping and filters as some blockage appeared on the piping over time.

Results

- Implemented/commissioned the new machine design in November 2010.
- Machine started smoothly and the vibration was less than 0.015 mm.
- Machine ran continuously for 14 months providing up to 12 MW (an average of 11.5 MW) power with no alarm and no trips until customer decided to inspect the condition of internal parts to check the design integrity.
- Vibration remained controlled in the range of 0.025 mm during operation.

Results

- Unit removed in February 2012 to be evaluated. Spare MCS with same design enhancements installed and started with same low vibration.
- Main unit disassembled, wheel was intact and complete X-ray and florescent dye check showed no signs of cracking.
- No sign of overheating observed on bearings.
- No sign of rubbing on back wheel seal.
- Main unit was cleaned, reassembled and is ready to be back in service.
- Spare MCS has been running continuously for 32 months now and it is running with low vibration and it is providing up to 12 MW power which is, at a minimum, 20% above any previous operating points.
- The whole process including engineering and manufacturing on the first stage of the re-design took 26 weeks and it took 20 weeks for the second phase of the redesign and the root cause analysis.

Conclusion

- Innovative re-design meets and exceeds performance requirements:
  - Wheel’s C.G. is located on the shaft and the attachment is transferring an average of 12 MW power.
  - Wheel is located tightly on the shaft, balancing procedure is repeatable which results in low vibration during operation.
  - Bearings are running cool and stable.
  - Wheel’s operating life has exceeded customer's expectation and is ready to be back in operation after minor clean up.

- New Shaft-Wheel attachment successfully proved to be a reliable replacement for Hirth coupling for any turbomachinery applications

Discussion

Thank You

Any Questions?