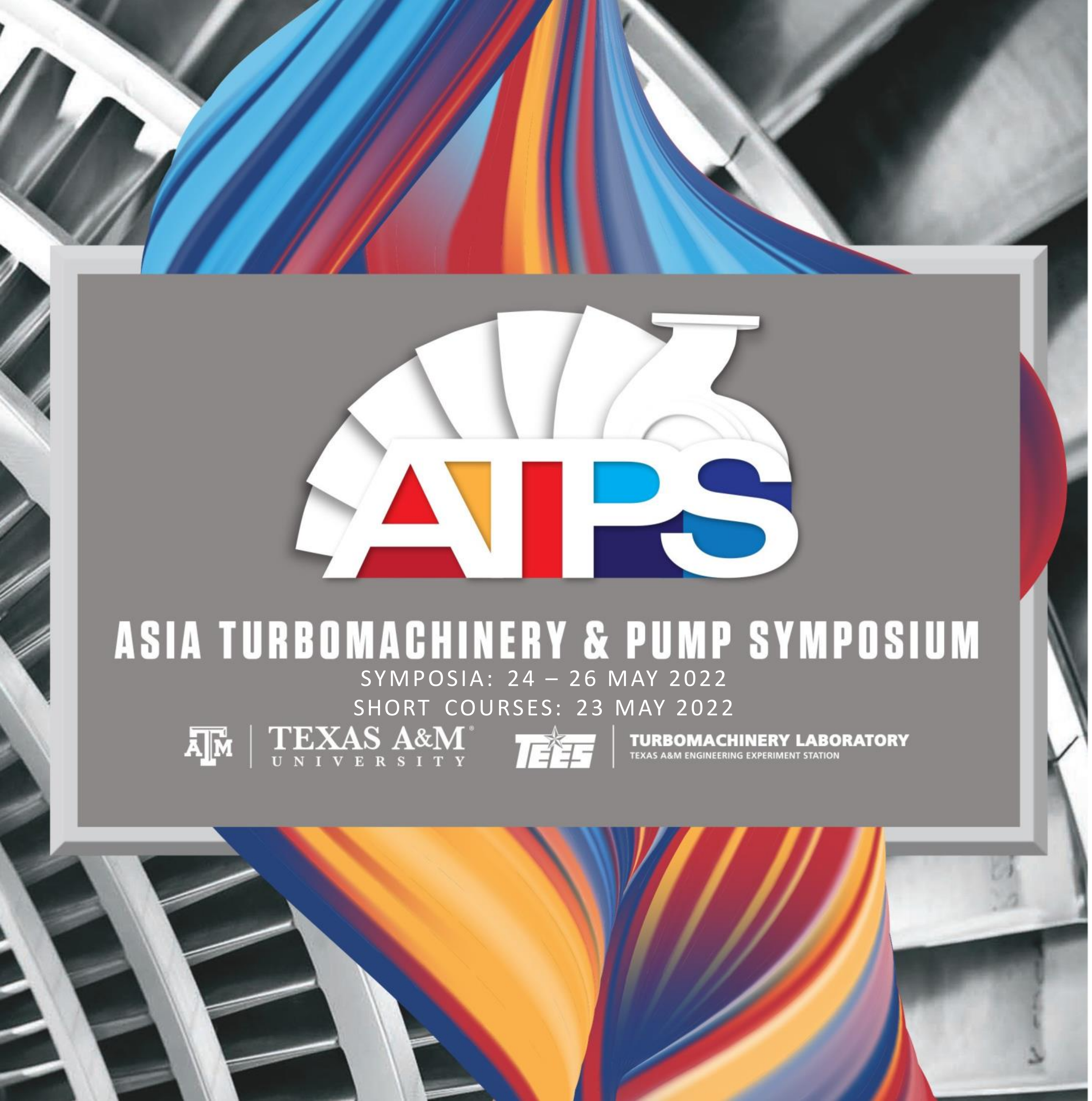

MECHANICAL DAMAGE TO PUMP IMPELLERS CAUSED BY LOW FLOW OPERATION

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- Currently working as an Applied Fluid Dynamics Specialist

Abstract

High-cycle fatigue damage imparted on a BB5 pump impeller operating at low flow operation points was analyzed via numerical methods.

A 1-way Fluid-Structure interaction approach whereby a transient CFD subsequently mapped to a structural FEA showed a significant increase in fluctuating stress ranges as the flow decreased.

The authors present several mitigation options in the case where low flow operation cannot be avoided.

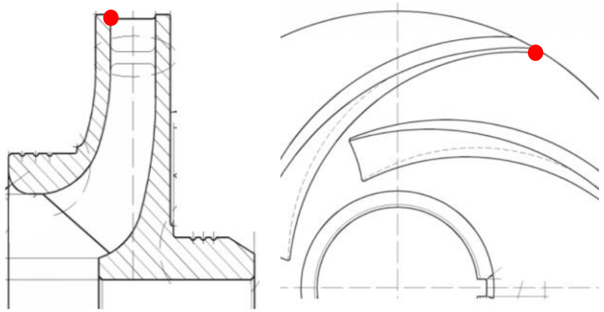
Background

A boiler feedwater pump servicing a combined cycle power plant began operating beyond acceptable vibration levels and was pulled for inspection.

- Problem was traced to 1^{st} stage impeller where a section of the shroud wall had broken off.
- The incident led to more frequent inspections which found cracks in the 1^{st} stage impeller were appearing regularly.

Cracks were found <u>only</u> in the 1^{st} stage impellers.

- Appear between 3 months and 1 year of operation.
- Same location: shroud side trailing edge fillet.



Root Cause Analysis Overview

Metallurgical Analysis Conducted

- Did not find any anomalies. Concluded material defects were not the cause.

Review of End User's Operational Data

- The pump was operated below prescribed minimum flowrate for brief periods.
- No VFD, no min flow recirc valve.
- End user requested an investigation as to whether operation below minimum flow could be a source of the cracks.

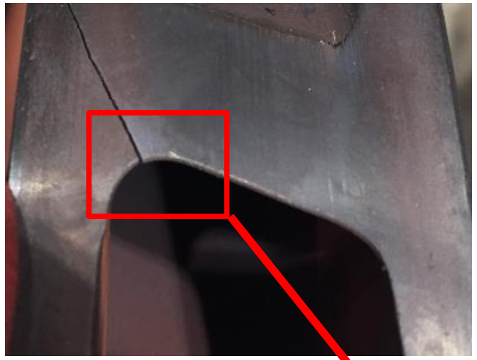
Numerical Analysis

- CFD Analysis: Transient, Full Wheel w/ front & back leak paths, 30+ revolutions, 1° of rotation per time step.
- Flowrates of 100% of BEP, 50%, 25%, 17%, 9%.
- Pressure data transferred from CFD to FEA.

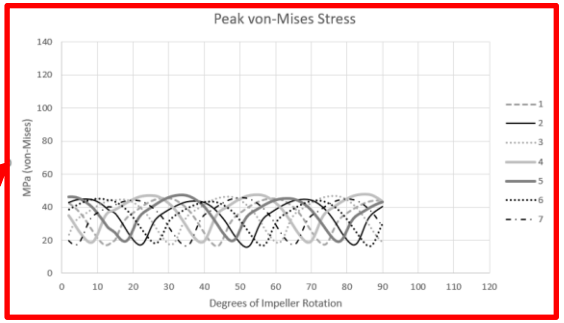
Analysis Process Map

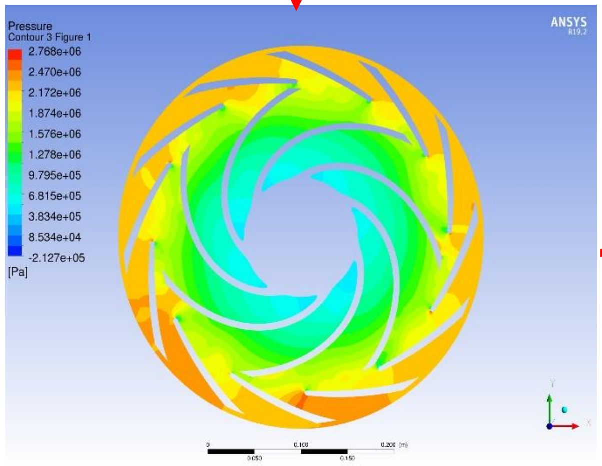
High Fidelity CFD Setup

Area of Interest

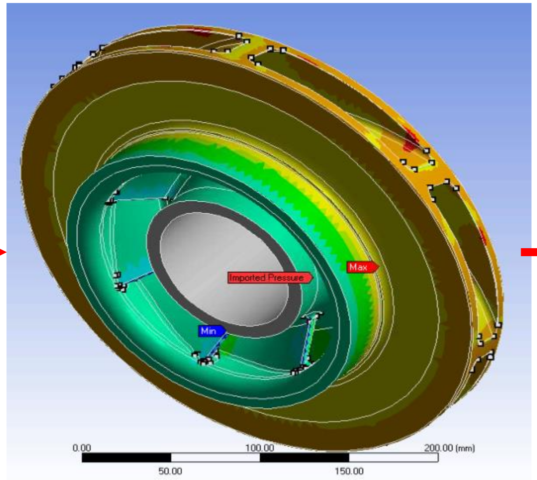


Transient/Cyclic Stresses

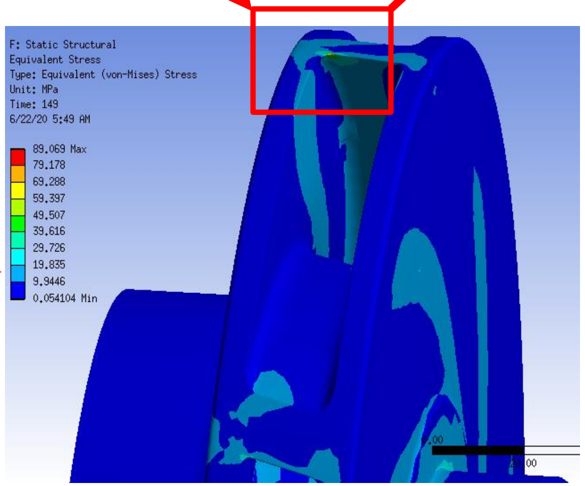




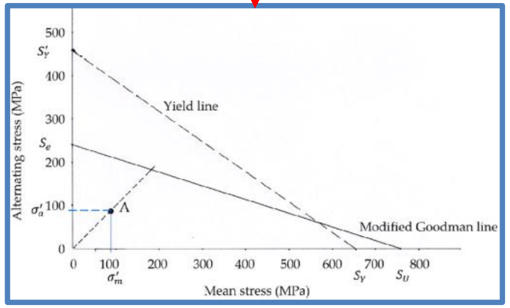
Pressure Results from CFD



Input to FEA Analysis



FEA Results scoped to area of interest

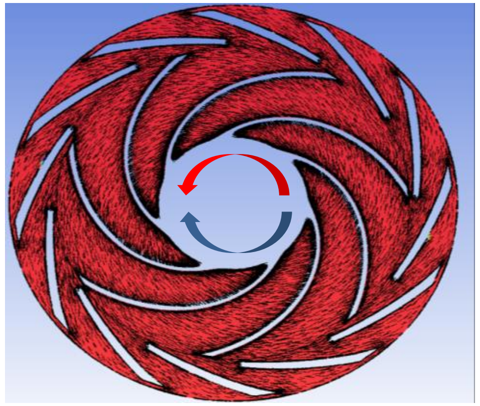
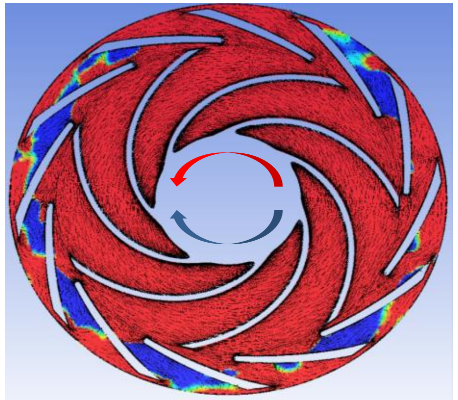


Modified Goodman Diagram

Fluid Dynamics Analysis

Bad Flow increases the variability of the local pressure at the rotor-stator interface.
A flow visualization technique in the CFD post processing was used to highlight the regions of *Bad Flow*.

- Velocity components were broken down into radial and tangential flow.
- *Good Flow* is where the radial velocity is outward from the rotating axis, and tangential flow is in the same direction as rotation.
- Velocity plot legend set such that positive direction velocity is red indicating *Good Flow* and negative direction is blue indicating *Bad Flow*.

Centerline Plane plots of Tangential velocity at 100% BEP flowrate (LEFT) and 10% BEP flowrate (RIGHT).

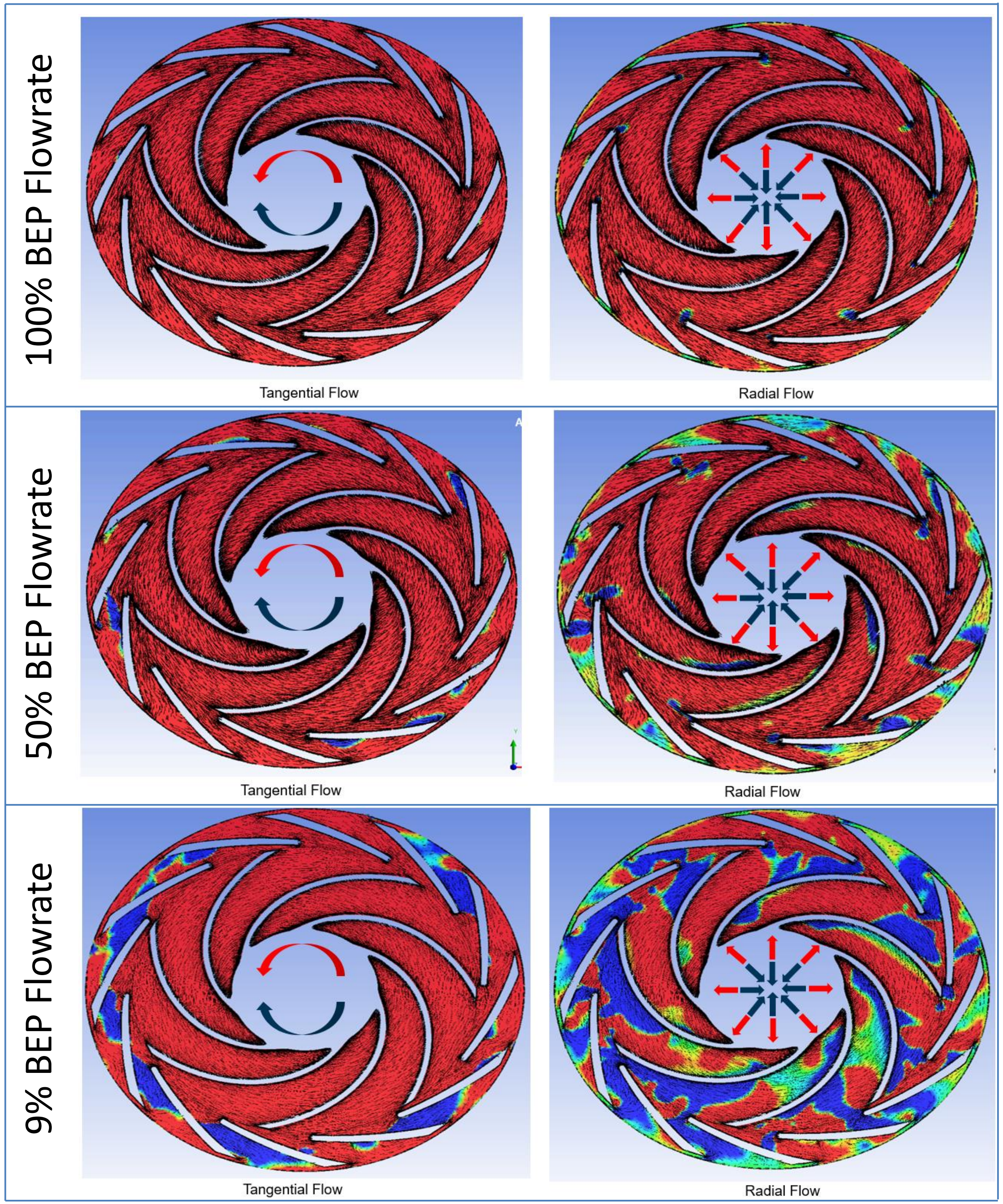
Bad Flow

Velocity plots showing where flow is moving radially inward (right) or in the opposite direction of impeller rotation (left).

The *Bad Flow* is colored **Blue**.

At 100% BEP, nearly all the flow is moving in the proper directions.

At 9% BEP, 9 out of 12 diffusor passages are fully stalled.



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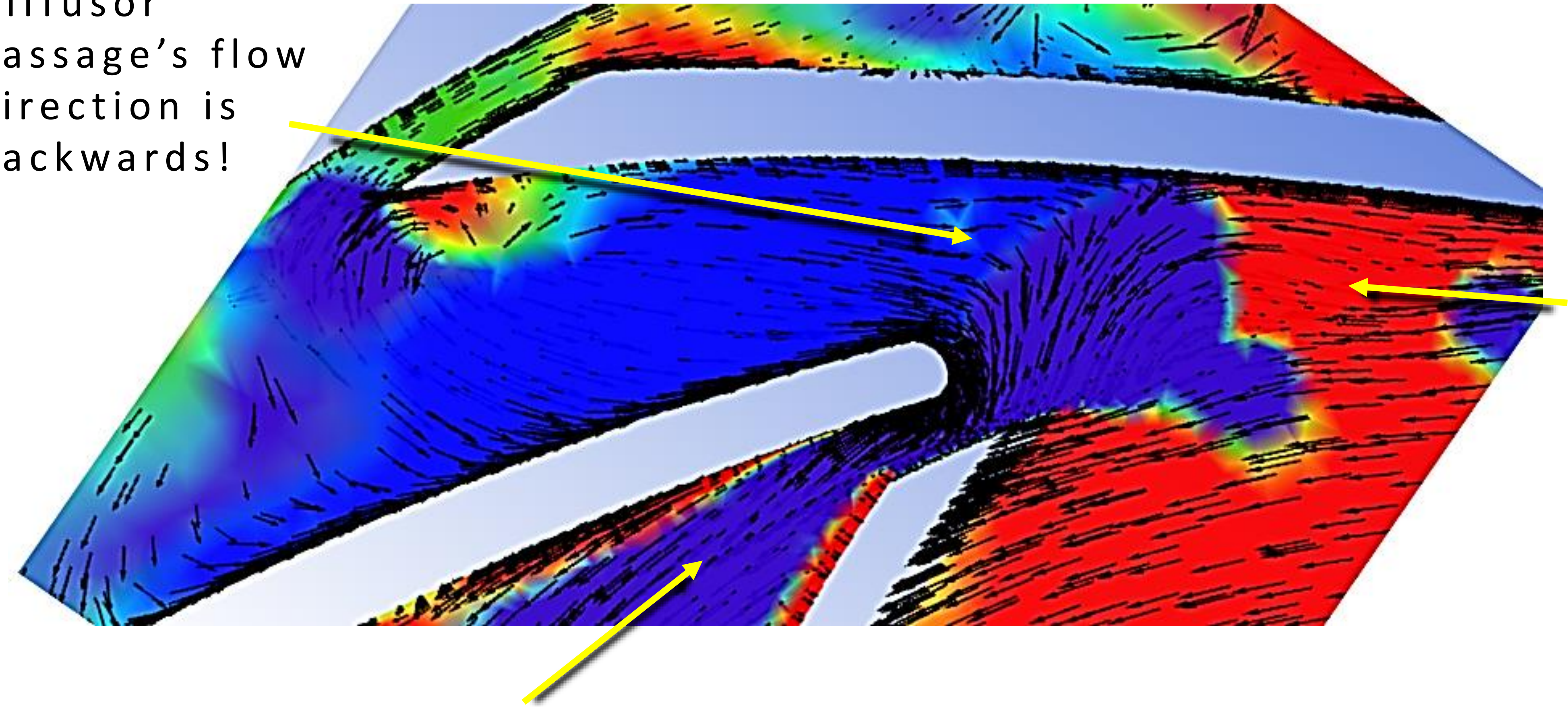
Bad Flow at Rotor-Stator Interface

Diffusor passage's flow direction is backwards!



Flow coming off the impeller cannot enter the diffusor and is forced back into the outlet of the impeller.

Flow entering the impeller's outlet

9% BEP Flowrate

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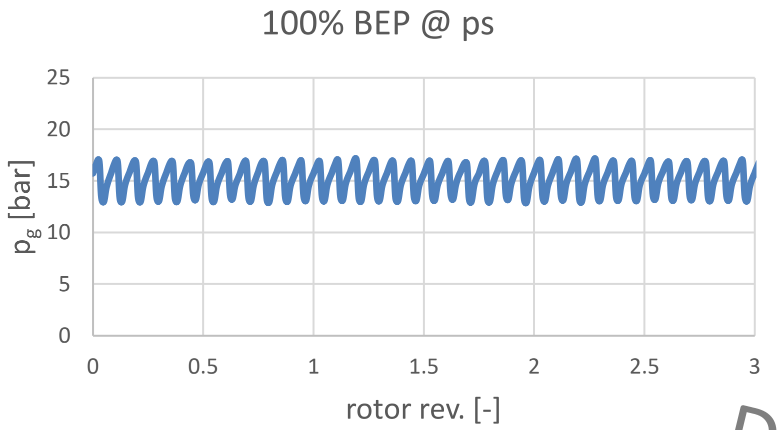
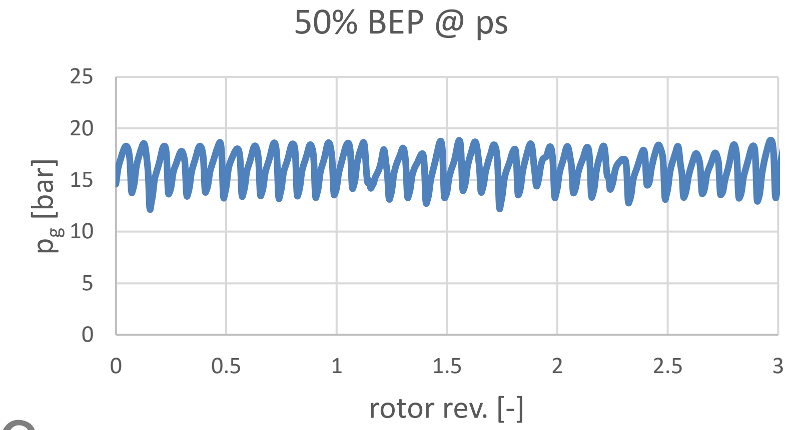
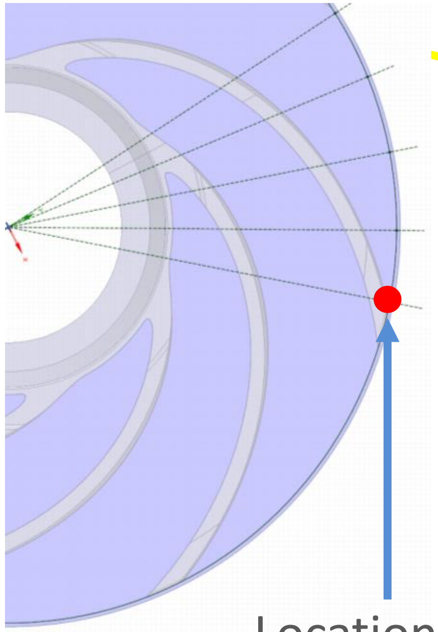
Pressure Data at the Impeller OD

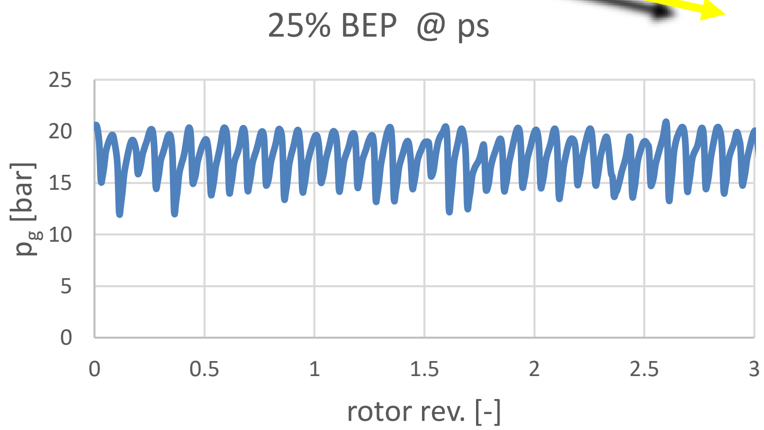






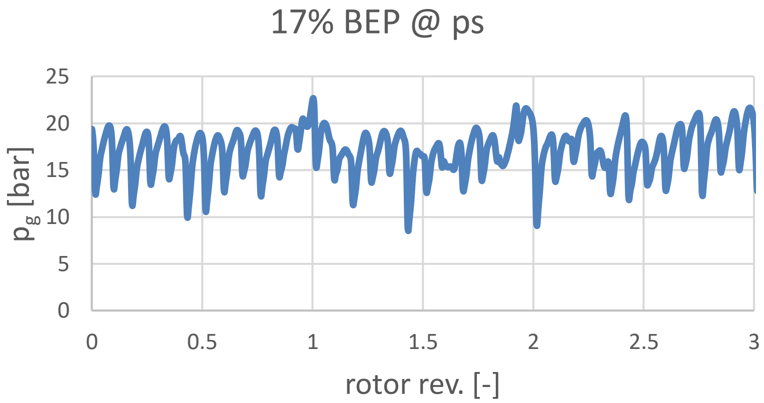
Location: ps

Decreasing Flowrate



A *Monitor Point* in the CFD analysis was used to understand the variability of the instantaneous pressure.

The periodic pressure signal become more erratic as the flowrate decreased.



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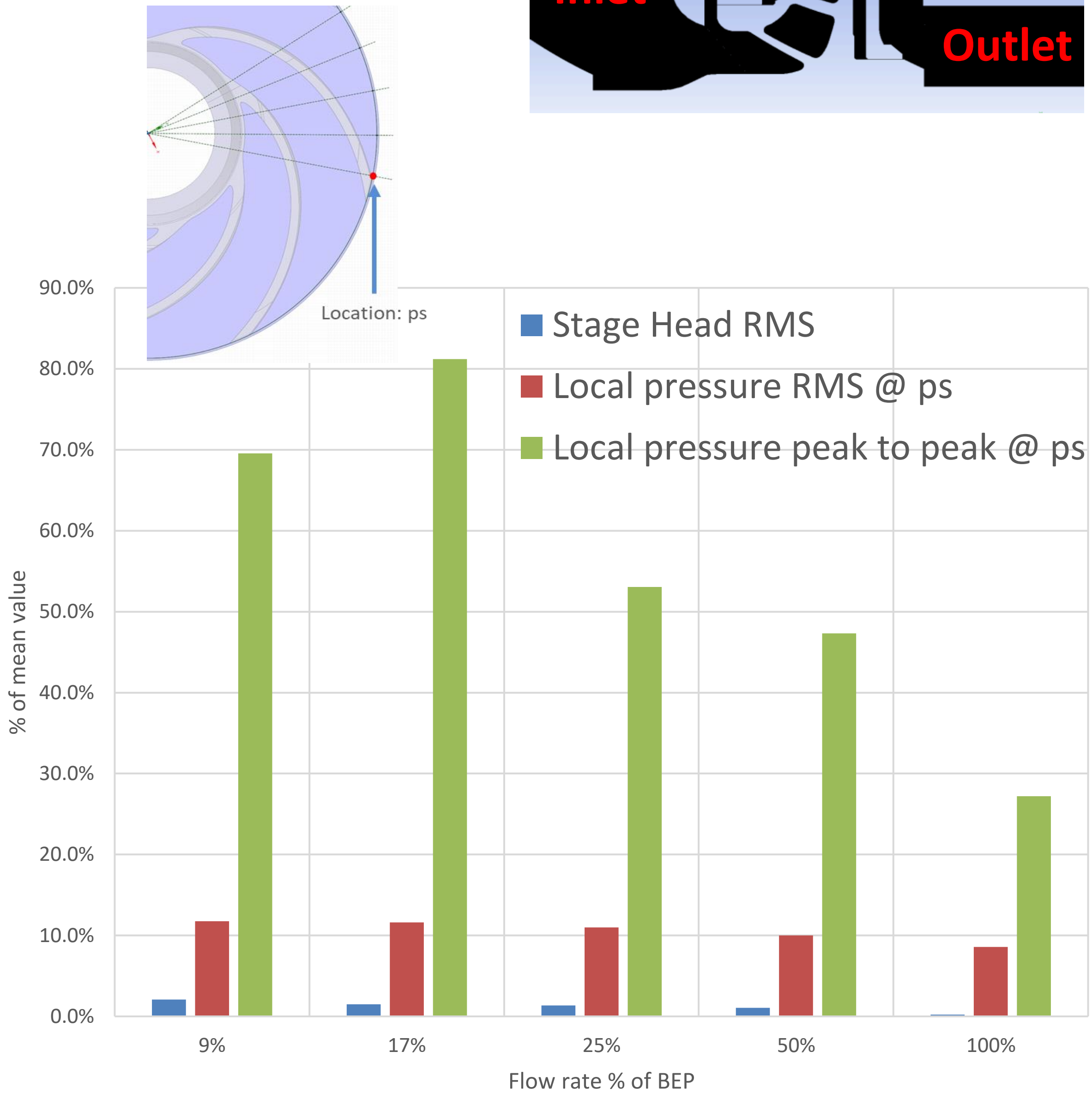
Pressure & Head Analysis

The total differential head across this stage (inlet to outlet) does not produce large fluctuations (< 3%), even at low flowrates.

The variability of the RMS pressure at the *Monitor Point* is generally low as well (< 12%), even at low flows.

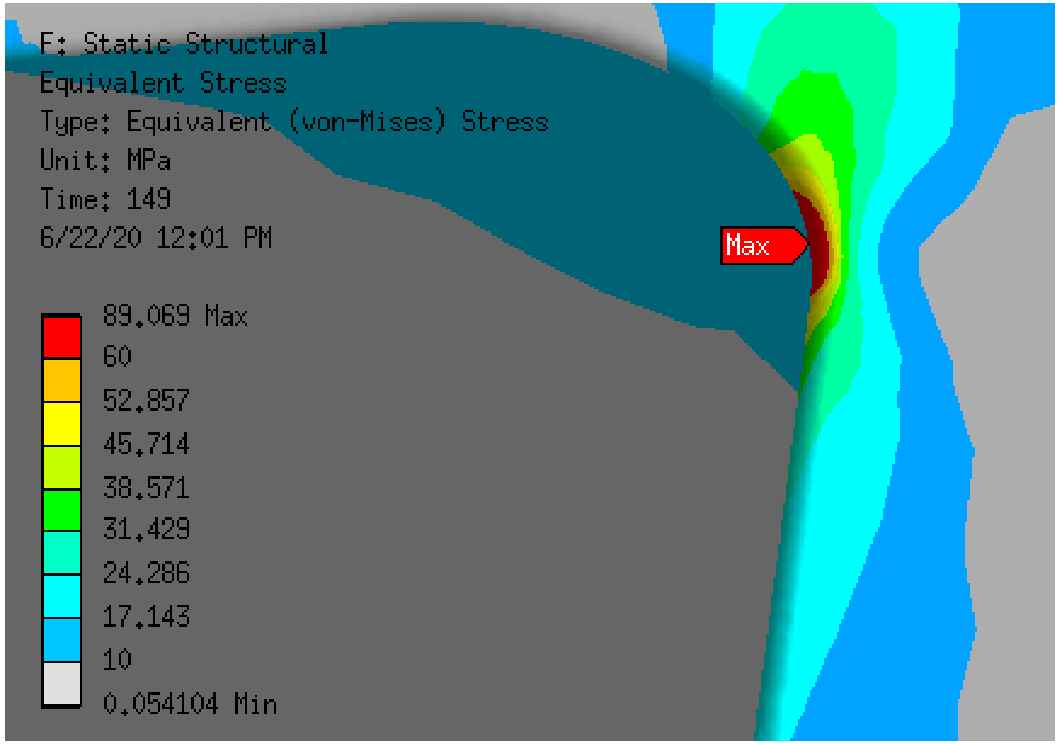
The variability of the instantaneous pressure at the Monitor Point, measured peak-to-peak is quite high (>80%).

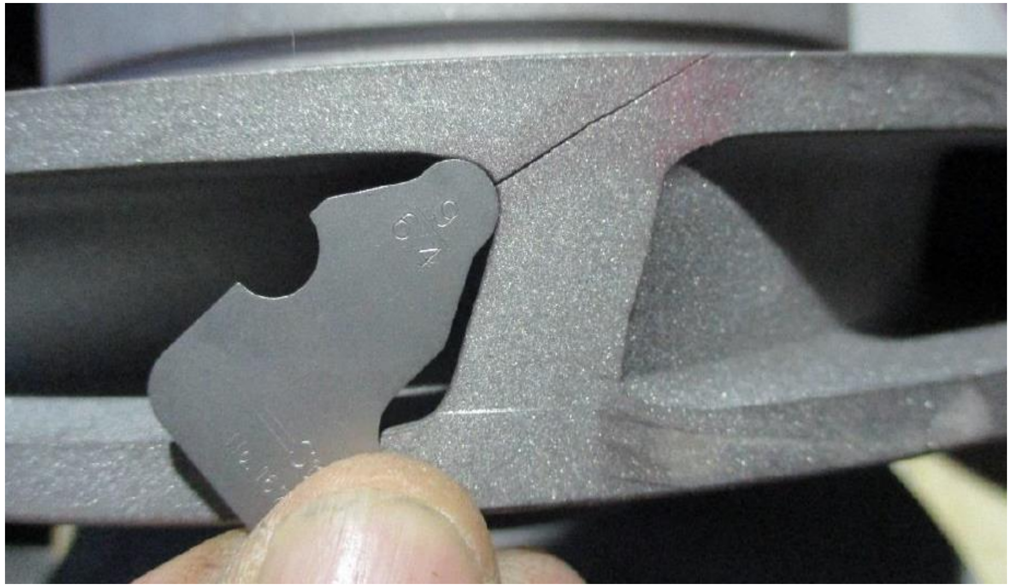
- This occurrence would not be able to be monitored or detected by typical pump instrumentation.

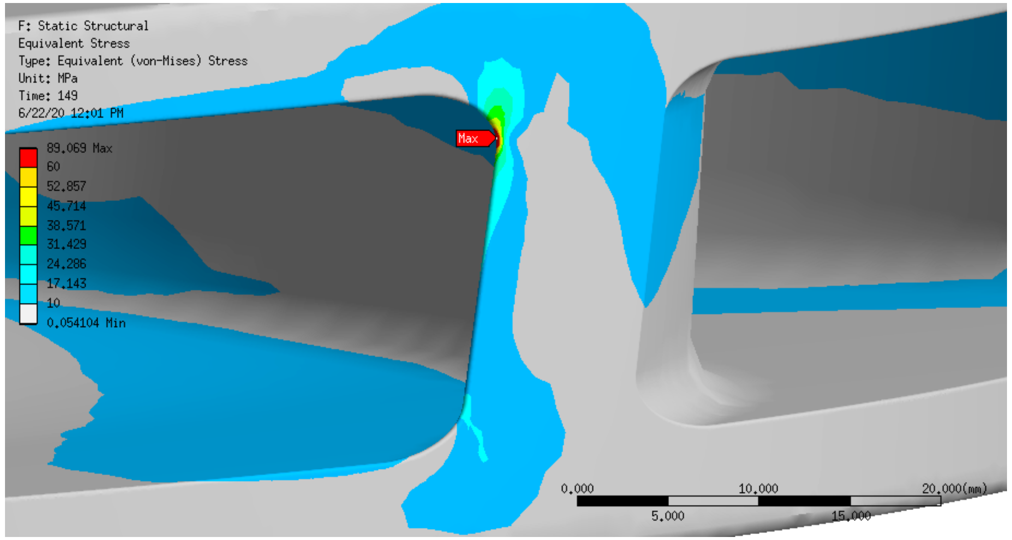


Structural Analysis

Mapping the transient pressure and adding a centrifugal load to the structural FEA revealed a peak stress location which coincides with the likely area of crack initiation.



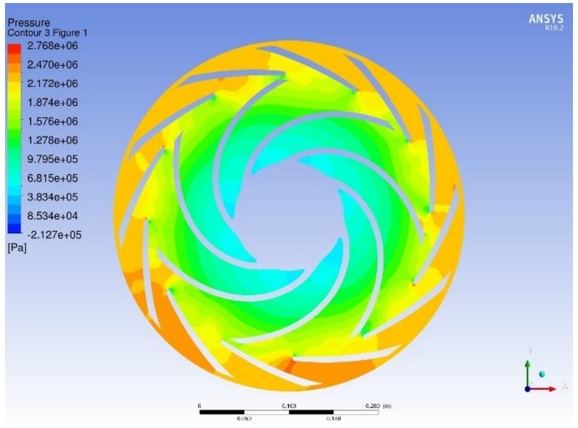


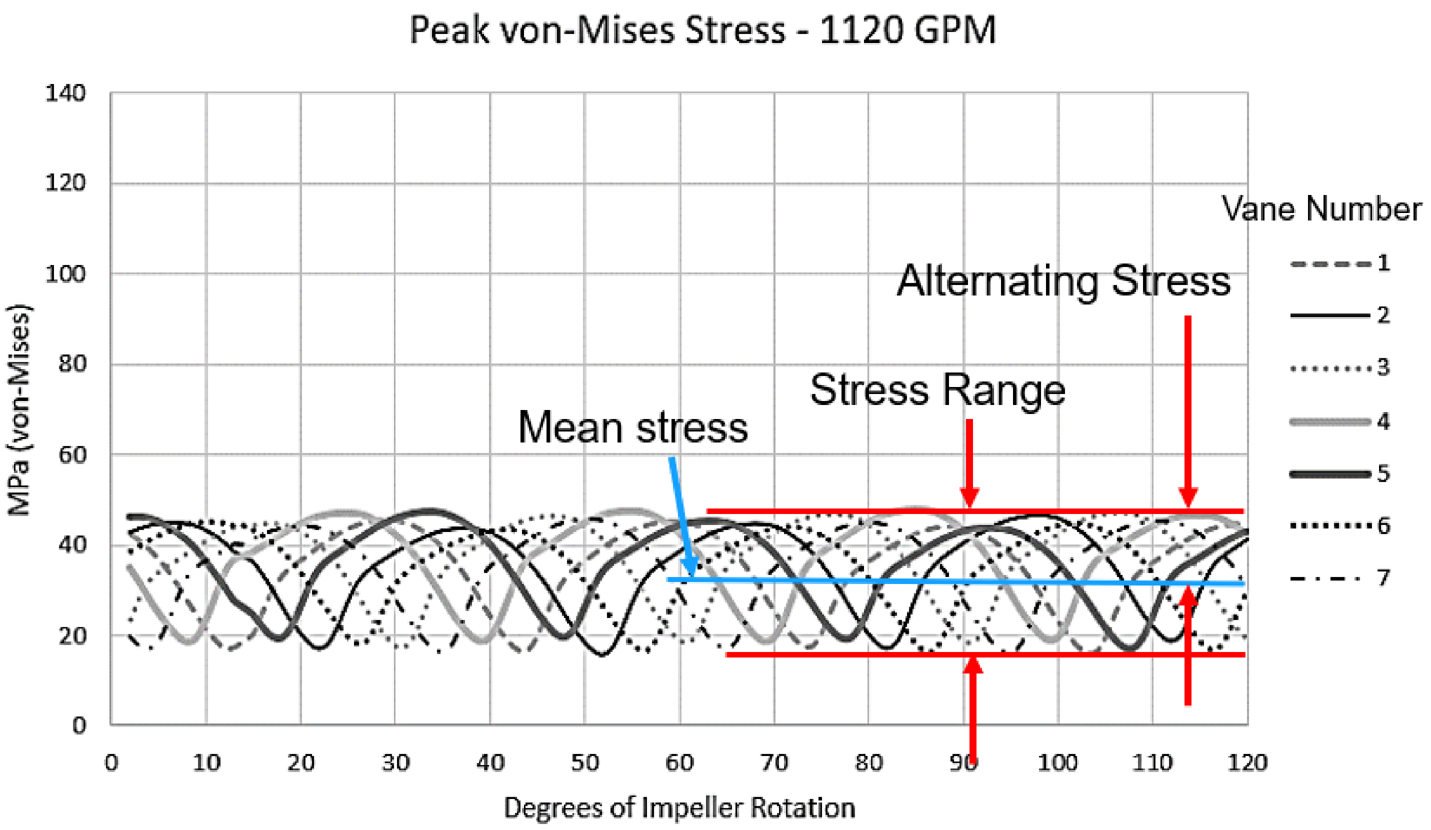


Structural Analysis

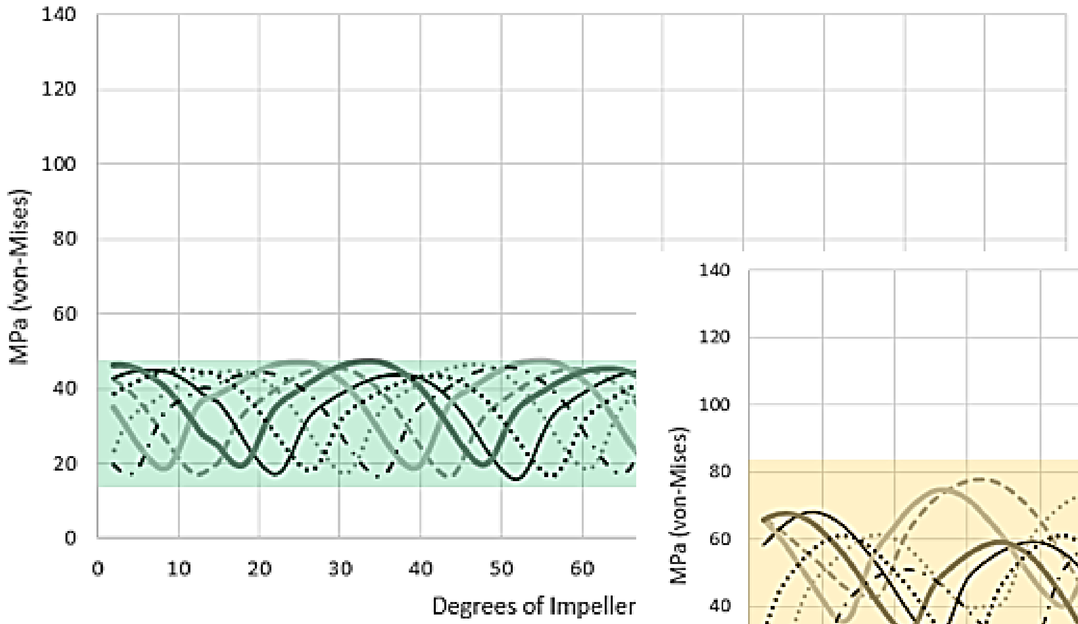
The peak stress for the critical fillet location was plotted at each of the 7 blades for various flowrates.

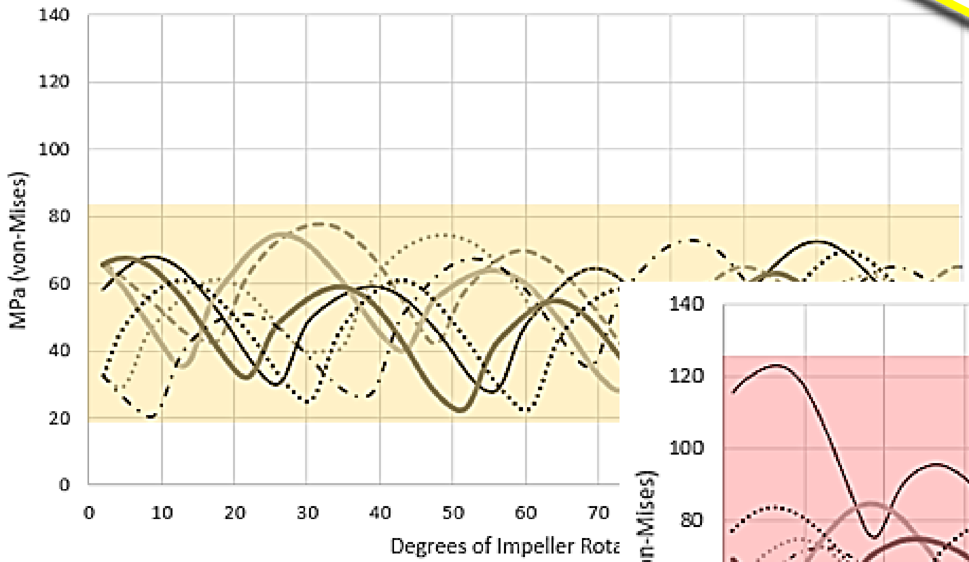
The periodic nature of the stress is a result of an increase in local pressure as the impeller blade rotates past the diffusor vane.



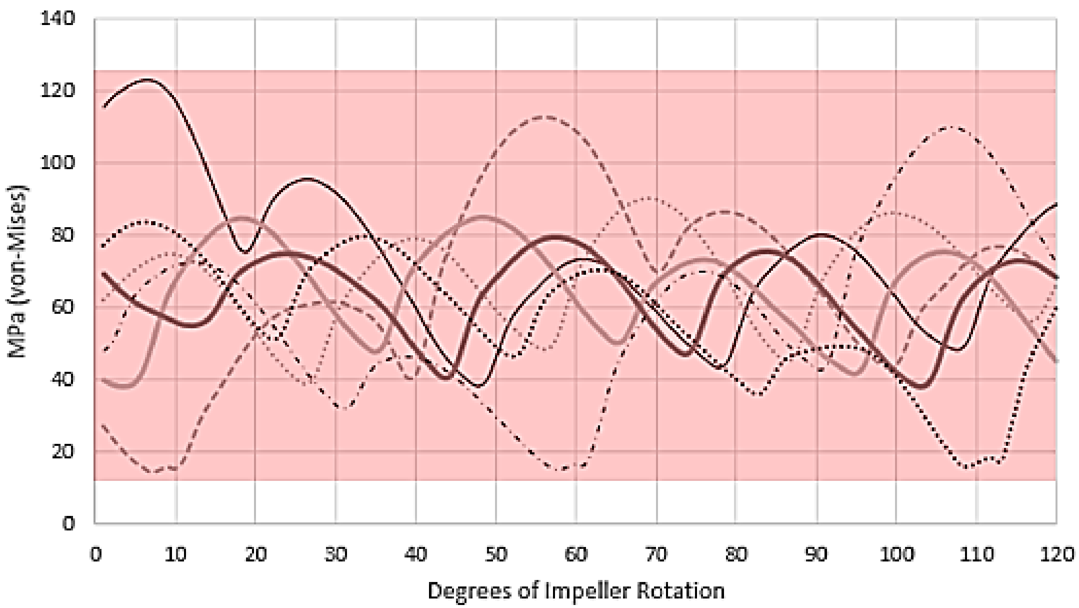


Structural Analysis





Decreasing Flowrate



As flowrate decreases, the stress range increases significantly.

- <u>**4x at 18% BEP vs. 100% BEP!**</u>

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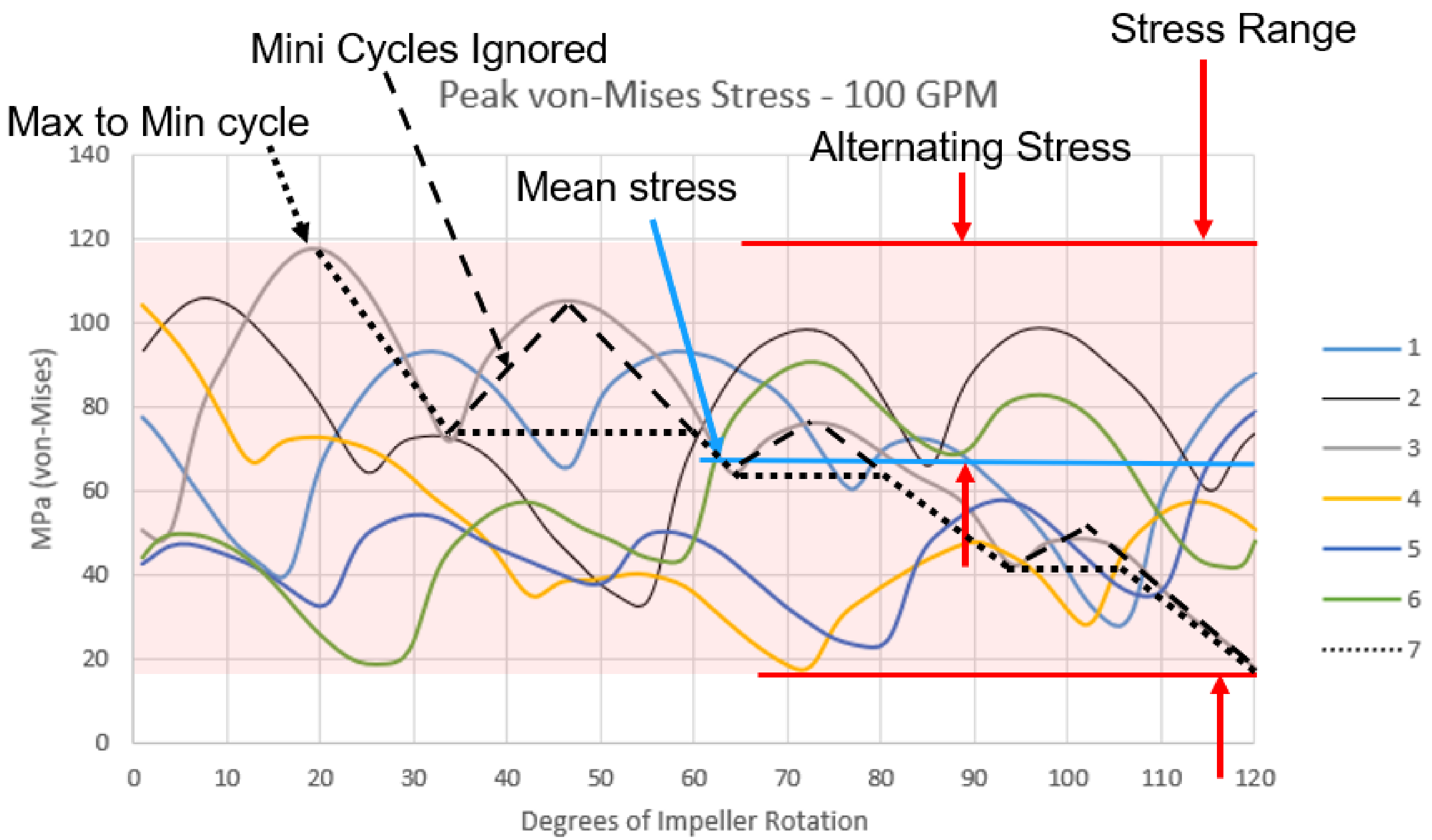
Structural Analysis

Cyclic stresses were extracted from these plots for the purpose of fatigue analysis.

Note: only 120 degrees of rotation was considered due to computational constraints. It is quite possible that higher peak stresses were not captured.

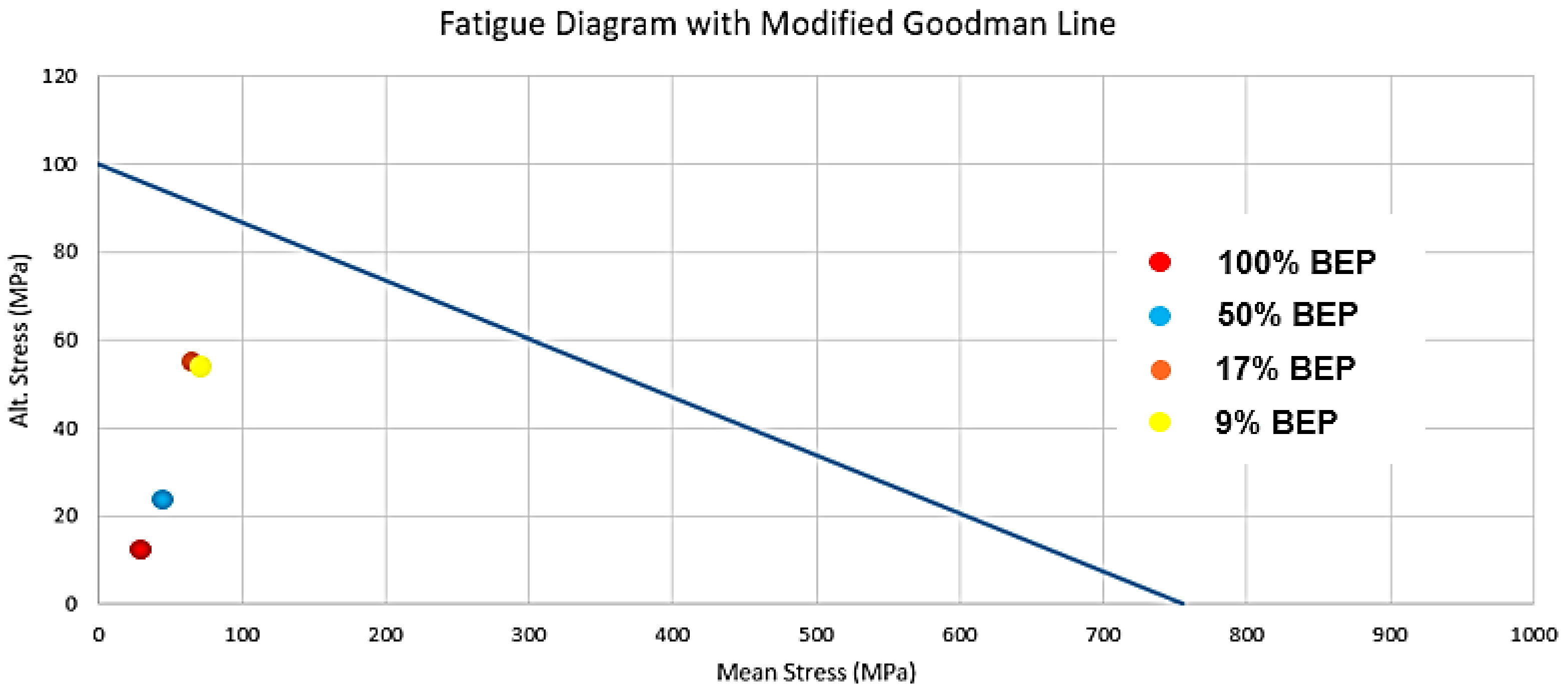


Fatigue Analysis

Cyclic stresses were extracted from these plots for the purpose of fatigue analysis.

Large reduction in factor of safety with respect to *Infinite Life* with decreasing flow.

Material is CA6NM

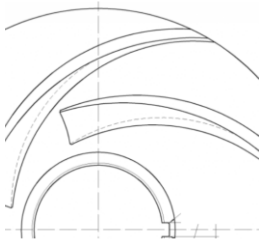


Fatigue Analysis Summary

Although Modified Goodman fatigue analysis technically indicated "infinite fatigue life" for the impeller at low flows, the variability of the many important of inputs means we are not surprised by the result of numerous but not all the seven impeller blade fillets experiencing crack initiation and growth.

Potential sources of error in Fatigue Life Analysis calculations:

- Corrosion effects ignored
- Residual Stresses from casting/quenching
- Stress risers from the fillet being rounded by hand grinding
- Stress risers from underside of fillet being a 'cast surface'
- Fatigue life of cast surface has high scatter
- Pressure data was only sampled for 120 degrees of rotation
- Specified trailing edge fillet value of R=.02mm is created by hand grinding operation and is impossible to apply a precise tolerance to.



Summary

The cracks on the impeller were highly likely to have been caused by the increasing stresses at the critical area when flow was reduced below 20% of the BEP flowrate.

Fatigue life calculations have a high level of uncertainty due to the variability of many of the inputs.

- CFD may not have captured the highest pressure-pulsation the impeller experiences due to the complex nature of simulating chaotic flow.
- The actual geometry of the impeller at the critical location comes from a hand grinding operation and cast surface.

Mitigation efforts to reduce susceptibility to high cycle fatigue are discussed in the subsequent slide.

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Lessons Learned

- The typical reasons for avoiding operation at low flow are generally limited to thermal, vibrational, and cavitation concerns, as well as poor efficiency and difficulties arising from operation on a very flat section of the performance curve.
- This study shows **cyclic fatigue damage can be a concern with respect to OEMs specifying a minimum flowrate**.
- Mitigation efforts with respect to **impeller design** include:
  - Reducing the outer diameter of the impeller in order to increase the gap between the impeller OD and the diffusor ID will reduce the magnitude of the pressure pulsations.
  - Increase the trailing edge fillet radius
  - Improve surface finish in critical area
- Mitigation efforts with respect to **pump operation** include:
  - Do not operate below minimum flow (~ 30% BEP)
  - Reduce motor speed (utilize VFD) to reduce flow.
  - Add an automatic recirculation valve.