



47TH TURBOMACHINERY & 34TH PUMP SYMPOSIA
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GEORGE R. BROWN CONVENTION CENTER

CASE STUDY: Impeller High cycle fatigue failure on a natural gas pipeline compressor following choked flow operation



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Abstract

The impeller of a natural gas pipeline compressor failed at the junction between the blade trailing edge and the hub.

A root cause analysis showed the machine had been operated beyond the compressor map right limit during short periods, in recent unit history (after 60000 hours of operation).

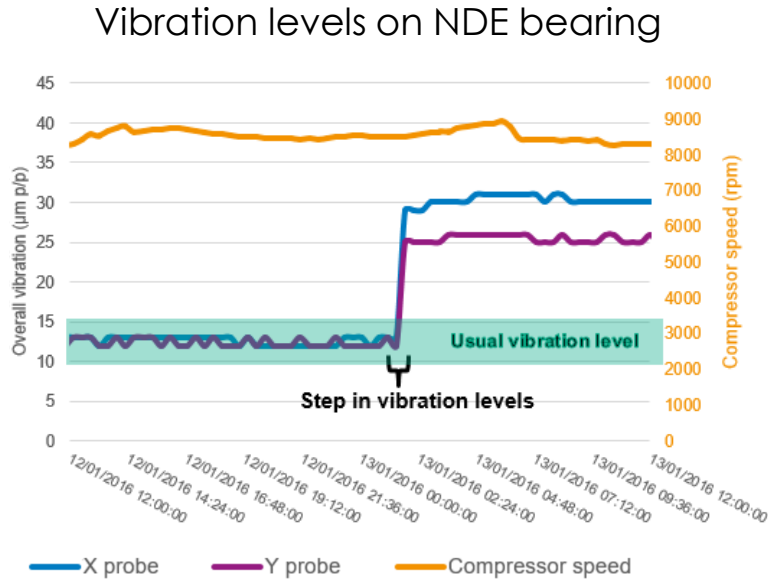
The impeller interference diagram analysis revealed the presence of a potentially critical interference at 100% speed, between an impeller trailing edge mode and an impeller/vaned diffuser aerodynamic synchronous excitation.

The metallurgical analysis and crack investigations confirmed the High Cycle Fatigue failure mode.

A reduced choke flow operational limitation implemented based on unsteady aerodynamic simulation results.



An unexpected step change in compressor vibrations



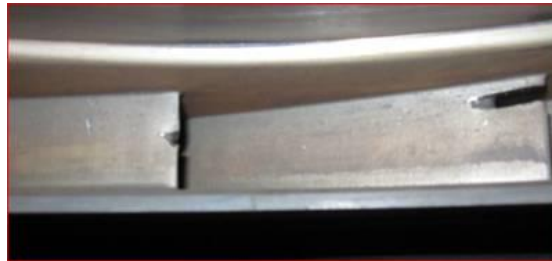
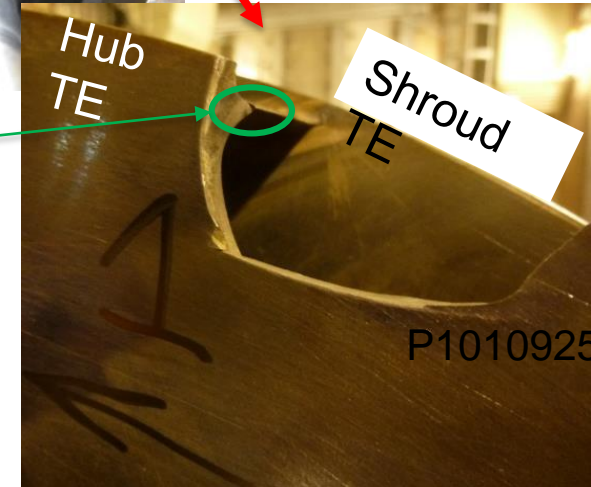
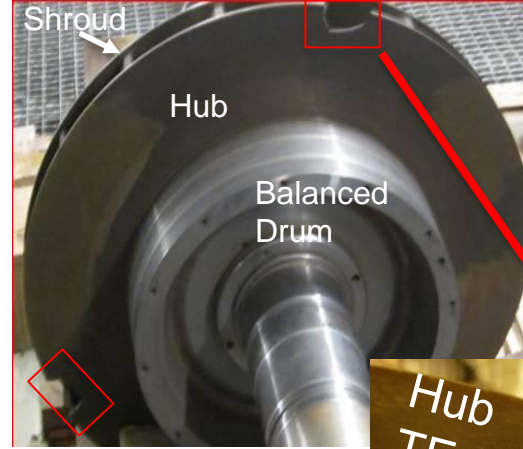
- Vibration levels suddenly multiplied by 2. 7 months later they were multiplied by 3.
- Detected during a periodic vibration analysis, 8 months after step change (alarm levels not reached).
 - Spectrum analysis showed imbalance (1X order).

Machine stopped. Decision to inspect the unit at site.



On site findings

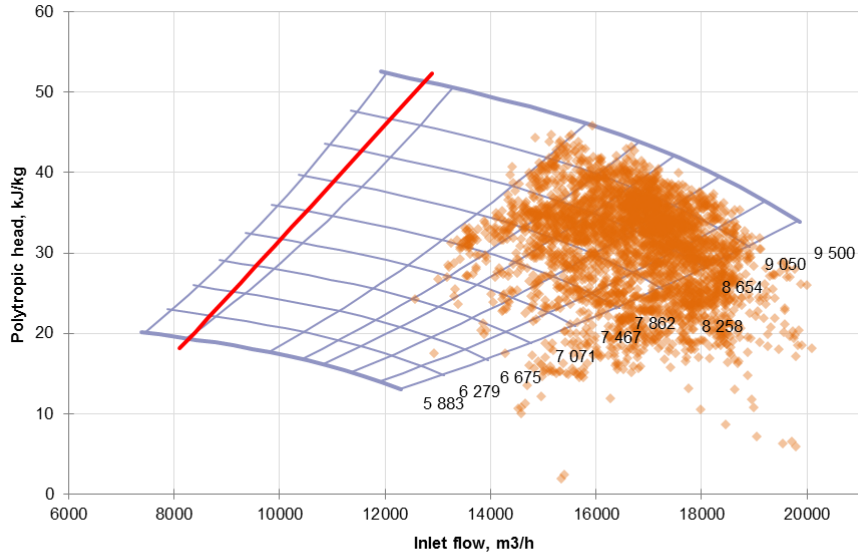
- 2 metal pieces liberated from impeller trailing edge at hub side (single stage rotor)
- Evidence of cracks initiated in the impeller blade tip/hub fillet radius
- Consequential damages at diffuser vane LEs



LE = Leading Edge
TE = Trailing Edge



Operating condition analysis

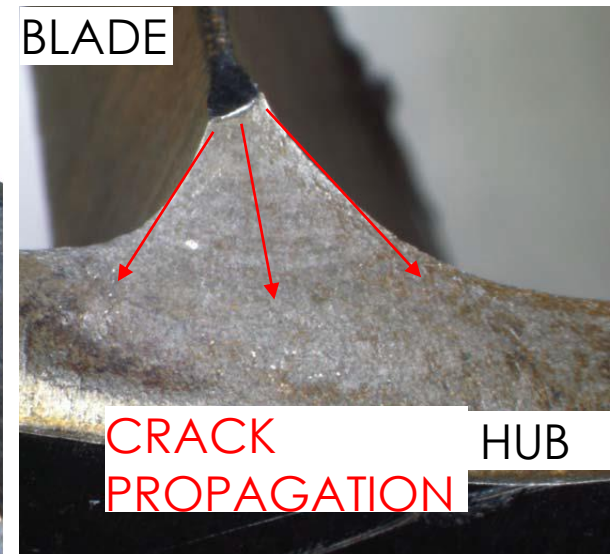
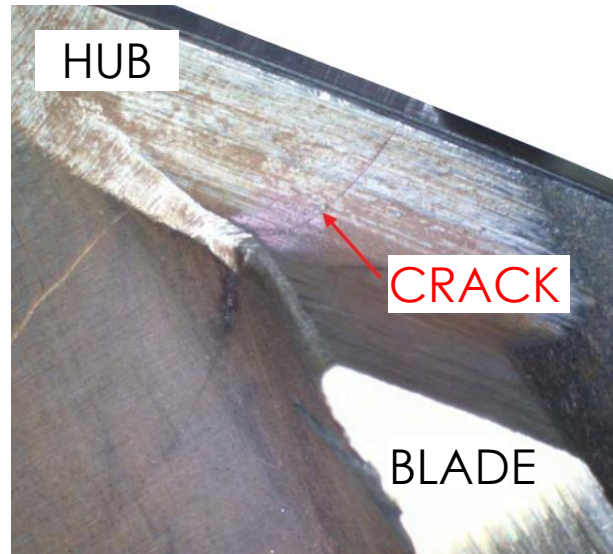
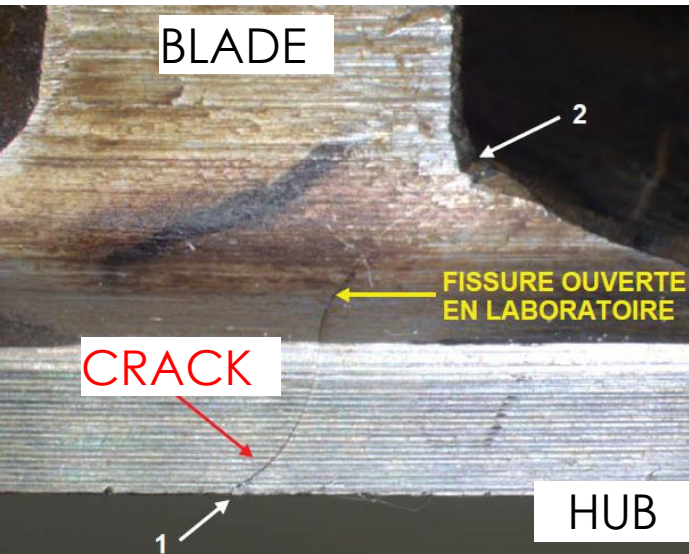


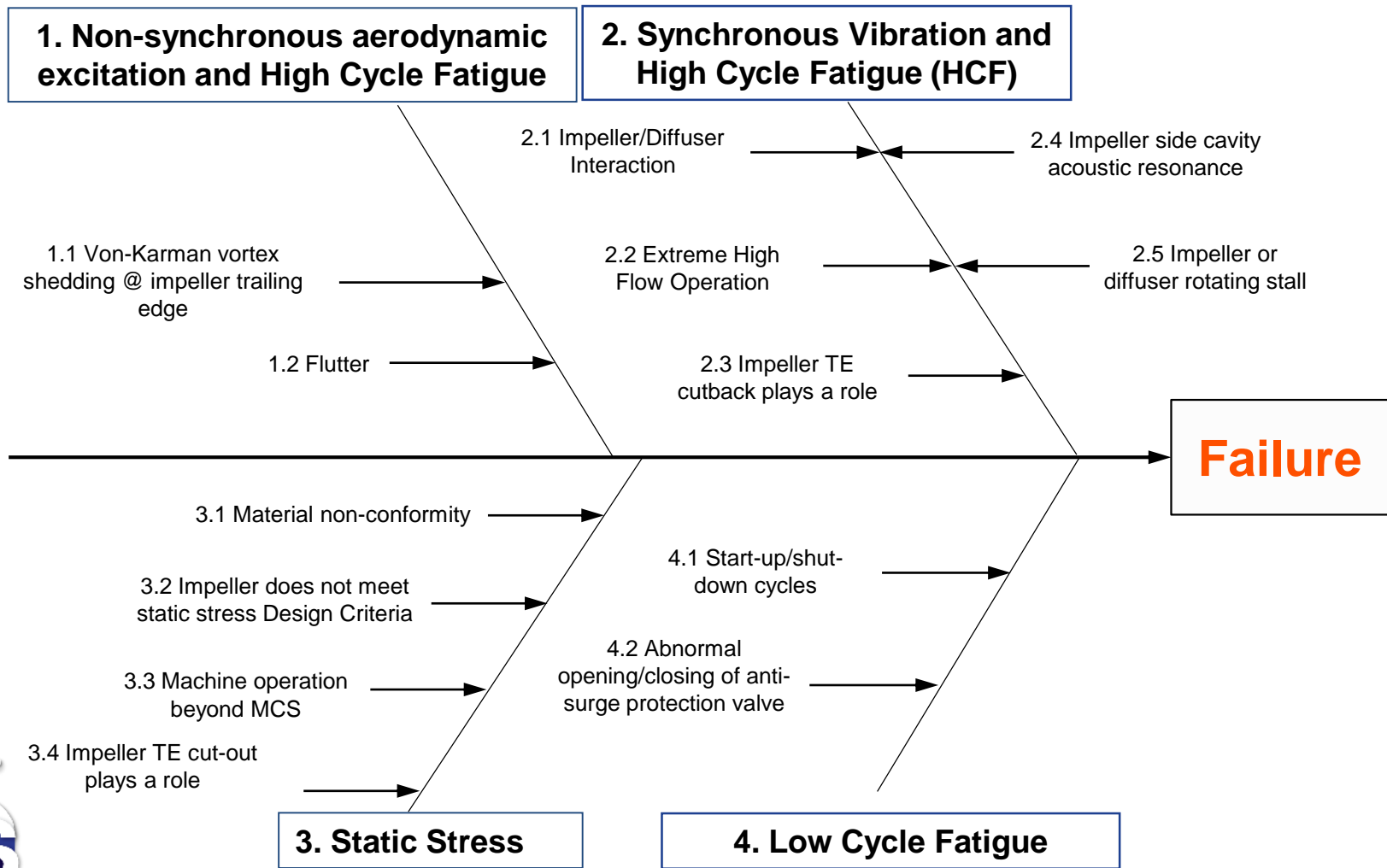
- 1 year of operating data gathered
- Evidence that compressor operation was often beyond defined compressor map right boundary
- Study undertaken by compressor provider to determine if it could be a root cause of the fault



Material analysis

- Cracks found on 4 sectors out of 11 sectors analyzed.
- Cracks fractography are compatible with high cycle fatigue.
- Failure modes related to impeller material, external contamination (corrosion) or wear are ruled out.

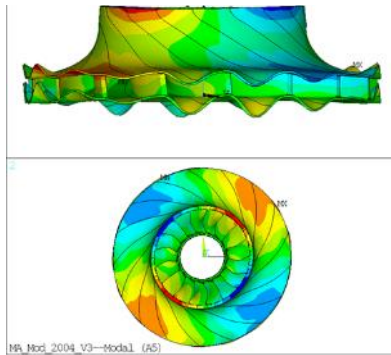




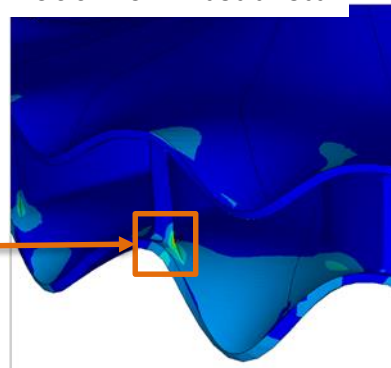
Impeller natural modes and aerodynamic excitations (RCA 2.x)

Crossing at 100% speed between 4.8kHz impeller hub TE mode shape and 32/Rev aero. excitation (vaned diffuser 2nd harmonic)

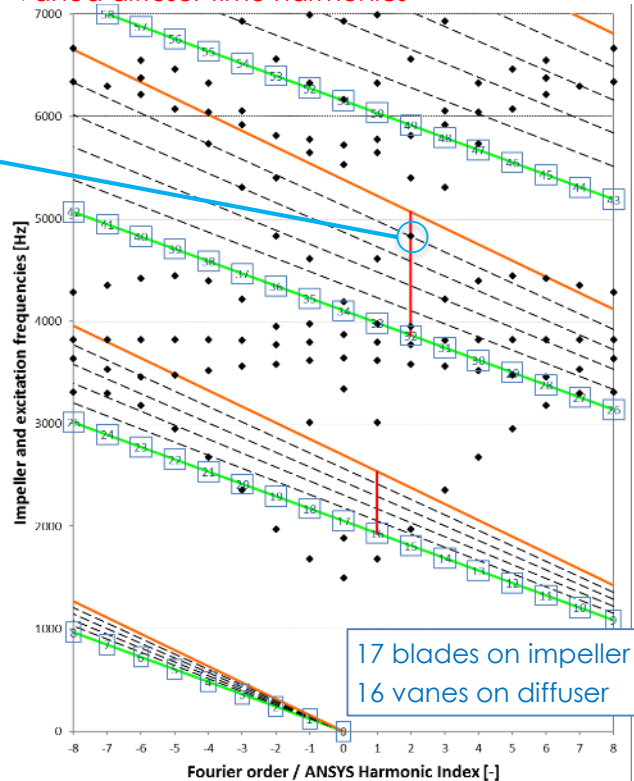
Impeller natural mode shape (2ND + 15ND/17ND at TE)



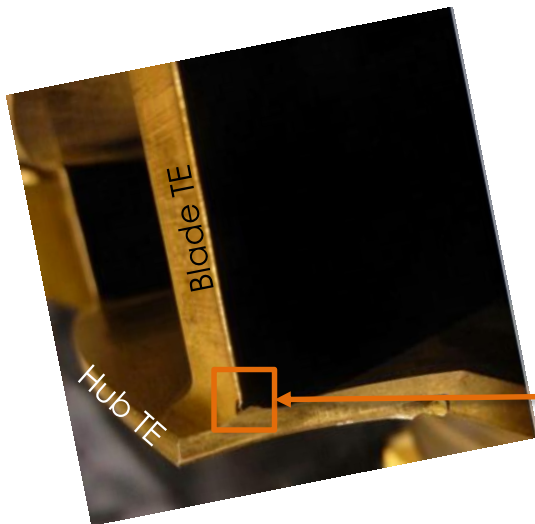
Modal Von Mises stress



Markers : impeller mode shapes
Iso-speed excitation lines : 80% and 105% speed
Vaned diffuser time harmonics

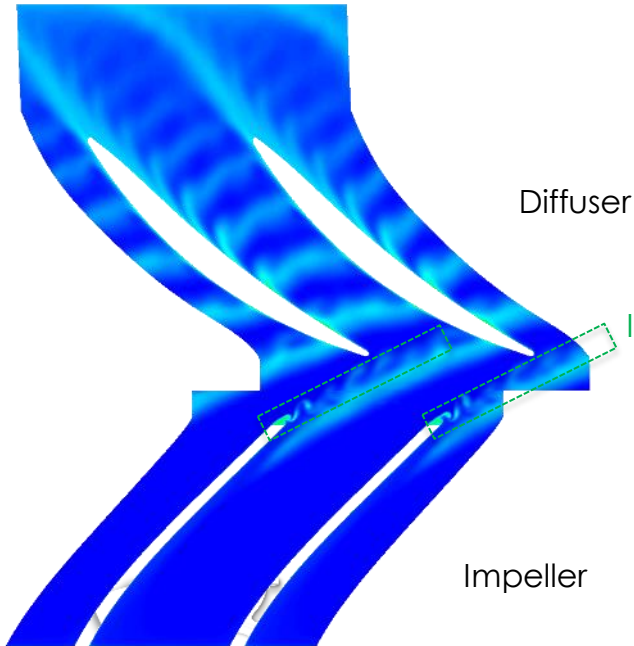


Modal stress field consistent with impeller HCF failure location

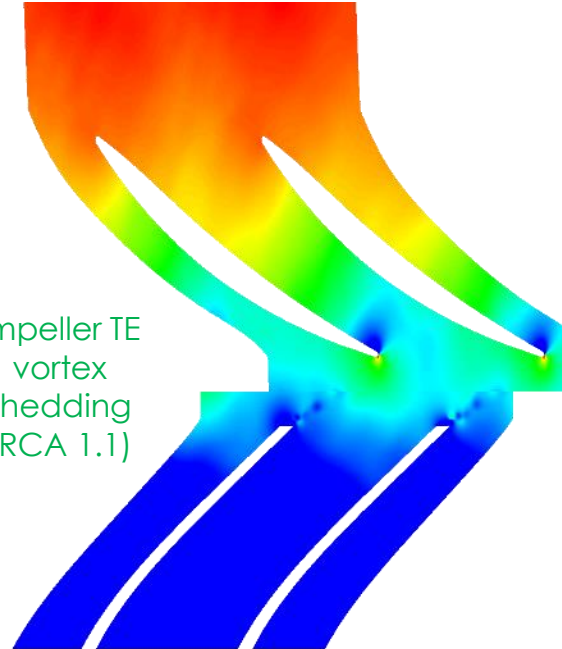


Impeller/vaned diffuser aerodynamic interactions (RCA 1.1, 2.1-2.2)

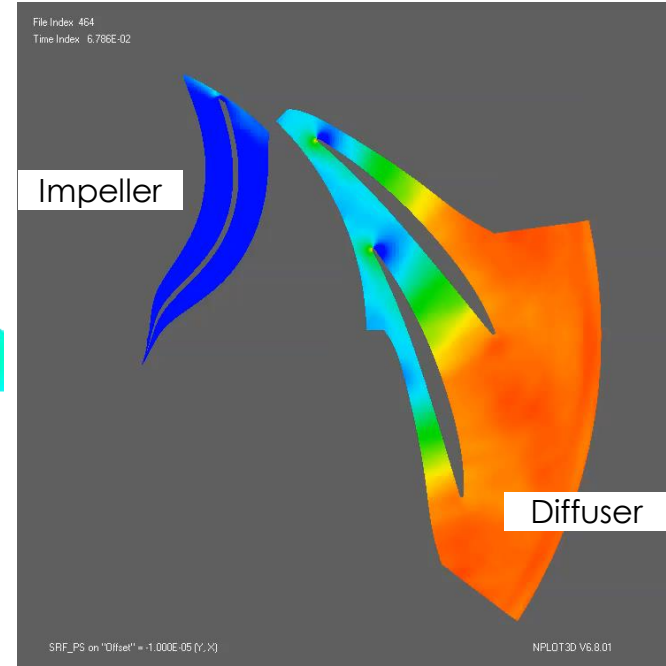
Entropy waves



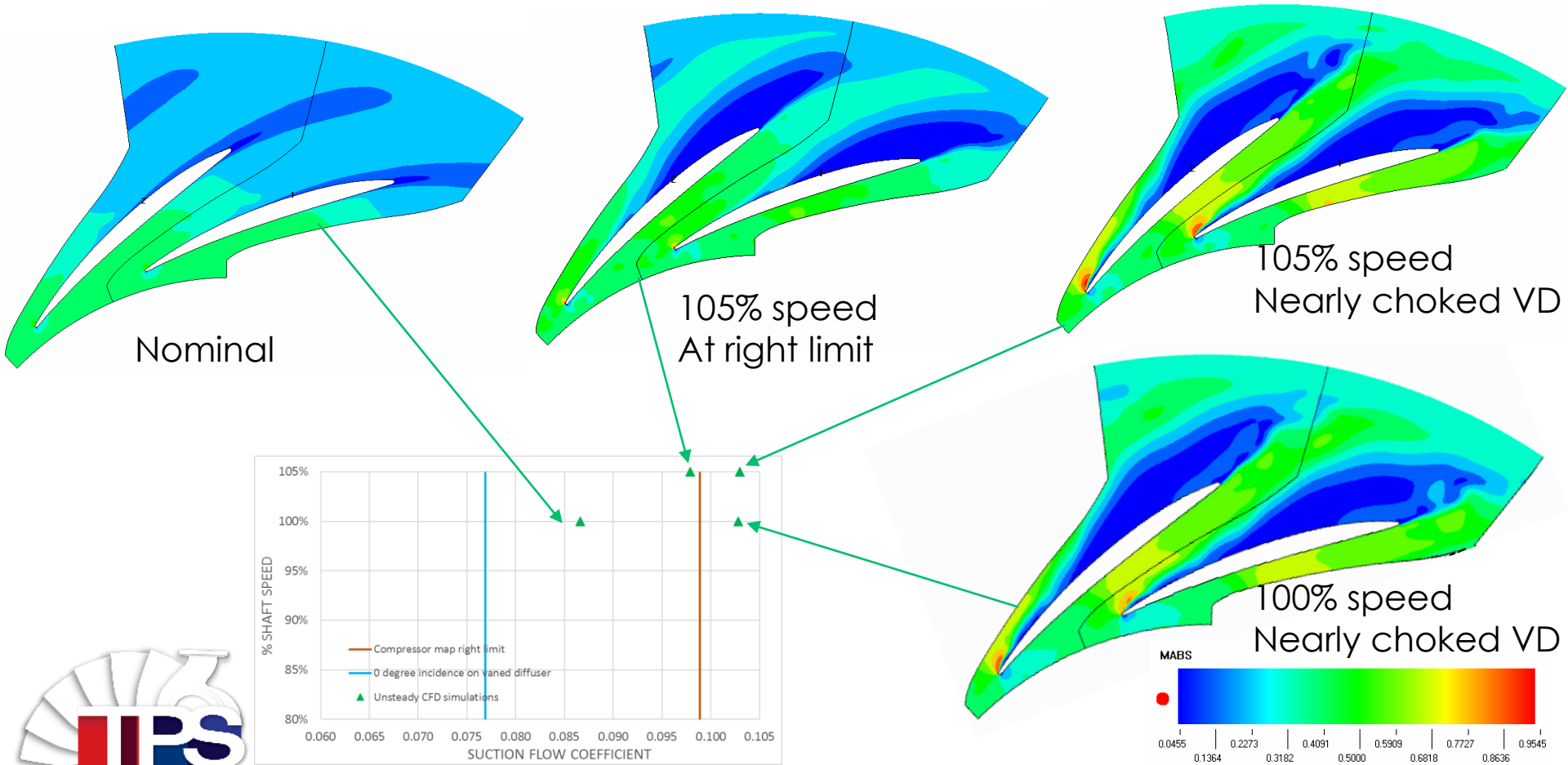
Static pressure



Spinning pressure waves (animation)



Vaned Diffuser (VD) Mach number (RCA 2.2)

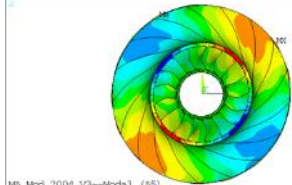
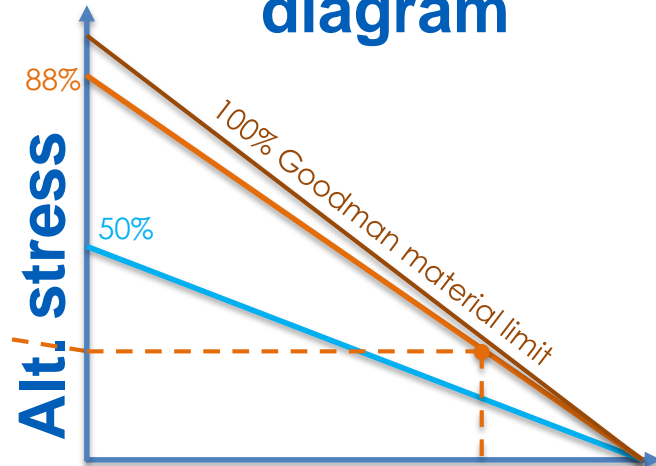
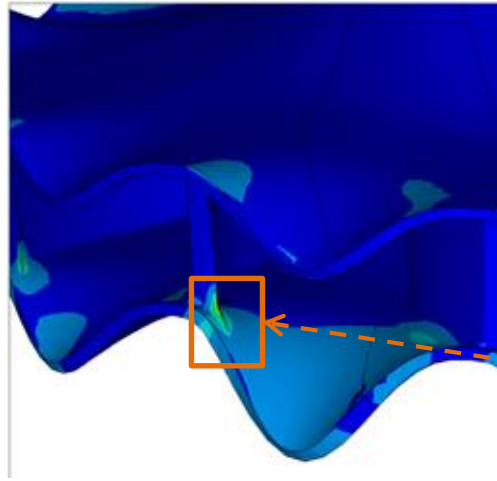
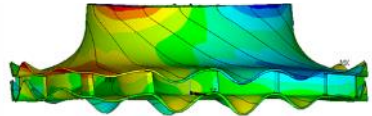


Predicted vibratory resonant response and HCF (RCA 2.1-2.4, 3.4)

Response of 4.8kHz impeller hub TE mode shape to 32/Rev aero. excitation (vaned diffuser 2H)

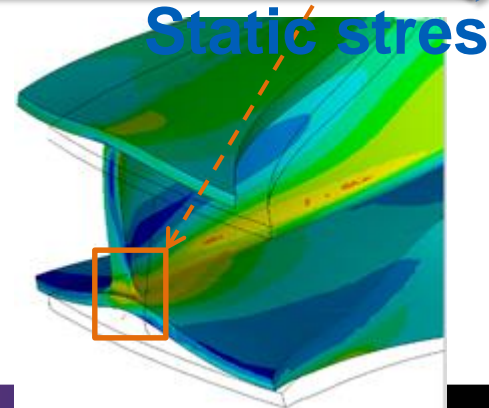
Goodman diagram

Impeller natural mode shape (2ND + 15ND/17ND at TE)



IMA_Misc_2004_V3-Model1 (AS)

| Aerodynamic forcing incl. side cavities acoustic impedances | % Goodman limit (numerical prediction) |
|---|--|
| Nominal | 13% |
| 100% speed, Choked VD | 25% |
| 105% speed(*), map RHS limit | 56% ~ 50% design limit |
| 105% speed(*), Choked VD | 88% > 50% design limit |



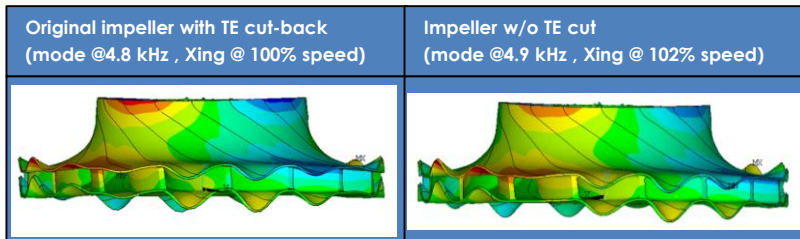
*: impeller resonant response for mode crossing predicted at 100% speed with aerodynamic forcing amplitude predicted at 105% (worse case)
62 operating hours beyond choke line btw 98/102% speed on the 2013-2016 period



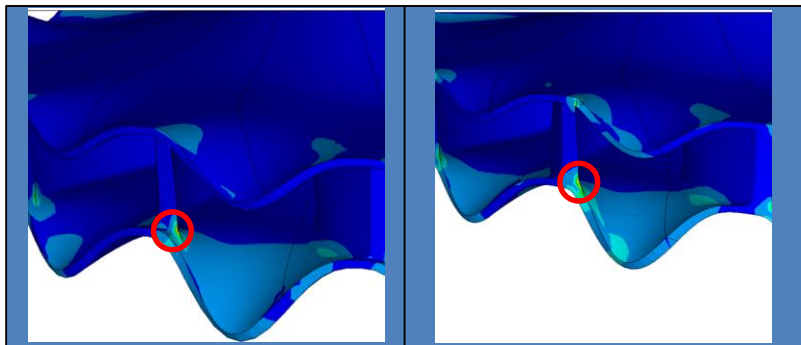
Impeller blade TE(*) cut-back effect (RCA 2.3, 3.4)

Here we compare numerical predictions of static stresses, modal frequencies and forced response simulation of original impeller (with blade TE cut-back) and impeller without TE cut (same hub and shroud TE diameter).

Impeller TE mode shapes excited by vaned diffuser at 32/Rev



Impeller TE modal stresses (O = fatigue critical location)



+20% in hub fillet peak modal stress with blade TE cut-back VS no TE cut

- FEA predictions show higher static stress on impeller without cut VS impeller with cut-back (added mass effect).
- Same TE mode shape and crossings within operating range (100% vs 102%)
- Lower resonant response predicted for impeller without cut VS impeller with TE cut-back (see table below), for identical aerodynamic forcing and aerodynamic damping
- Eventually TE cut-back has a detrimental impact on durability.

Impeller vibratory resonant response (Goodman diagram)

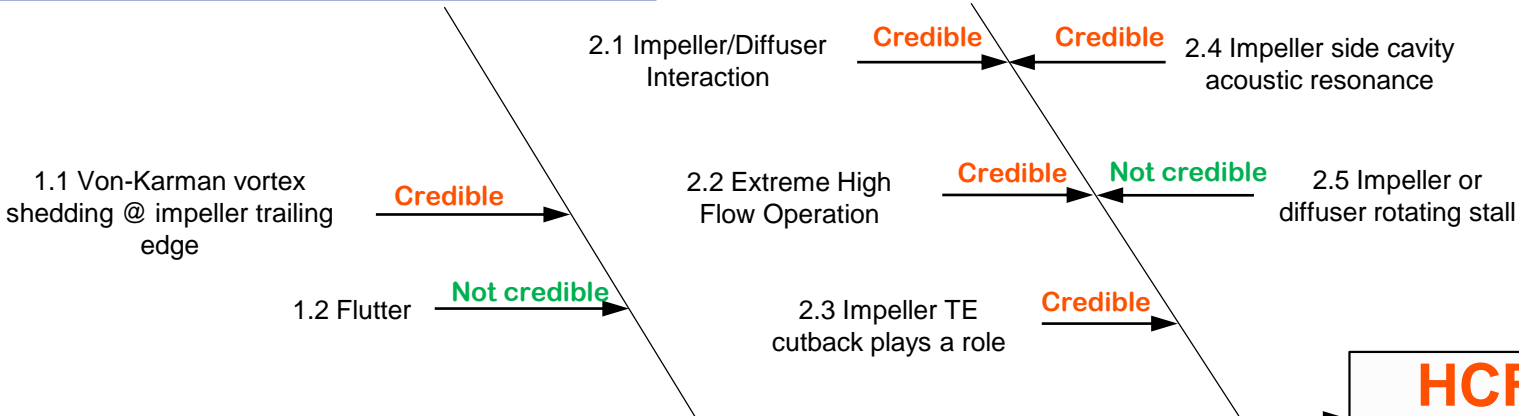
| Impeller TE design | Aero condition (forcing and aero damping) | % Goodman limit |
|------------------------|---|-----------------|
| TE cut-back (baseline) | 105% speed, Nearly choked VD | 88% |
| No TE cut | | 78% |



*: TE = Trailing Edge

1. Non-synchronous aerodynamic excitation and High Cycle Fatigue

2. Synchronous Vibration and High Cycle Fatigue (HCF)



HCF Failure

3.1 Material non-conformity **Not credible**

3.2 Impeller does not meet static stress Design Criteria **Not credible**

3.3 Machine operation beyond MCS **Not credible**

3.4 Impeller TE cut-out plays a role **Not credible**

3. Static Stress

4.1 Start-up/shut-down cycles **Not credible**

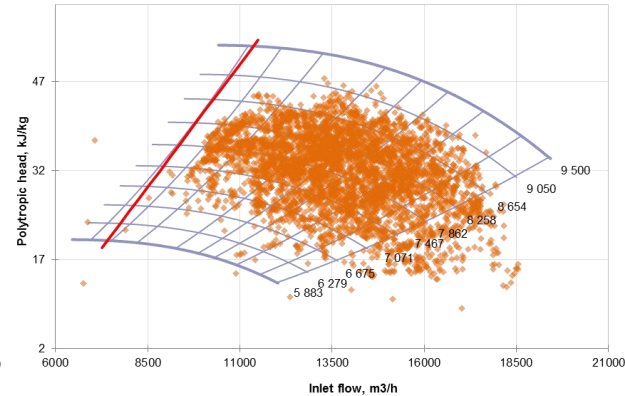
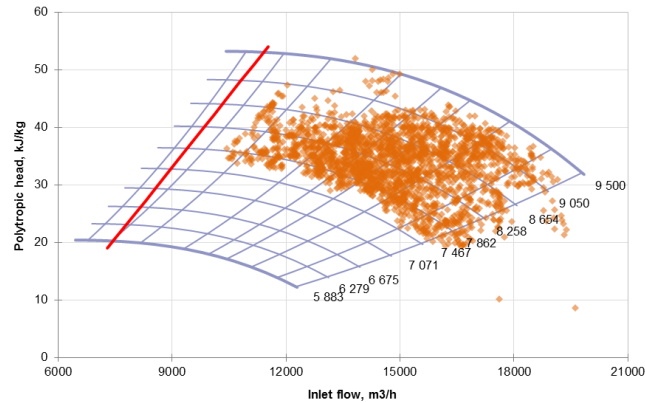
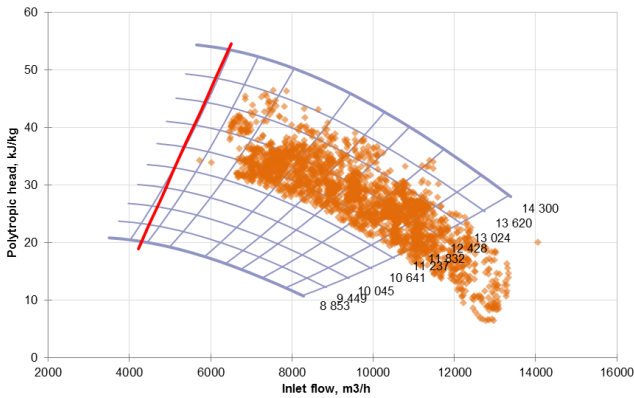
4.2 Abnormal opening/closing of anti-surge protection valve **Not credible**

4. Low Cycle Fatigue

See slide



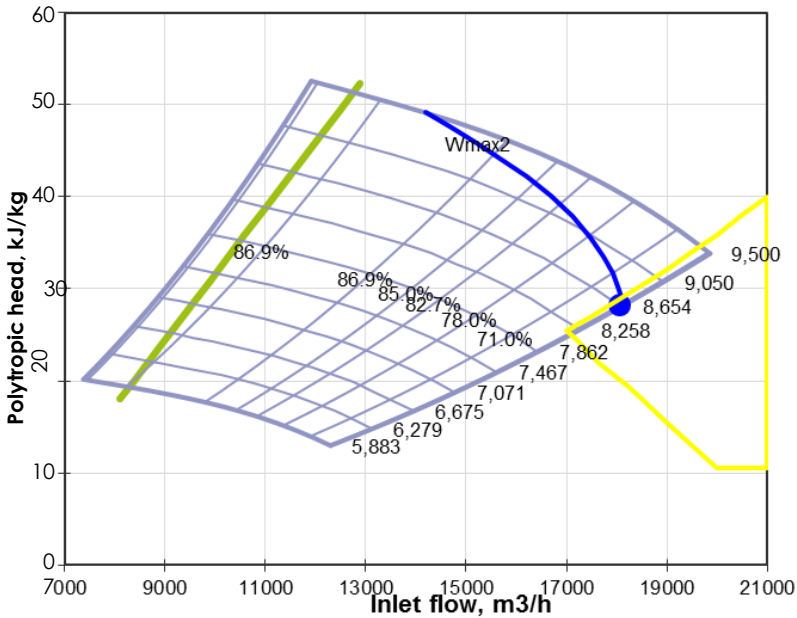
Conservatory measures /1



- Analysis of the other compressors of the fleet running conditions on an extensive period
- Identification of units at risk
 - Vaned diffusers
 - And/or running at high flow, beyond compressor map right limit



Conservatory measures /2



- Choke no-go zone defined with the determined criteria
 - Choke line (flow coefficient = 0,1)
 - Over 90% compressor speed
- Operating point displayed live at national dispatching center
- Monitoring operators warned not to operate in the yellow area.



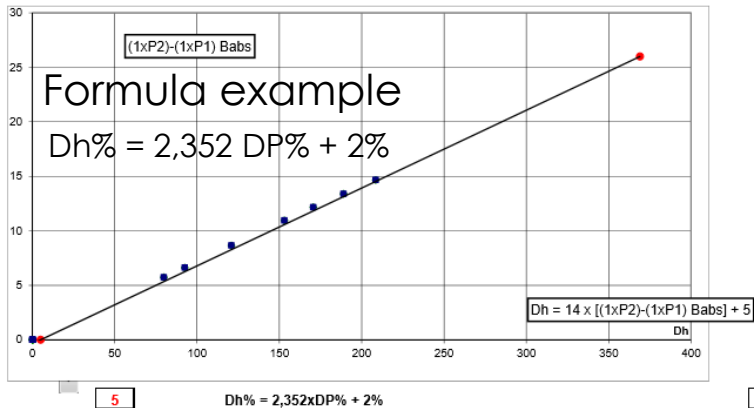
Long term mitigation measures

- Implemented choke flow protection on units at risk (stages equipped with vaned diffusers)
- As the concerned compressors did not run in choke, no major inspection but storage of a spare rotor (common to 4 units)



Anti-choke protection implementation

- Protection line formula, based on flow DP and compression height (same principle as a surge line with a flow DP sensor with a larger range)
- Active within 90%-105% range of compressor speed
- Online alarm if operating point stays in chock zone >60s



- Gas turbine and compressor provider common work
- Protection set on 4 units
- Total cumulated operating time with protection implemented : 12 000 hours

Summary and conclusion

- Centrifugal compressor wheel trailing edge failure after 60k hours of operation
- Site data analysis, CFD simulation and metallurgical analysis, consistently pointed out an HFC failure related to running in choke
- The failure mode was identified to be an impeller aerodynamic excitation of one of the impeller natural mode at 100% rotating speed, due to impeller/vaned diffuser interactions.
- The close cooperation between the OEM and the end user results in successful analysis and mitigation measures implementation





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Backup slides



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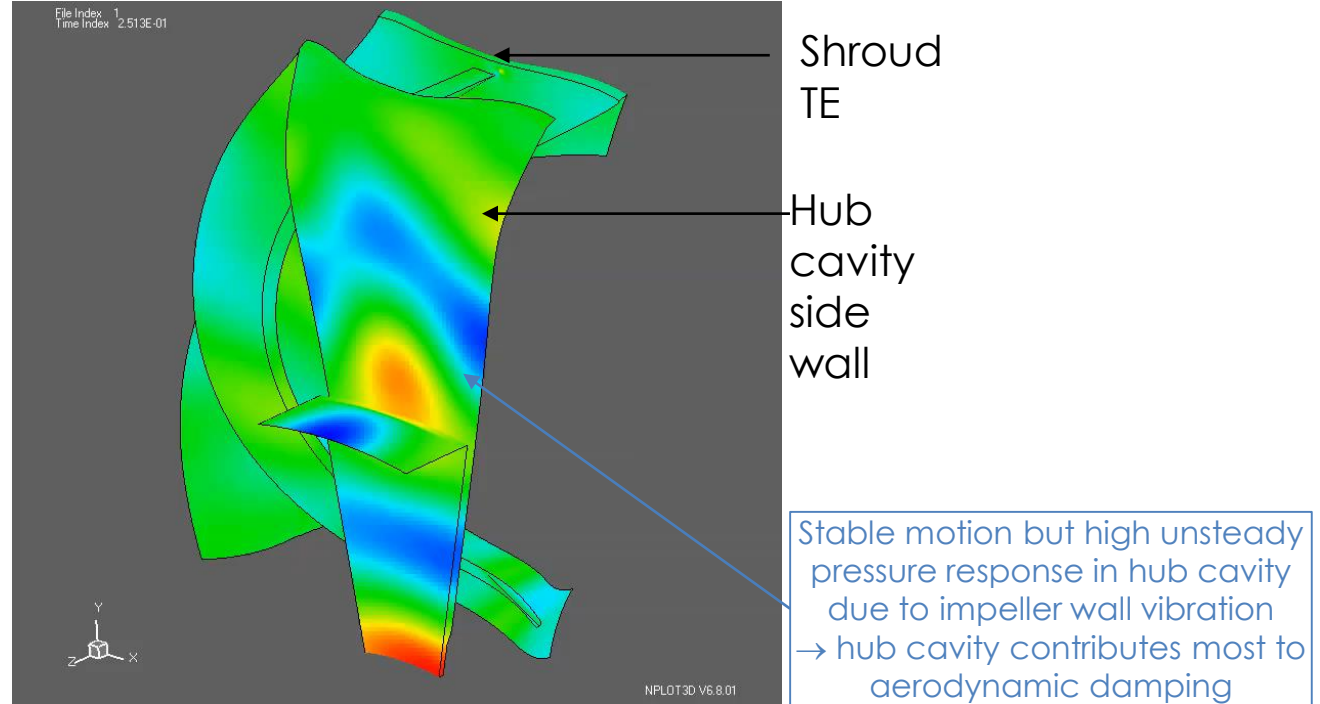
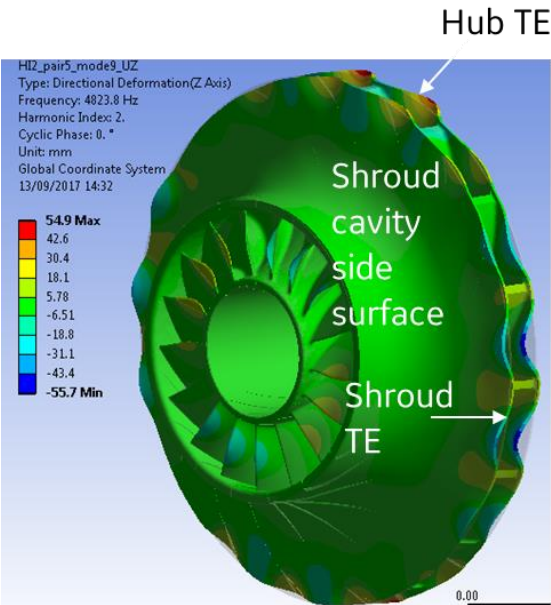


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Flutter (RCA 1.2) and aerodynamic damping (RCA 2.4)

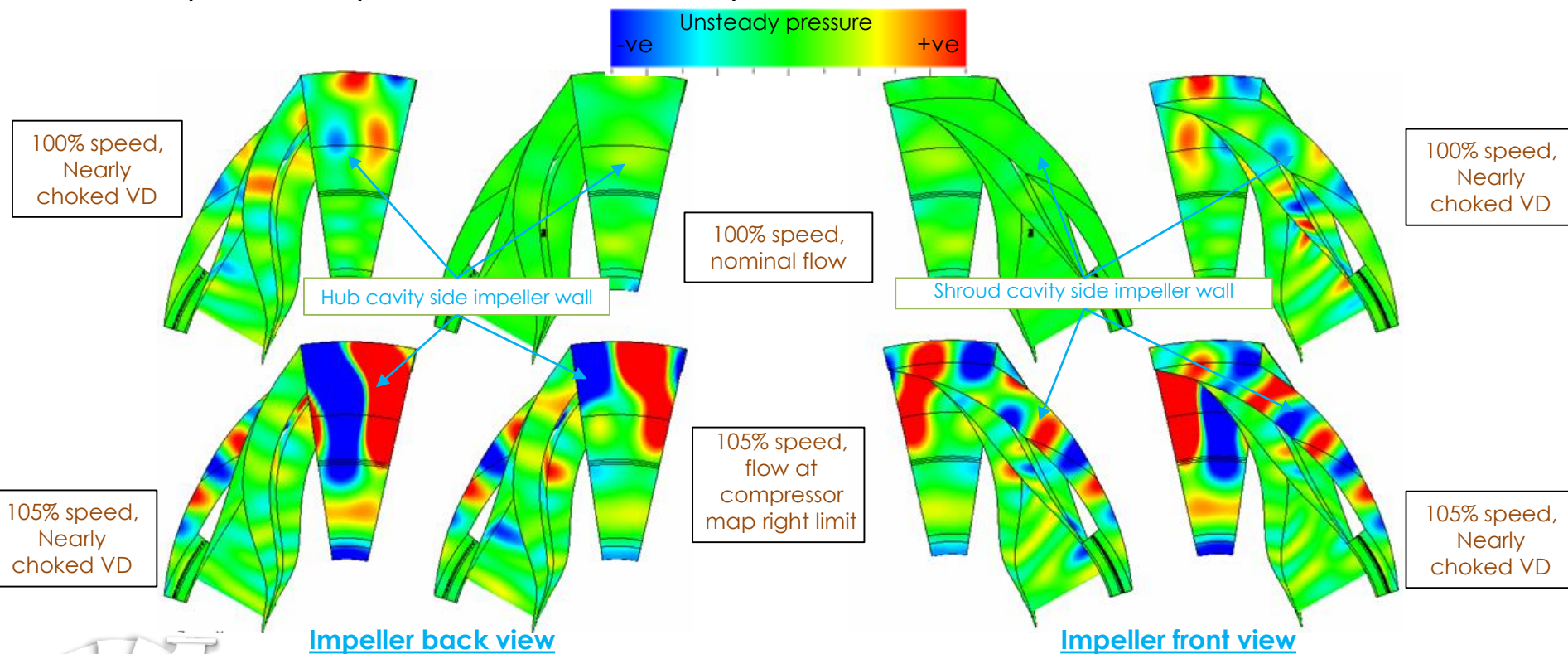
Unsteady flow response to impeller wall vibration under impeller mechanical resonance

Impeller natural mode



Click on figure to animate

Aerodynamic forcing (RCA 2.1) and acoustic resonance (2.4) 32/Rev pressure perturbations on impeller walls as a function of OP condition



4X in aerodynamic forcing amplitude from nominal operating point to choke flow and 105% speed, due to increased vaned diffuser circumferential flow distortion and high unsteady pressure responses in hub and shroud cavities (acoustic resonances)



Closure statements for other RCA elements

| | Method | Evidence |
|--|--|--|
| 1.2 Flutter | Unsteady CFD simulation to predict response of unsteady flow due to impeller wall vibration in resonance condition (no aerodynamic excitation) | No aeroelastic instability predicted for suspected impeller natural mode (sign of aerodynamic work and damping showing inherently stable vibratory motion) |
| 3.1 Material non-conformity | Failed impeller analyzed by an independent material laboratory | Failure modes related to impeller material, external contamination (corrosion) or wear are ruled out. |
| 3.2 Impeller does not meet static stress Design Criteria 3.4 Impeller TE cut-out plays a role | FEA static stress calculations at impeller over-speed (IOS) and in post-IOS/MCS operating condition | Acceptable static stress level at location of the failure (hub trailing edge) Peak static stress is at junction between blade and shroud. |
| 3.3 Machine operation beyond MCS | Analysis of customer site data prior to failure | No operating point beyond MCS |
| 4.1 Start-up/shut-down cycles | Analysis of customer site data prior to failure | At time of failure, number of cycles is <1000, since machine commissioning. |
| 4.2 Abnormal opening/closing of anti-surge protection valve | Analysis of customer site data prior to failure | Normal operation of ASV system (valve and control logics) |



CFD: Computational Fluid Dynamics
 FEA: Finite Element Analysis
 MCS: Maximum Continuous Speed
 ASV: Anti Surge Valve