Large Vibrations on Centrifugal Compressor Caused by Inappropriate Operation During Mechanical Running Test

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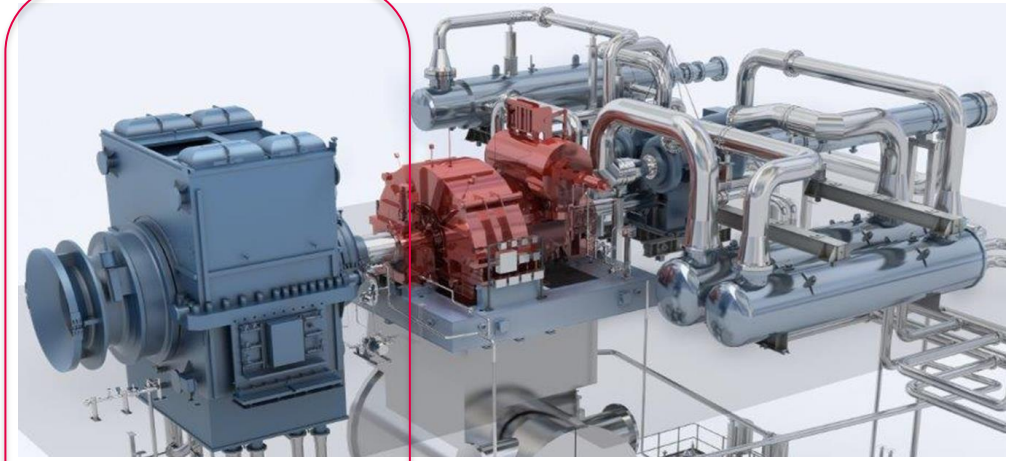
Responsible for providing technical support in rotordynamics and stress analysis.
Function: development and analysis of components of centrifugal compressors for oil and gas application.
Before joining the site in Switzerland in 2003 he was employed for 6 years in MAN Diesel & Turbo, Berlin where he was involved in the design, finite element analysis, rotordynamic analysis, testing and development of centrifugal compressors.
He received his diploma (Mechanical Engineering, 1995) from the University of Valenciennes (France).

Synopsis

- During the mechanical test of a centrifugal compressor, the rotor experienced a sudden increase of the radial vibrations. After re-start, the compressor showed unacceptably high vibrations.
- The RCA revealed: The vibrations increased while running at trip speed close to surge. The shrink of the impeller, which had moved on the shaft, was too low to withstand these conditions.
- The impeller was removed and the shrink increased. After reassembly no high vibration appeared at trip speed anymore.
- Generally, the operation time at trip speed shall be reduced to its minimum and shall not be considered as “normal” continuous operation.

Outline

Background – Train Arrangement, Compressor



MAC
(Main Air Compressor)

ST
(Steam Turbine)

BAC
(Booster Air Compressor)

- Air Separation Unit
- Steam Turbine (ST) Driven
- Main Air Compressor (MAC):
  - 3 stages, in-line
  - Internal cooling

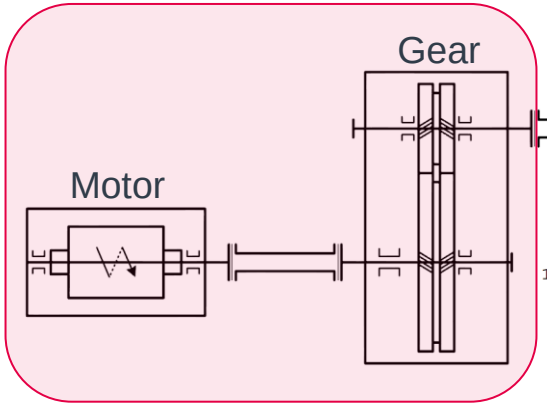
Feature		SI Unit	
Suction pressure		bara	1.0
Discharge pressure		bara	6.2
Suction Temperature		°C	39
Discharge Temperature		°C	91
Mass Flow		kg/h	660'900
Power (max)		kW	40'284
Gas		-	Air
Rotor speed	rated	rpm	4'135
	max.cont.		4'259
	trip		4'685

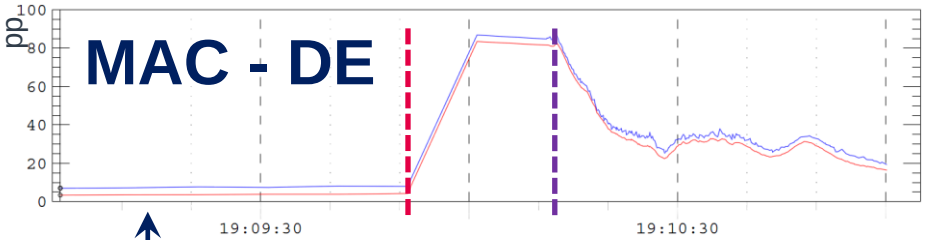
Description

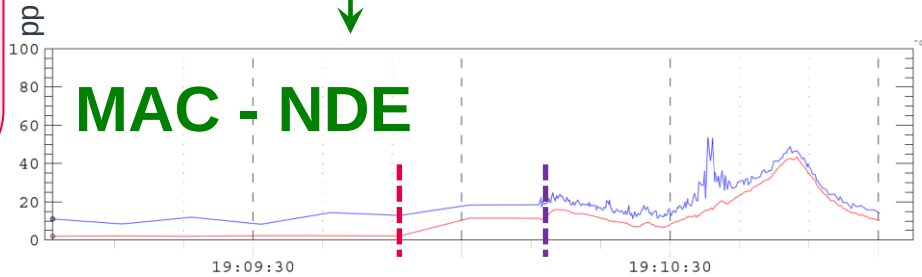
- In house mechanical test in facility test
- Sudden increase of radial vibrations on DE bearing probes → shut-down
- After shut-down
  - Compressor started again
  - Excessive vibration levels

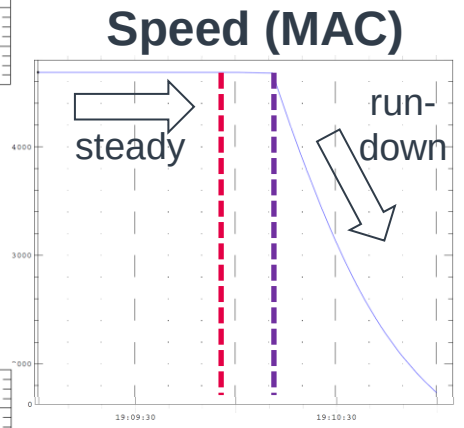
Findings – Lateral Vibrations

Testbed equipment



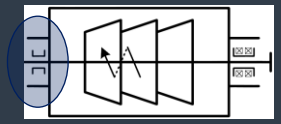




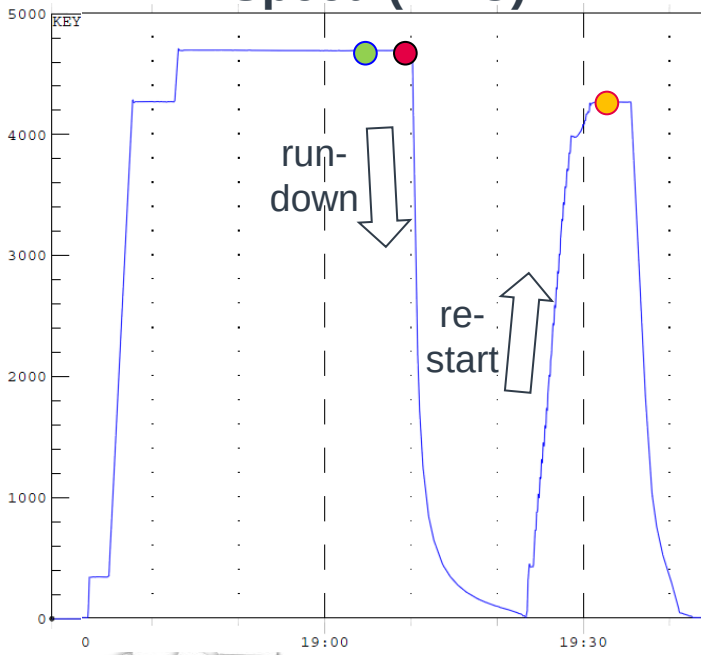


→ Sudden increase of vibrations at DE (constant speed)

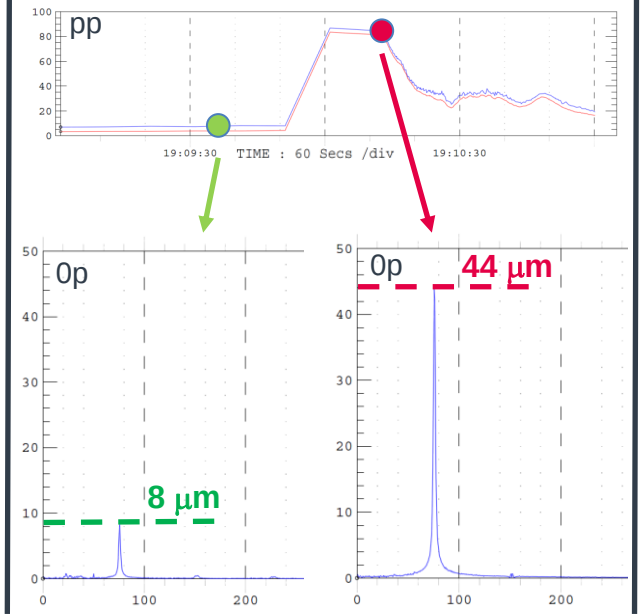
Findings – Lateral Vibrations (MAC – DE)



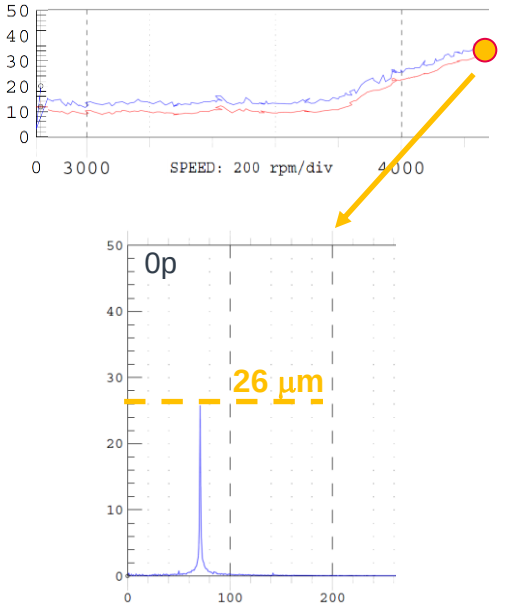
Speed (MAC)



Vibrations @ 4’686 rpm



Vibrations @ 4’248 rpm

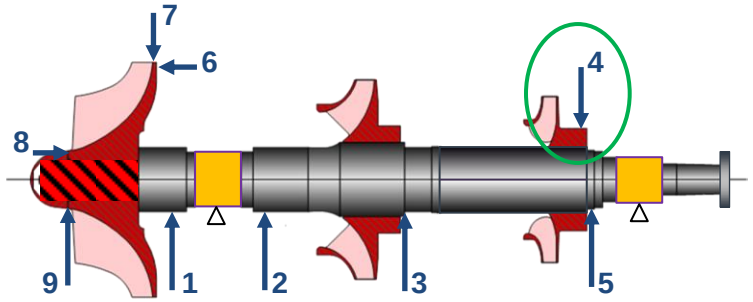


→ Vibration levels too high after re-start

Root Cause Analysis – Recorded Run-Outs

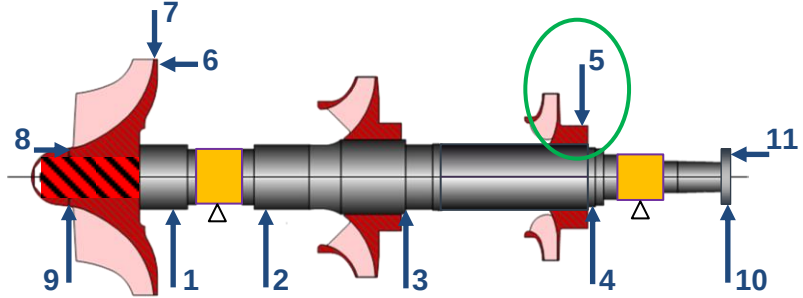
Before Testrun

Zustand Rotor / State of rotor / Etat du rotor		Messstellen / Measuring points / Points de mesure												
		1	2	3	4	5	6	7	8	9	10	11	12	
C	R	3	3	6	7	10	26	8	15	50				Before HS Balancing
	<	/	/	220°	60°	90°	/	190°	/	15°				
D	R	2	2	3	5	3	32	6	10	60				After HS Balancing
	<	/	/	/	90°	/	/	140°	/	340°				



After Event

Zustand Rotor / State of rotor / Etat du rotor		Messstellen / Measuring points / Points de mesure											
		1	2	3	4	5	6	7	8	9	10	11	12
D2	R	6	9	12	12	34	26	18	8	20	35	45	
	<	160°	70°	90°	170°	100°	/	150°	/	280°	320°	300°	

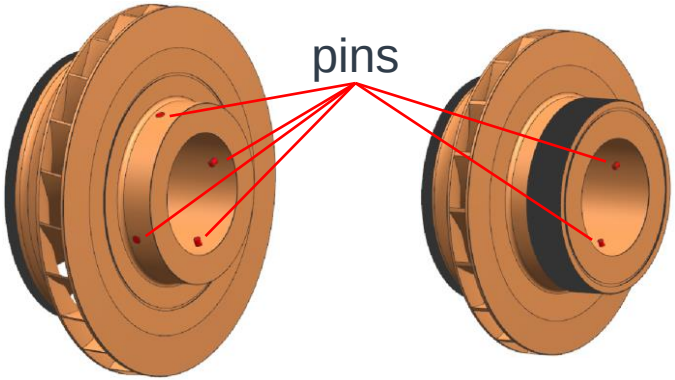


→ Run-out at Impeller 3 increased from **5** µm up to **34** µm !

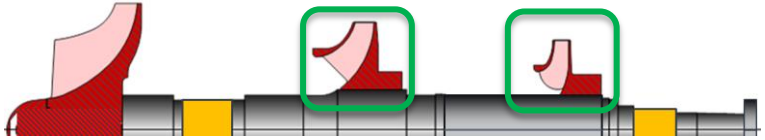
→ Run-out just behind Impeller 3 increased only from 3 µm up to 12 µm

Root Cause Analysis – Removed Impellers

Impellers 2 & 3 are mounted onto the shaft by an interference fit along with pins.



Impeller 2 Impeller 3

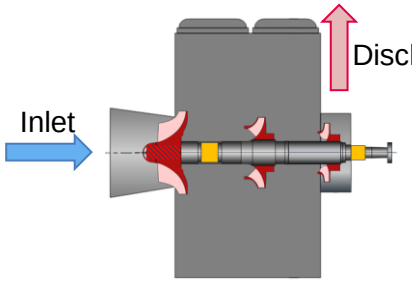


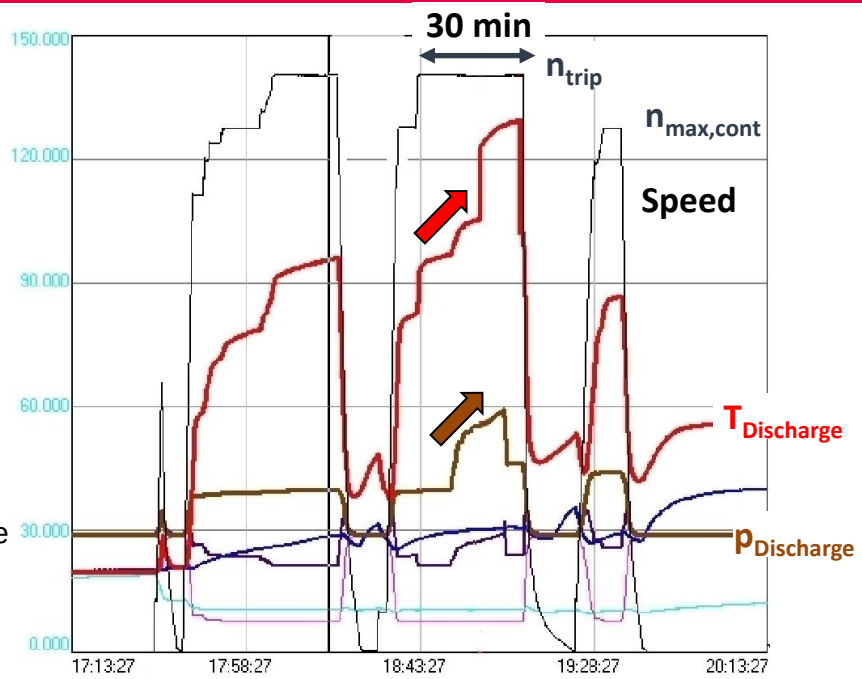
Removed pins from impeller 3

- Clear traces of shear on pins of impeller 3
- This confirms the impeller had moved on the shaft during the test

Root Cause Analysis – Operation Data

- For internal investigation purpose, a surge test at trip speed had to be performed (no customer specific requirement)
- Event happened after:
  - 30 min in operation at trip speed (4'686 rpm)
  - Continuous increase of discharge pressure and temperature

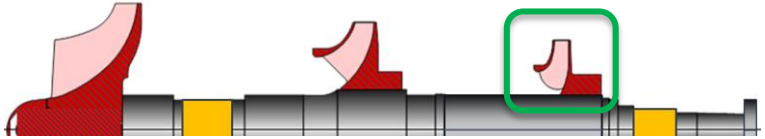


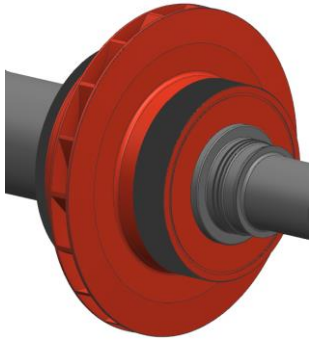


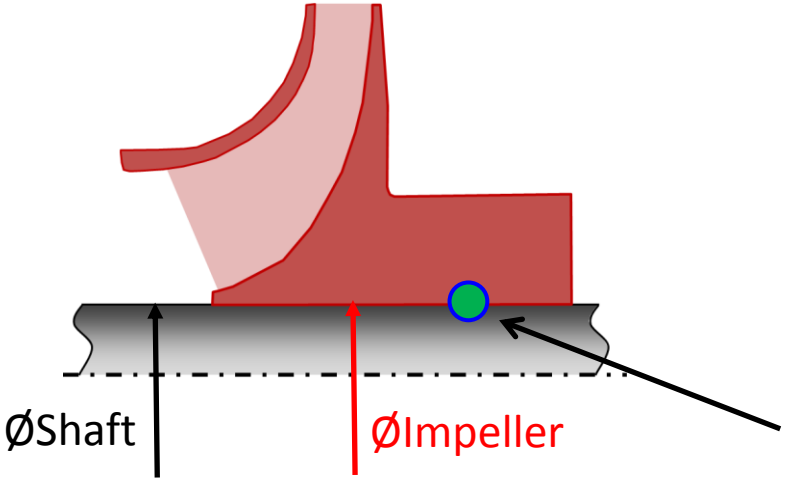
→ High vibrations appeared while running at trip speed and close to surge

Root Cause Analysis – Interference Fit

Interference fit evaluated from Manufacture Data records





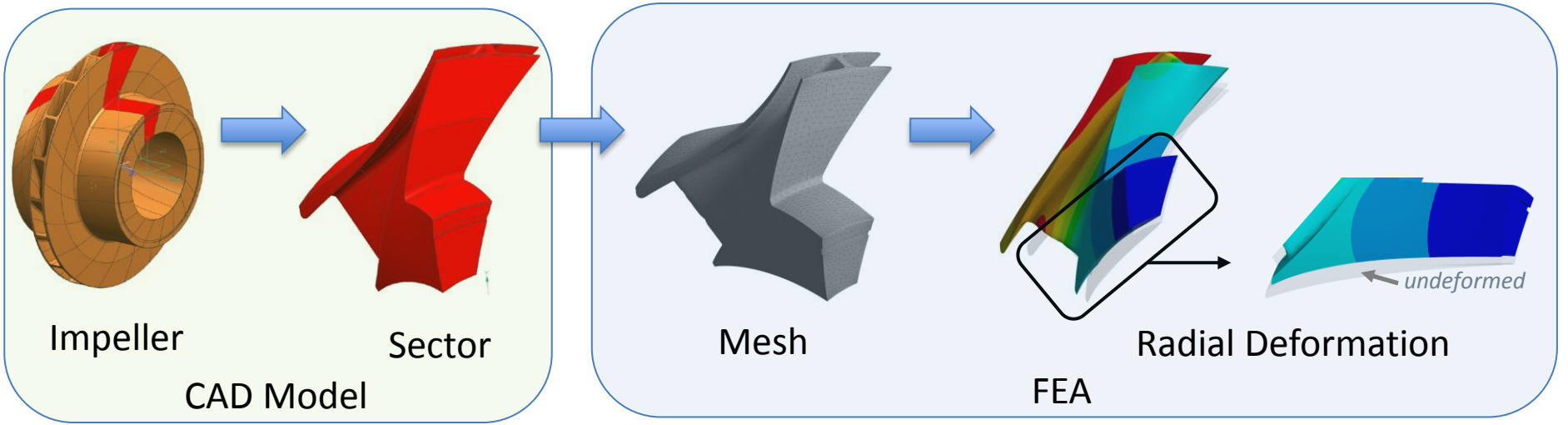


Interference fit (realized shrink):

$$\frac{Ø_{Shaft} - Ø_{Impeller}}{Ø_{Shaft}} = 1.22\ ‰$$

Root Cause Analysis – FEA

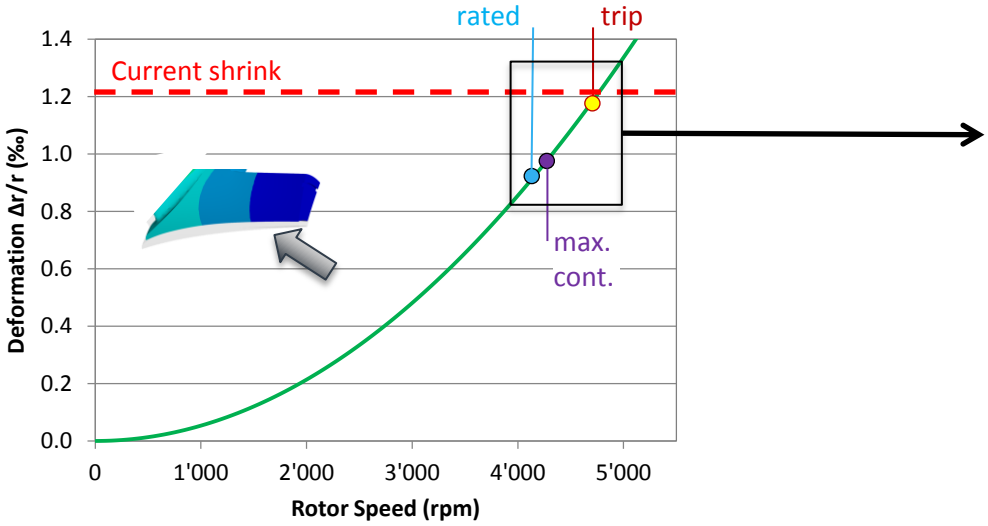
Evaluation of impeller radial displacement at the interference fit due to centrifugal forces



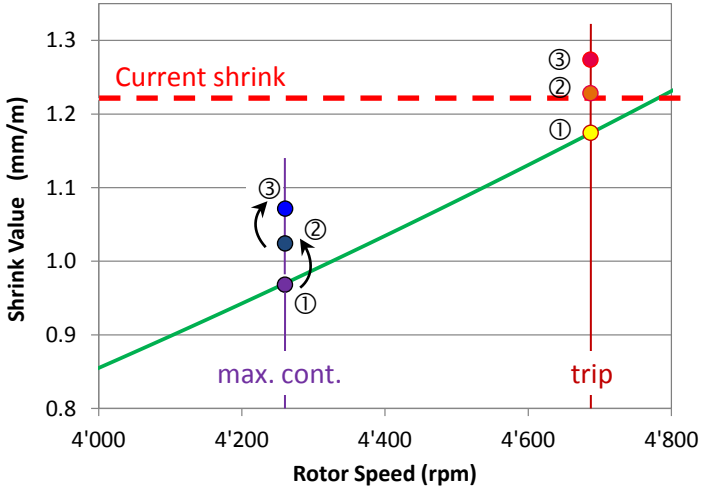
Root Cause Analysis – FEA

Evaluation of required shrink

Radial displacement at impeller fit due to centrifugal forces (only)



Required shrink at impeller fit due to overall loads



Loads	
①	Centrifugal
②	+ Torque + Thrust
③	+ Thermal (surge)

Root Cause Analysis – FEA

Summary

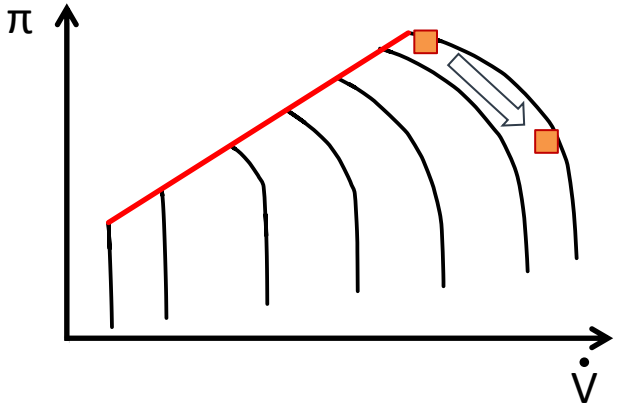
Operation		Shrink (1.2 ‰) o.K. ?
n_{max} (4’259 rpm)	Within performance map	✓
	Near Surge	✓
n_{trip} (4’685 rpm)	Within performance map	✓
	Near Surge	✗ (thermal)

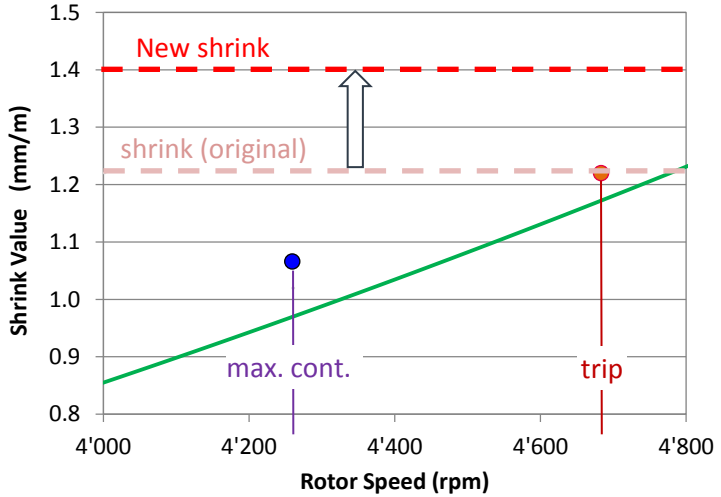
- Current shrink 1.22 ‰ is sufficient for normal operating conditions
- Shrink is not sufficient for operation at n_{trip} **&** surge !

Actions

1. Shrink increased from 1.22 ‰ to 1.40 ‰

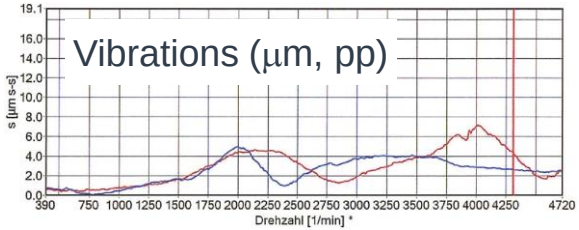
2. Mechanical test run carried out at trip speed for 15 minutes duration and well outside the stability limit



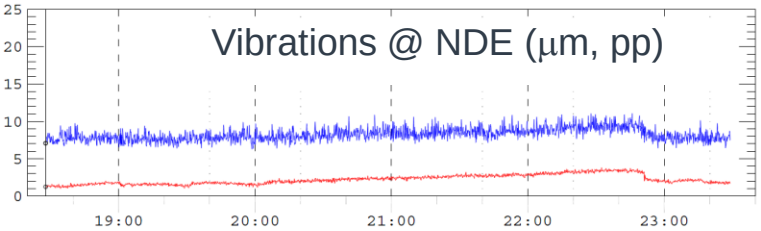


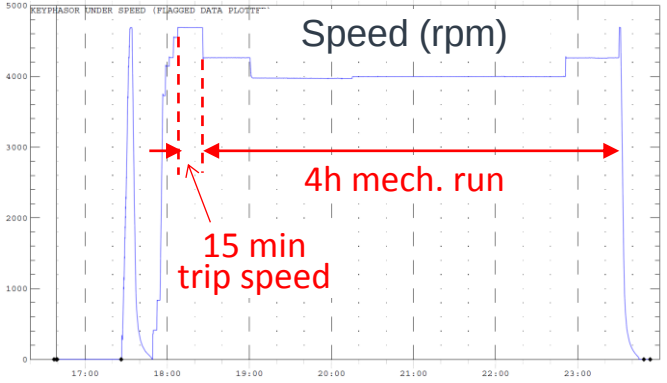
Measurements after modification

- After modification, this rotor was successfully balanced and delivered to site.



- Afterward, a second rotor (same geometry) with increased shrink was tested in the machine

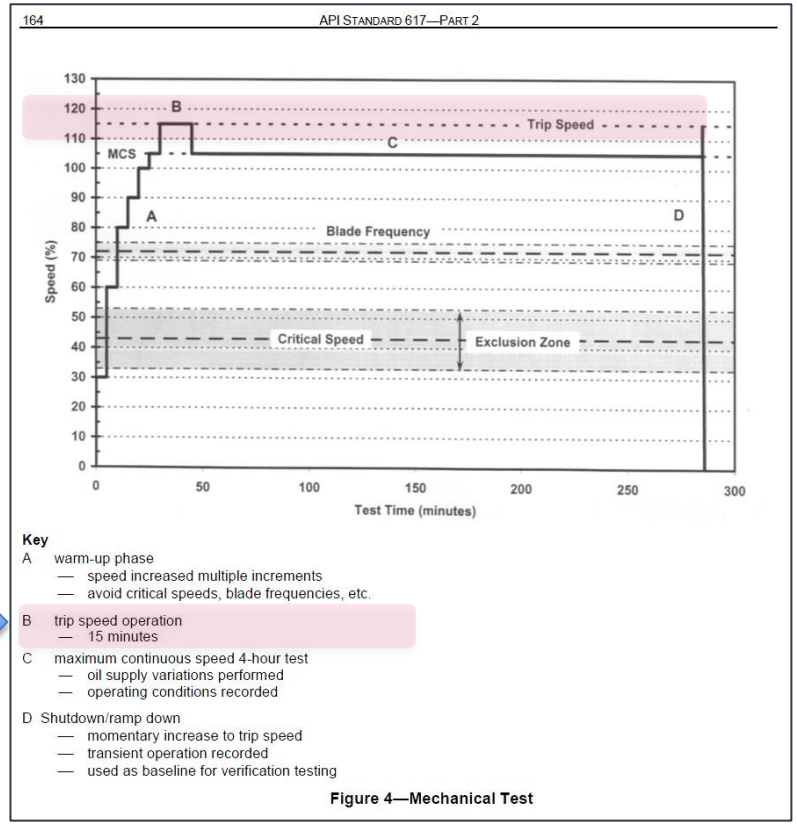




→ No peculiar vibration observed, machine accepted and delivered

Lessons learnt / Summary

- With a correct assessment of the planned testing conditions, this test would not have been performed.
- Generally the shrink of each impeller shall be designed with sufficient safety margin to overcome not only the normal (specified) operation but also any undesirable condition.
- Operation at trip speed shall be reduced to its minimum (15 min according to API 617) and shall not be considered as «normal» continuous operation.



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Thank you !
Questions ?