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Redesign of Centrifugal Compressor Impeller by means of Scalloping

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Biographies

- **Kirill Grebinnyk**
  - Leads Sulzer program of aerodynamic rerates and upgrades of turbomachinery.
  - Areas of expertise: failure analysis and redesign of the rotating equipment components, structural and modal analysis and modal testing.
  - 8 years of experience in fluid dynamics, finite element methods, design of turbomachinery.
  - MSc Mechanical Engineering (2007).
- **Rob Widders**
  - 37 years of experience, worked in the areas of design/manufacturing, consulting and plant operations.
  - Areas of expertise: structural design for mechanical plant items, analysis and fitness for purpose confirmation using FEA and fatigue analysis, design audits, troubleshooting, design rectifications and others.
  - MEngSc UNSW (1978).
  - Registered P.E. Queensland.

Abstract

Impellers of centrifugal compressors may experience resonance with vane passing frequencies, especially when operated away from the design conditions. Resonance can cause a serious structural damage to impeller. Complete redesign of an impeller to avoid resonance often requires major changes of the compressor stage design.

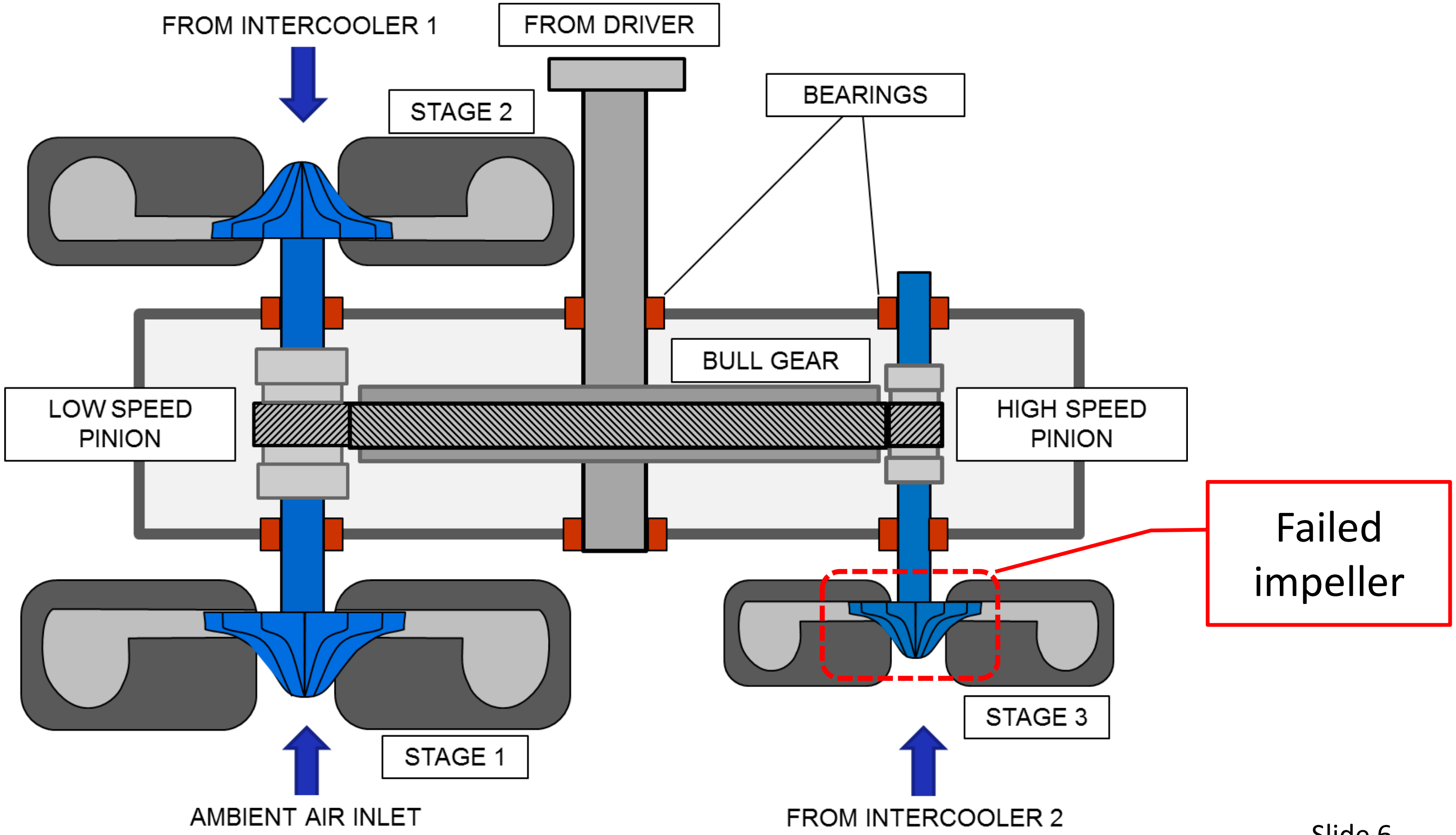
This case study illustrates alternative approach to redesigning an impeller - scalloping of its coverplate and backplate. Scalloping changes impeller’s natural frequencies and allows achieving a separation margin from resonance, which is sufficient for reliable operation. At the same time, scalloping does not have a detrimental effect on impeller’s performances and allows to maintain existing configuration of compressor stage.

Contents

Description of the Equipment

- Industrial gas company operates three stage integrally geared compressor at the air separation plant in Australia (>1,000 TPD of oxygen).
- Compressor characteristics:
  - Inlet air flow = 20,000 m^3/hr (11,770 ACFM)
  - Pressure at the compressor discharge = 3,030 kPa (440 psia).
  - Compressor is driven by an electric motor at 1,500 RPM.
  - Power input = 9.5 MW (12,740 hp)

Layout of Integrally Geared Compressor



Problem Statement

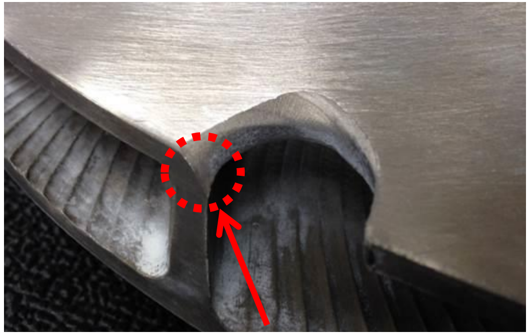
- The high-speed pinion (14,040 RPM) with the 3rd stage impeller has been in service since 2009 and accumulated around 40,000 running hours.
  - Impeller tip speed = 295 m/s (976 ft/s).
  - Construction method – brazed coverplate.
- Four pieces of material liberated off the coverplate.
- During last months before the failure the compressor was operated close to turndown due to lower supply needs of the plant.
- Objective: determine the cause of the failure and redesign the impeller to avoid future failures.

Methodology: Impeller Failure Analysis

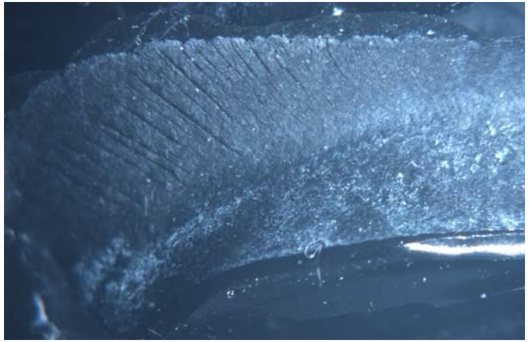
- Perform NDE and crack surface metallography to identify nature of the failure.
- Perform modal testing of the impeller to determine its natural frequencies.
- Perform steady state 3D FEA to determine stresses in the impeller.
- Perform modal analysis by means of 3D FEA to determine natural frequencies, and confirm the results from the modal testing of the impeller.
- Identify the path forward to redesign the impeller.

Impeller Failure Analysis

Crack Surface Metallography

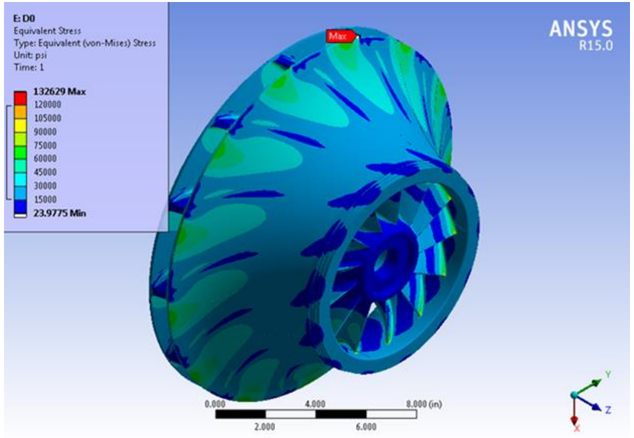


Crack initiation site at vane fillet



Crack progress lines (beach marks)

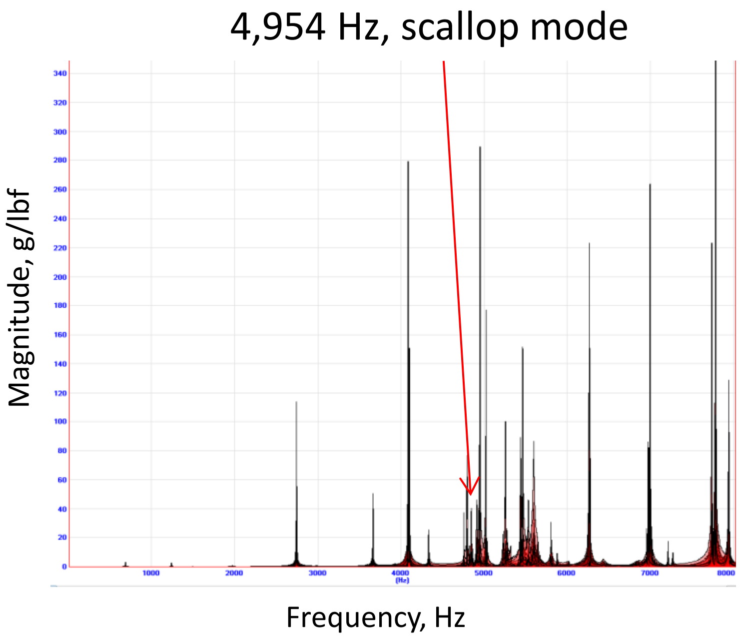
3D Steady State FEA



Imp. material is equiv. to A182F6NM (QT900).
Yield strength = 930 MPa (135 ksi).
Max. equivalent stress = 910 MPa (132 ksi) at Operating Speed. Stress concentration is at the location of crack initiation.

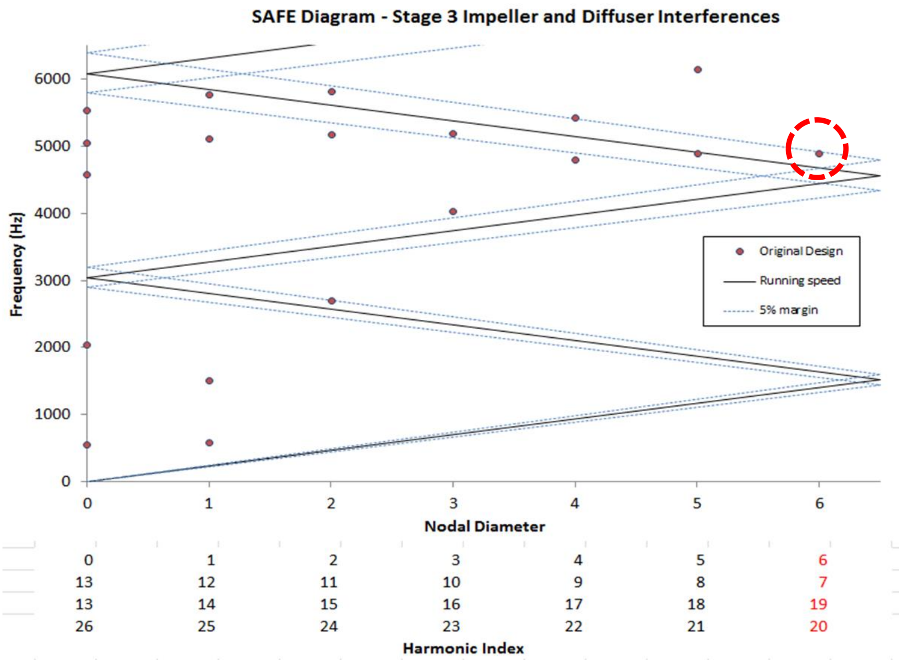
Impeller Failure Analysis: Modal Testing

- Modal testing is performed to determine the natural frequencies of the impeller.
- Uniaxial accelerometer is attached to the impeller to collect the data. Calibrated hammer is used to impact the coverplate at 34 points.
- The data acquired during modal testing is post-processed and the natural frequencies are identified by the high response magnitude.
- The natural frequencies predicted by the FEA are in 3% range from the results of modal testing.



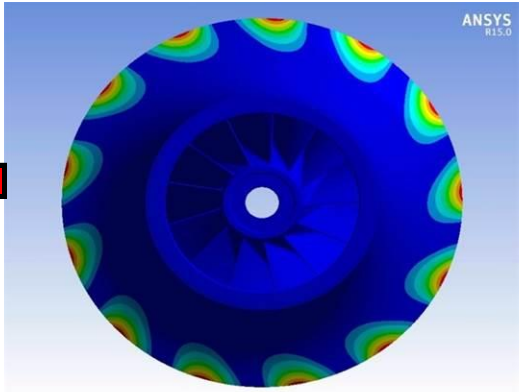
Modal testing results

Impeller Failure Analysis: Modal Analysis



Interference (SAFE) diagram – Original Impeller

The Singh's Advanced Frequency Evaluation (SAFE) diagram approach introduces frequency and mode shape matching instead of just the frequency matching. See reference [1].



Natural frequency = 4,884 Hz, 6ND, coverplate only mode

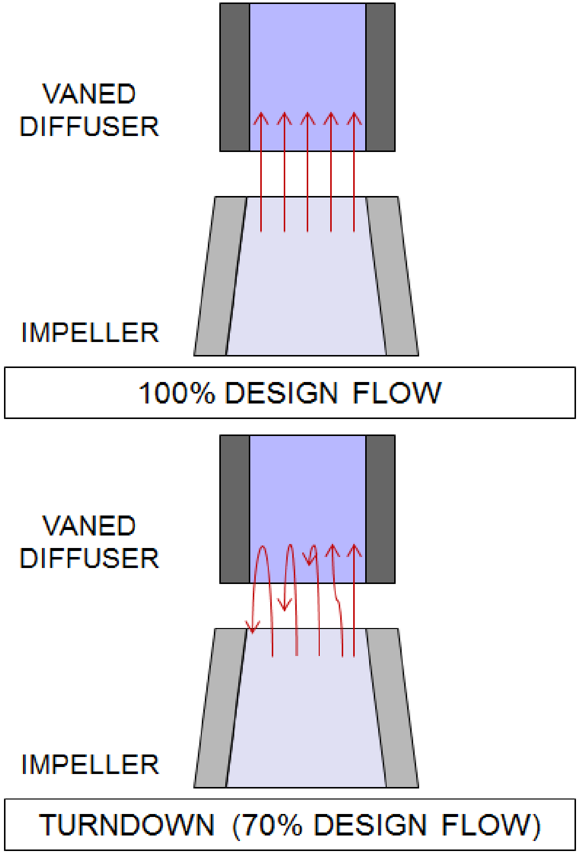
- # of diffuser vanes = 20;
- # of impeller vanes = 13;
- Number of Impeller Nodal Diameters (ND) = 6
- Harmonic Indexes that can be excited are 6, 7, 19, 20

Failure Analysis: Conclusions

- Stress concentration at the coverplate does not exceed the material yield strength, but may cause a fatigue issues in conjunction with high alternating stresses due to resonance.
- Using Interference (SAFE) diagram the impeller natural frequency at 4,884 Hz was identified as the one being excited by the external forces. The mode can be excited with a 20X excitation, which corresponds to the diffuser vane count. The mode shape of this frequency closely resembles the failure pattern observed.
- Scalloping of the impeller coverplate and backplate is considered as the primary method for the redesign.
- The following issues needs to be mitigated: resonance with the impeller natural frequency at 4,884 Hz and high stress in the coverplate fillet.

Failure Analysis: Conclusions cont'd

- The ratio between the diffuser leading edge diameter and impeller outside diameter is equal to 1.1. This value indicates an average proximity of impeller and diffuser.
- While the compressor was operating in normal (close to design) mode, the alternating stresses caused by the diffuser vane passing interference were low.
- When the compressor flow was reduced to operate in turndown mode, backflow from the diffuser vanes appeared and initiated the resonance.

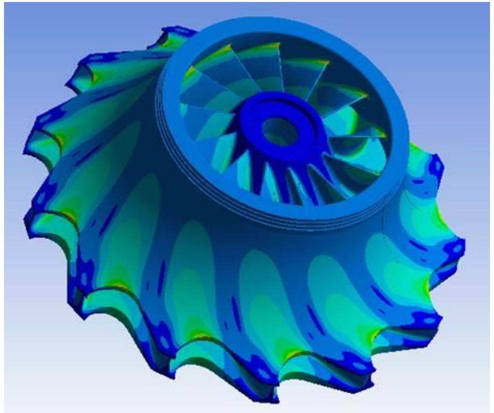


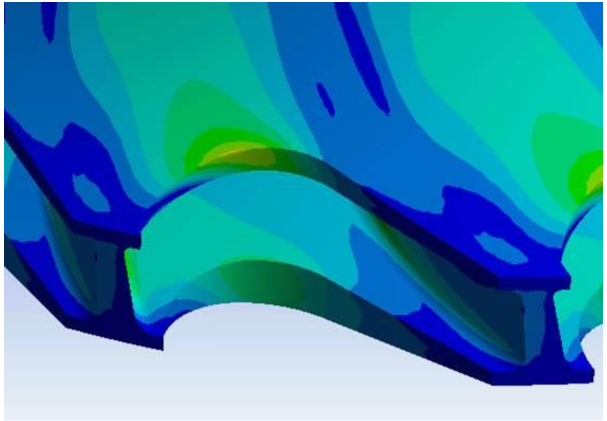
Methodology: Redesign of the Impeller

- To redesign the impeller the following steps are taken:
  - Create an impeller design candidates with scallops made in the coverplate/backplate.
  - Validate the candidates by means of 3D steady state and modal FEA to confirm the following:
    - The stresses in the impeller are within the expected ranges.
    - 5% separation margin between the impeller natural frequencies and vane passing frequencies is achieved.
  - Choose the optimum design from the developed candidates. Determine whether coverplate only or coverplate and backplate scalloping provides optimum results in terms of stresses and natural frequencies separation.
  - Perform 3D CFD (Computational Fluid Dynamics) analysis on the final design to determine the expected efficiency drop due to the implemented scalloping.

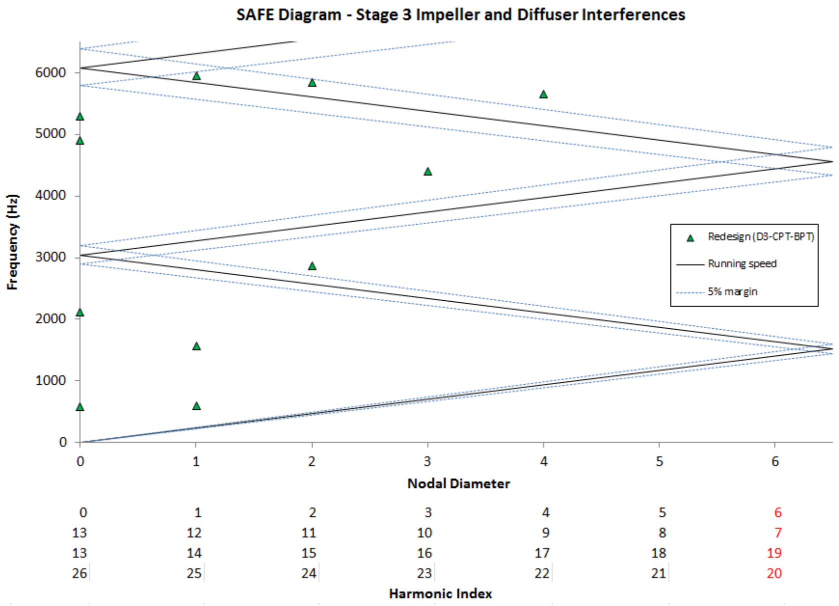
Redesign of the Impeller: Steady State FEA

- Steady state 3D FEA of the redesigned impeller is performed at operating speed.
- Scalloping of the coverplate completely eliminates the stress concentration found for the original impeller design.
- However, reduction in the depth of the scallop leads to increase in stresses at the scallop arc itself. Therefore, the minimum depth of the scallop is determined by the maximum stress level acceptable in it.





Redesign of the Impeller: Modal FEA

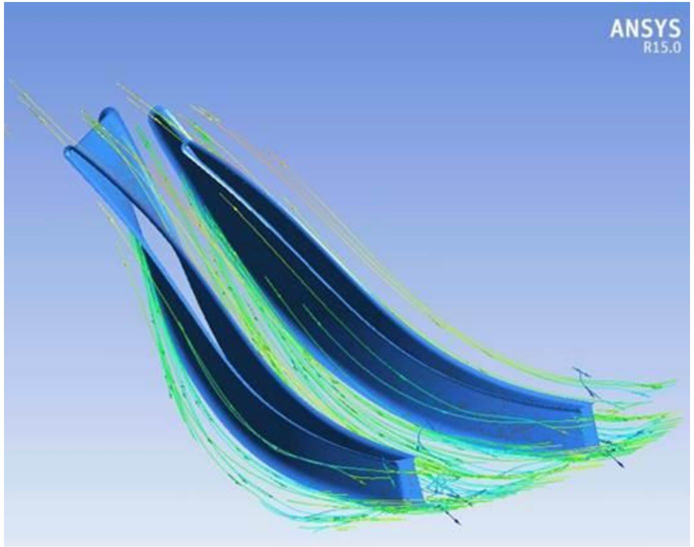


Interference diagram – Redesigned Impeller

- Scalloping both coverplate and backplate appears to be beneficial for obtaining 5% separation margin between impeller's natural frequencies and potential interferences.
- In the new design no natural frequencies are having interference with the potential sources of excitation.

Redesign of the Impeller: 3D CFD

- CFD analysis is performed at the design point conditions. The results of it show that the impeller flow characteristics are not significantly affected by scalloping. Main flow parameters (pressure, velocity distribution, flow angles) are not changed in the major part of the channel due to scalloping.
- The stage efficiency reduction due to scalloping is estimated as 0.81%, total pressure at the impeller outlet is reduced by 22 kPa (0.65%). This reduction was deemed as acceptable by the customer.

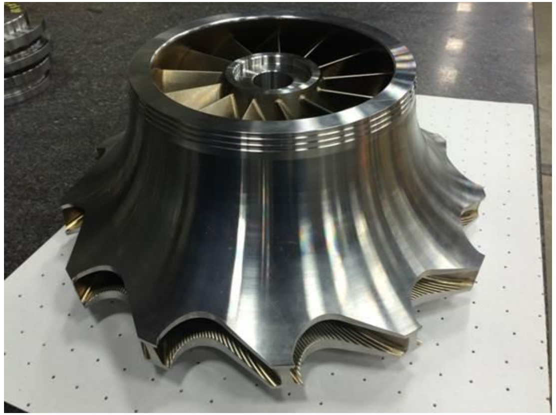


Conclusions

- Complete redesign of an impeller to avoid resonance can be time and resource consuming endeavor. Scalloping can provide an alternative, which can help to reduce engineering time, minimize the extent of modifications needed and provide a robust solution to mitigate the resonance issues.
- 3D CFD analysis showed that moderate scalloping does not have an adverse effect on the impeller performance, thus it is an acceptable solution from an aerodynamic point of view.

Field Implementation

- The new impeller with the brazed coverplate was manufactured and tested within 20-week period after the engineering analysis is complete.
- The impeller was spin-tested at 15% above maximum operating speed (MOS) and non-destructively tested to confirm its structural integrity.
- Modal testing of the new impeller is performed. The obtained test results are within 2% range from the frequencies predicted numerically by modal FEA.
- As of May 2016 the pinion with the redesigned impeller has not been installed in the machine.



Lessons Learned

- When centrifugal compressor is operated at regimes far from the design conditions, unexpected excitation forces may start to act and cause a resonance, which was not experienced when operating around design point.
- Interference (SAFE) diagram has proven itself to be an excellent tool to help match resonance with potential external forcing functions.
- Scalloping of a reasonable shape does not create a major adverse effects in the impeller flow, thus resulting only in a very minimum performance loss.

References

1. Murari Singh, PhD, "History of Evolution, Progress and Application of SAFE Diagram for Tuned and Mistuned Systems", Proceedings of the Forty-Second Turbomachinery Symposium, October 1- 3, 2013, Houston, Texas

THE END

QUESTIONS?