45TH TURBOMACHINERY & 32ND PUMP SYMPOSIA
HOUSTON, TEXAS | SEPTEMBER 12 – 15, 2016
GEORGE R. BROWN CONVENTION CENTER

Investigation of process gas compressor shaft vibration phenomena

Mr. Ashutosh Vengurlekar
ExxonMobil Research and Engineering, Singapore
Mr. Teo Woon Lip
ExxonMobil, Engineering Services, Singapore
Mr. Nathan Little
ExxonMobil Research and Engineering, Houston
Mr. Satoru Yoshida
Mitsubishi Heavy Industries Compressor Corporation, Hiroshima Japan

ExxonMobil
MITSUBISHI HEAVY INDUSTRIES COMPRESSOR CORPORATION
TEXAS A&M UNIVERSITY
TURBOMACHINERY LABORATORY
TEXAS A&M ENGINEERING EXPERIMENT STATION

Presenter/Author bios

Mr. Ashutosh Vengurlekar
ExxonMobil Research and Engineering, Singapore
Discipline Technology Lead – Machinery Asia Pacific
ashutosh.vengurlekar@exxonmobil.com

Mr. Teo Woon Lip
ExxonMobil, Engineering Services, Singapore
Lead Engineer (Machinery)

Mr. Nathan Little
ExxonMobil Research and Engineering, Houston
Advanced Engineering Associate (Machinery)

Mr. Satoru Yoshida
Mitsubishi Heavy Industries Compressor Corporation, Hiroshima Japan
Design & Engineering Center Division
satoru2_yoshida@compressor.mhi.co.jp

Abstract

This paper presents details of investigation results of issues observed during plant start-up on a centrifugal compressor. Compressor was operated with air/ nitrogen during start-up and high shaft vibration (approx. 75 um) were observed on DE side of compressor accompanied by high levels of coast down vibration levels (exceeding alarm levels). This paper presents subsequent detailed rotor dynamics analysis to understand root cause of the high vibrations.

Investigation for Process Gas HP Compressor (PGC) Shaft Vibration Phenomena

<u>Problem Background:</u>

- Higher than expected vibration of about 45um encountered in the DE HP casing of the PGC during air run
- Increased vibration of about 75um encountered during nitrogen run
- Vibration levels exceeded alarm levels during coast down of the machine

<u>Observations:</u>

- Strong correlation with operating conditions (operating pressure and temperature) and shaft vibration level was observed during both air and nitrogen operation
- Compressor casing was opened for inspection and some rusts on the rotor and casing found. Root cause of rusts was established as exposure to hydrotest water during piping hydro test at site
- Rotor residual unbalance found higher but not adequately high to cause the observed vibration level

<u>Analysis Performed:</u>

- The rotor dynamics analysis including thermal bending of the rotor caused by the non-uniform heat transfer could simulate the shaft vibration phenomena qualitatively. This paper presents details of analysis, observations and techniques used for establishing effect of rust on a rotating component.

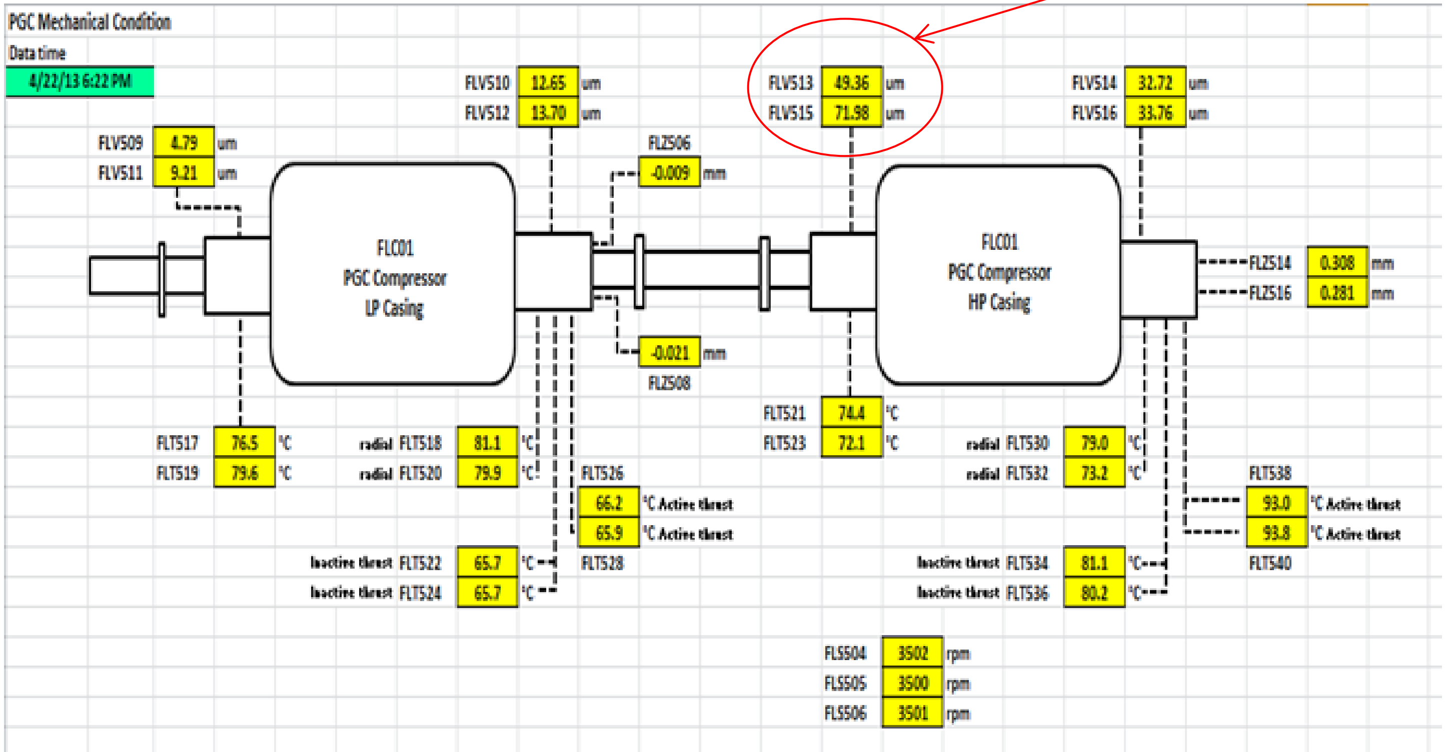
History

Run 1 (Working)	November , 2012:	PGC started with air, and shaft vibration of 45 µm was observed on DE side of HP compressor.
Run 2 (Working)	February , 2013:	PGC Compressors were operated with air, and shaft vibration was same level as Nov. 2012.
Run 3 (Working)	April , 2013:	PGC compressors were operated with nitrogen, and shaft vibration of 75 µm was observed on DE side of HP compressor, Phase change noticed during shutdown. Detailed operation data for PGC reviewed again. Rotor replacement carried out. - no abnormal rubbing was identified. - Significant rust was observed on lower casing.
Run 4 (Spare)	May, 2013:	PGC compressors re-started. The vibration level was 19µm. After few days of operation t the vibration level was 13µm (close to design operating conditions).
	2013-2014	Working rotor was sent back to MCO shop for detail investigation. Several times meeting was held between ExxonMobil and MCO.

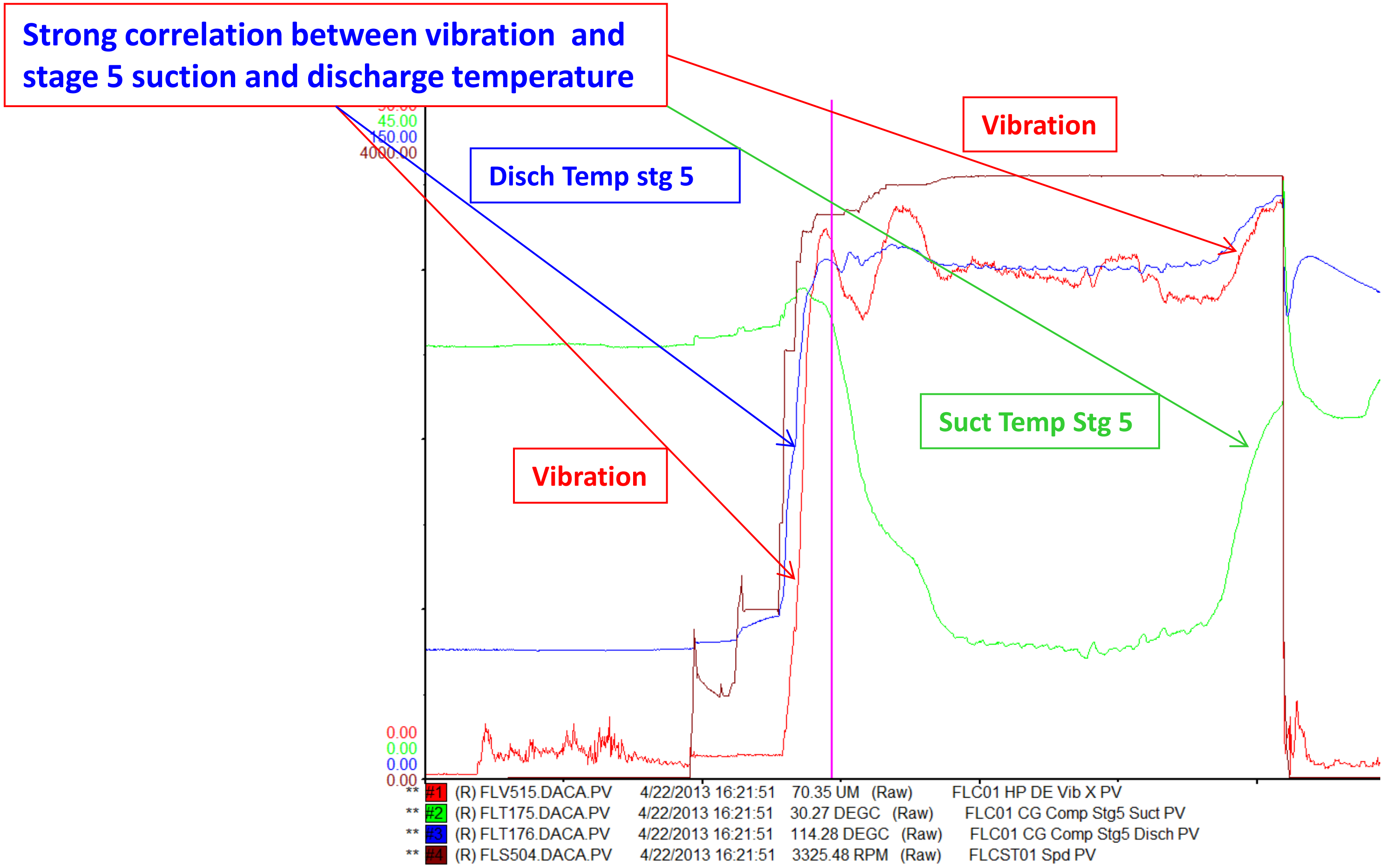
Operating data of working rotor – N2 run

April 22nd 2013: Working rotor

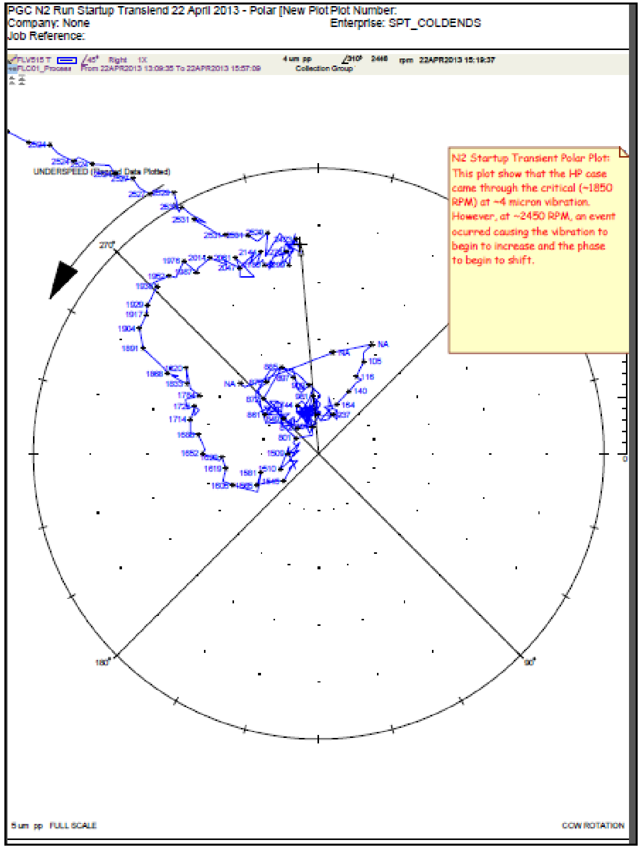
DE side vibration is higher than NDE side vibration

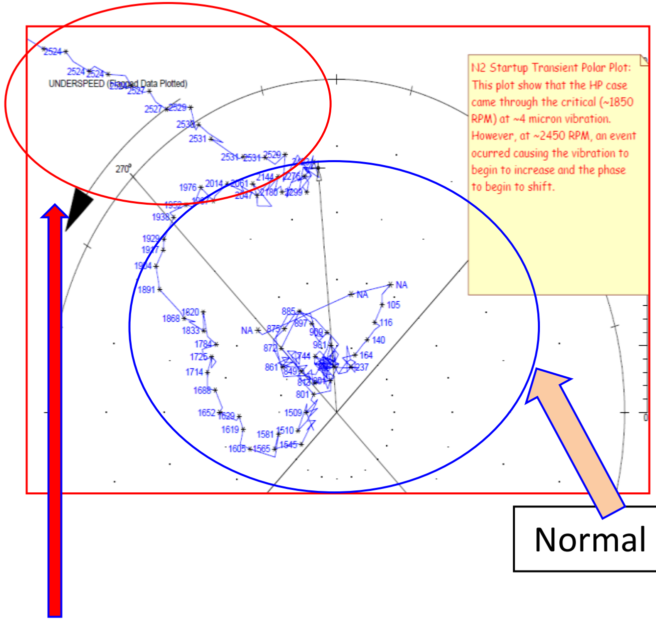


Trend data of working rotor – N2 run



Transient polar plots of working rotor – N2 run

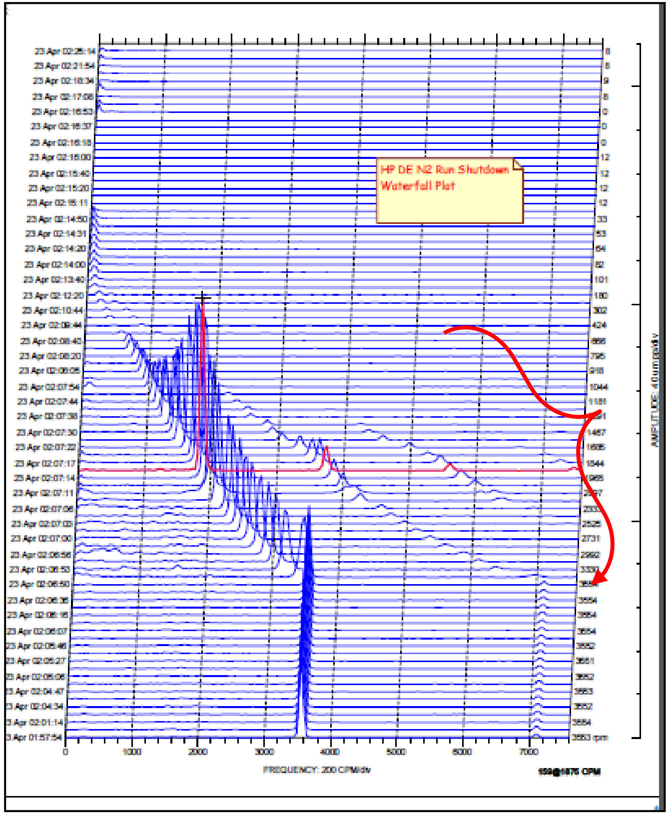


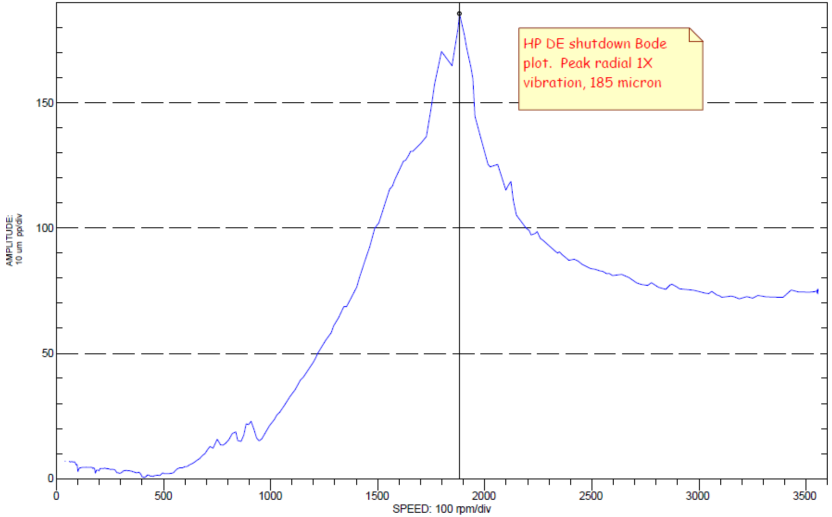


Normal behavior

Abnormal change noticed
– Vibration level was increased during constant speed operation. (Vibration phase was not so much changed.)

Shutdown waterfall plot of working rotor – N2 run





Abnormal waterfall plot for shutdown – Vibrations up to 185 microns observed during shutdown

Rotor replacement initiated

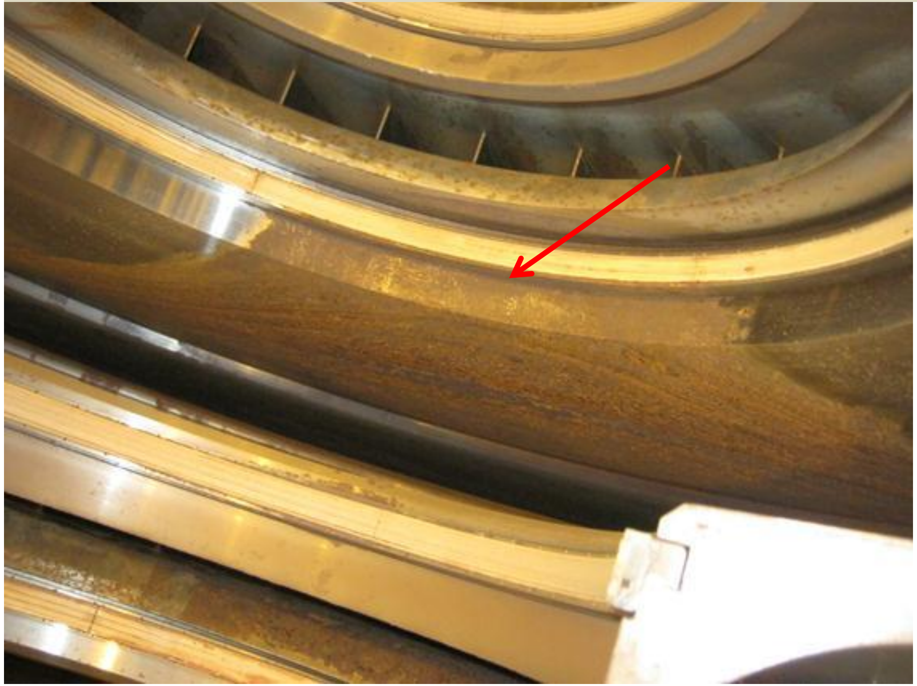
Rotor Inspections and Observations

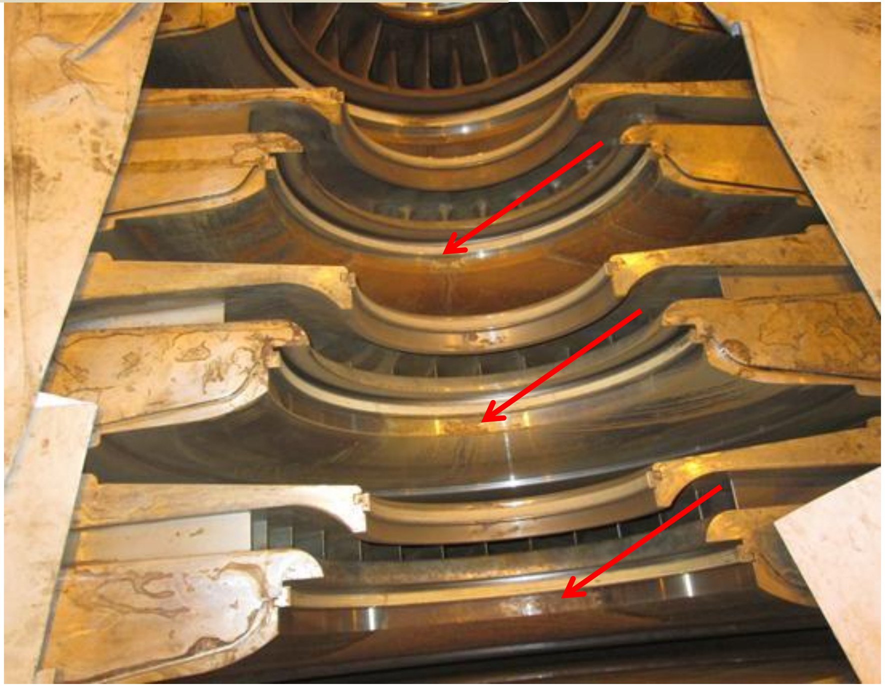
Onsite as-found conditions

- Slight rust observed on rotor; otherwise rotor still looked good from outside

Rotor Inspections and Observations

Onsite as-found conditions





- Significant rust observed on stationary diaphragms
- Water mark visible and indicated water accumulation to shaft centerline at 5th stage section

Rotor Inspections and Observations

Workshop Inspection Scope: (at OEM facility)

- Both high and low speed balancing check conducted: Residual unbalance exceeded value of API 617 at low speed balance check. Shaft vibration was less than 25um during high speed balance check at Max Continuous Speed (still exceeded shop test readings)
- Rotor visually inspected and stack-up dimensions checked: No issues
- Impellers de-stacked for detailed inspection: Rust sediments found within the clearances under the 4^{th} to 8^{th} impellers. (Severe sediments in 4 and 8 impeller)
- Dimensional checks on all components performed: No issues
- User witnessed as-found conditions of shaft and impellers and conducted joint RCFA with OEM engineers

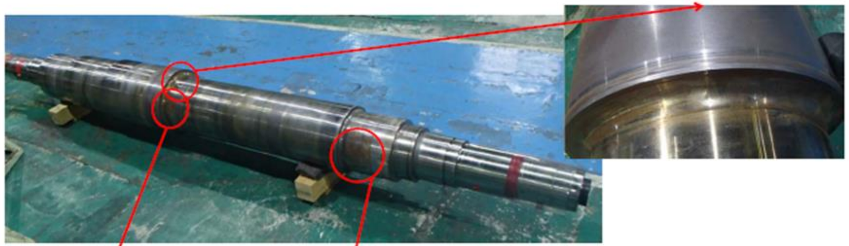
Root Cause Analysis

Phenomena	Possible Cause-1	Possible Cause-2	Description	Possibility
High Shaft vibration ･Main DE side bearing ･Main component was 1X ･Vibration amplitude change during constant speed	Rotor Unbalance	Unbalance change due to impeller movement	After receiving inspection; •Color distribution was observed at shrink fit area. (Shrink fit contact pressure might be not uniform) •Expansion of impeller bore size was observed.(1^{st} and 2^{nd} impeller.)	
		Impeller restrained by the rust or sediments	After receiving inspection; •Scratch on the rotor was observed at 4th impeller (Some sediments may be located.)	
		Thermal bending of shaft	• The heavy rust was observed around HP section (4th to 8th impeller)	

Rotor Inspections and Observations

- **Heavy rust** observed around HP section (4th to 8th impeller) mainly. (Stage 1-3 is Stainless steel. Stage 4-8 is Carbon steel.)

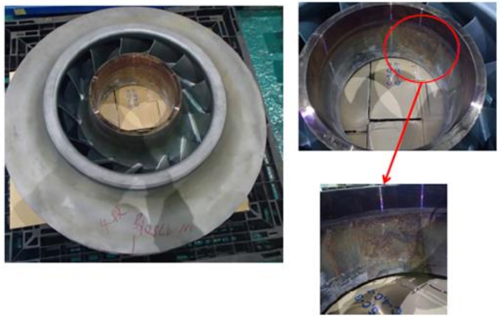
Compressor shaft



8th impeller position

4th impeller position

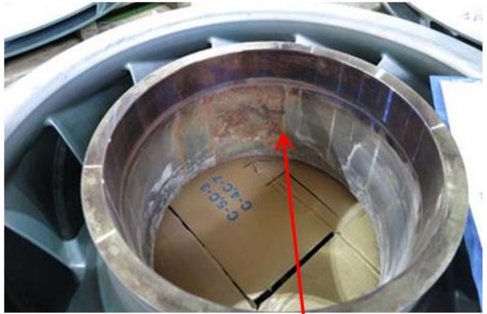
4th impeller



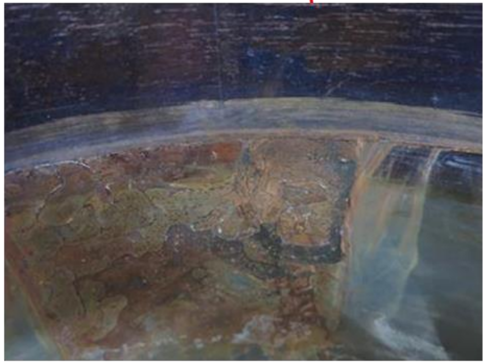
8th impeller

Rotor Inspections and Observations

Rotor as-found condition after disassemble   4th Impeller and shaft



Under 4th impeller



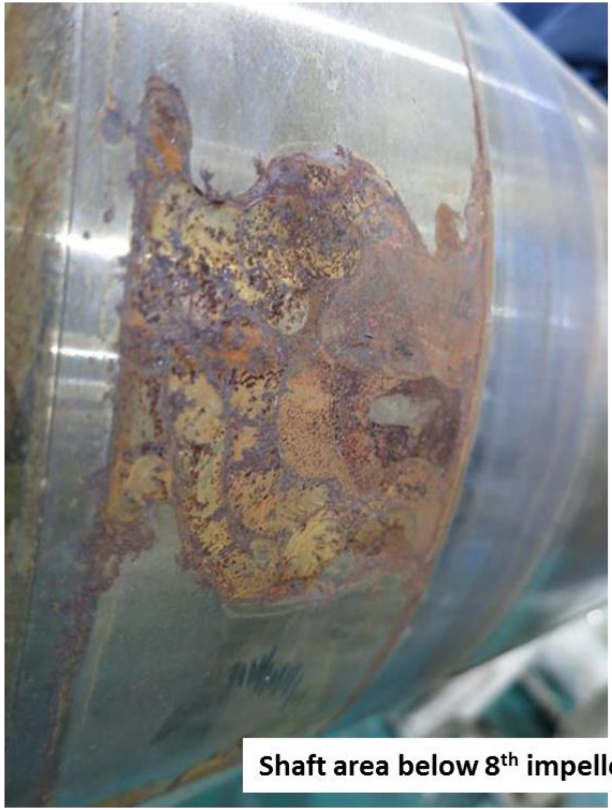
Deep scratch marks across the width of the impeller created during impeller removal. This indicated the presence of hard particles within the clearances between the shaft and impeller

Rotor Inspections and Observations

Rotor as-found condition after disassemble

8th Impeller and shaft

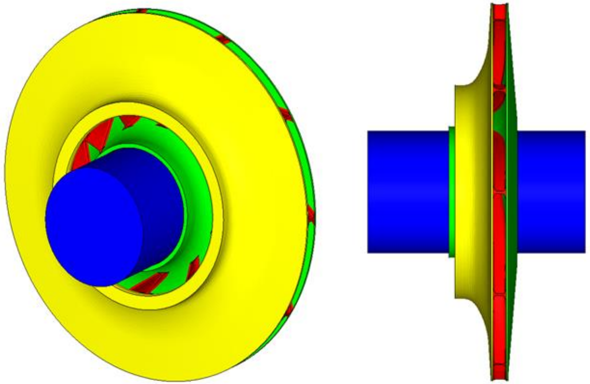
Under 8th impeller



Shaft area below 8th impeller

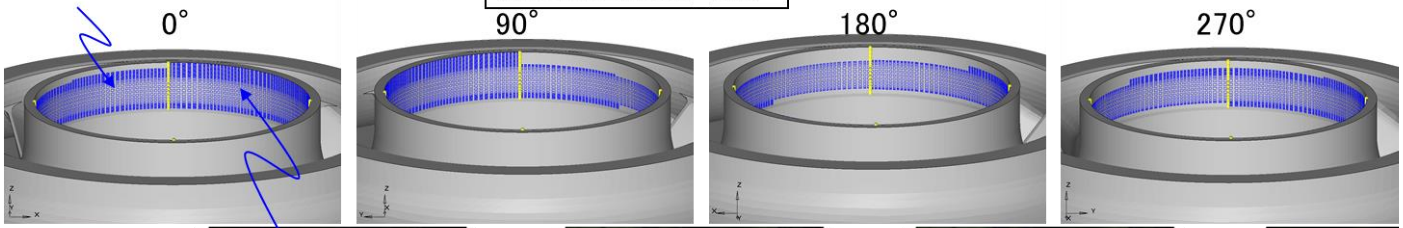
FEM Analysis for impeller grip condition

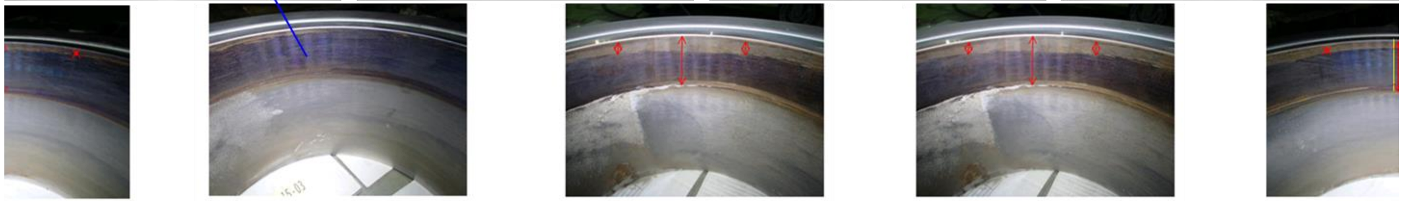
Item	Analysis condition
Objects	Shaft and 5th Impeller
Speed	3982rpm(MCR)
Load	Centrifugal force + Shrink fit pressure
Assumptions	・Recorded dimension was used. ・Color distribution was considered as contact area. (Area is 76.6% of design.) ・Thermal expansion was not considered.



Analysis model

Modelled Contact area



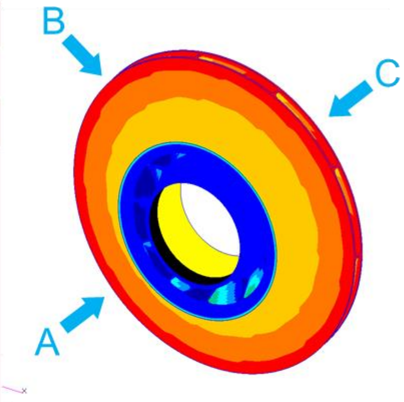


As found condition of contact area

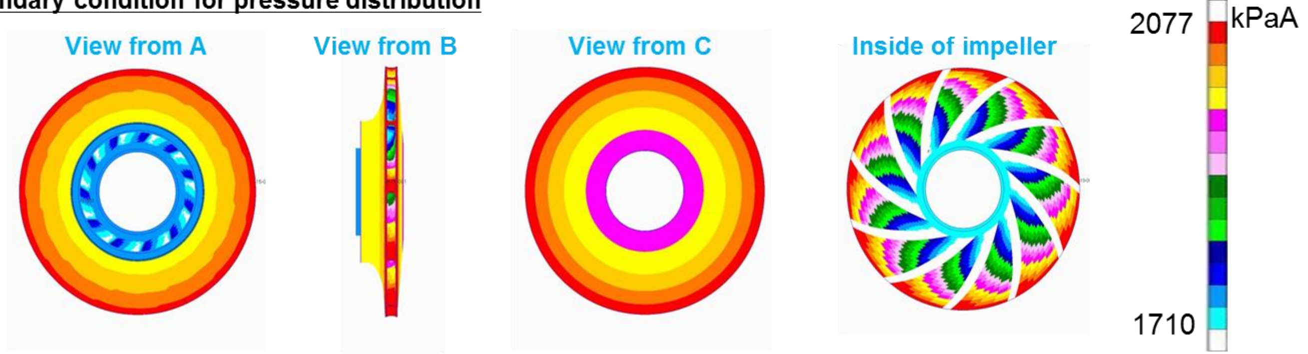
FEM Analysis for impeller grip condition

Second FEA model to estimate impeller deformation under operating pressure and speed

Item	Analysis condition
Objects	Shaft and 5th Impeller
Speed	3982rpm(MCR)
Load	Centrifugal force + Shrink fit pressure + Gas pressure
Assumptions	・Recorded dimension was used. ・Color distribution was considered as contact area. (Area is 76.6% of design.) ・Thermal expansion was not considered. ・Suction pressure of 5th impeller : 1710kPaA(*) Discharge pressure of 5th impeller : 2077kPaA(*) (*) Estimated as per site operation data



Boundary condition for pressure distribution



FEM Analysis for impeller grip condition

<u>Gripping force evaluation result</u>

	Contact area [mm2]	Ratio [-]	Gripping Force [kgf]	S.F. [-]
Actual (at MCR)	3.79×10^4	76.6%	18810	2.82

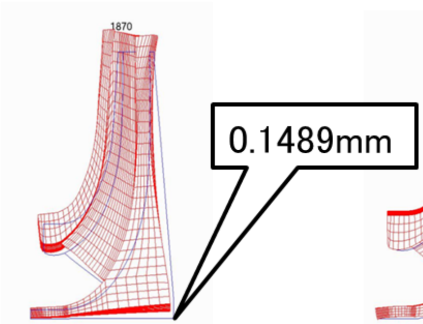
Note 1 : Gas thrust force is 6659kgf.

Note 2 : Static friction coefficient is 0.15.

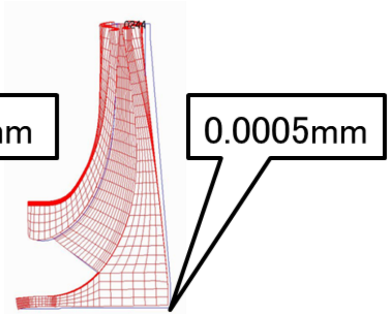
- Contact area did not change with impeller centrifugal deformation.
- Contact area did not change with impeller deformation due to gas pressure too.
- Enough gripping force against gas thrust force confirmed by FEM analysis.
- The impeller did not shift during operation.

FEM Analysis for impeller grip condition

- 0.0005mm of deformation at impeller inside edge was caused by gas pressure.
- The impeller deformation by gas pressure was very small comparing to the deformation by centrifugal force.

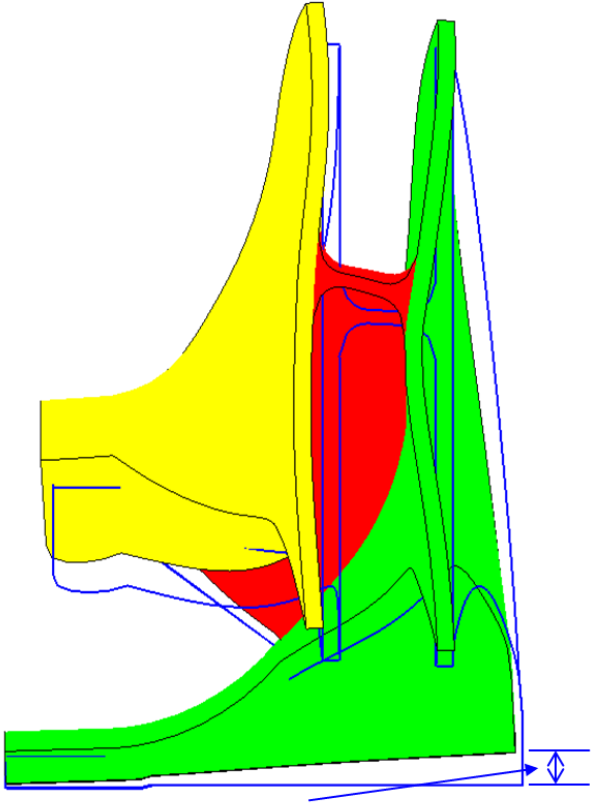


Centrifugal force



Gas pressure

Impeller deformation (at MCR)



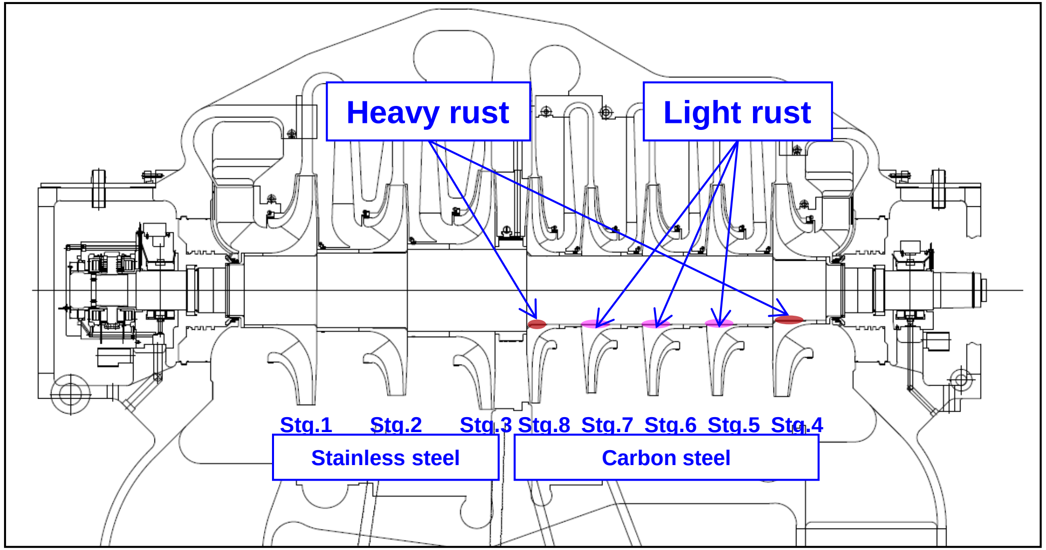
0.1494mm / on radius
(Centrifugal force+Gas pressure)

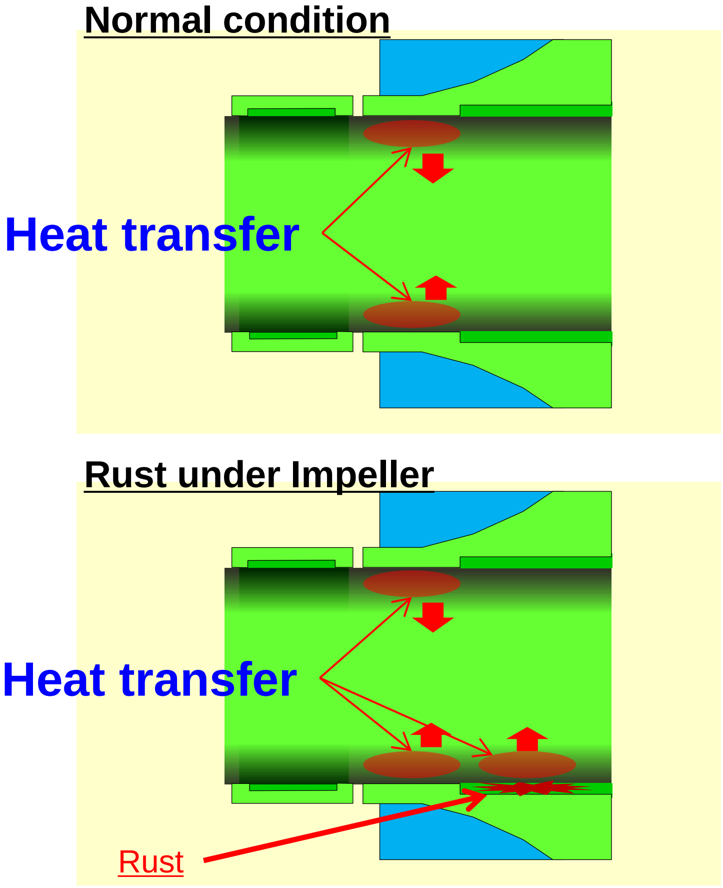
Root Cause Analysis

Phenomena	Possible Cause-1	Possible Cause-2	Description	Possibility
High Shaft vibration ･Main DE side bearing ･Main component was 1X ･Vibration amplitude change during constant speed	Rotor Unbalance	Unbalance change due to impeller movement	After receiving inspection; •Color distribution was observed at shrink fit area. (Shrink fit contact pressure might be not uniform) •Expansion of impeller bore size was observed.(1^{st} and 2^{nd} impeller.) LSB and HSB check result were not so much changed from previous MCO test result.	Not Possible.
		Impeller restrained by the rust or sediments	After receiving inspection; •Scratch on the rotor was observed at 4th impeller (Some sediments may be located.) ⇒The impellers might be restrained by the rust or sediments and then rotor robustness to vibration decreased, because distribution of impeller displacement is not symmetric. FEM analysis shows the gap between impeller and shaft is increased by impeller centrifugal deformation.	Not Possible.
		Thermal bending of shaft	• The heavy rust was observed around HP section (4th to 8th impeller) ⇒ Thermal bending of the rotor might be caused by the rust, due to the no uniform heat transfer.	Possible. FEM analysis shows it. (P.21-24)

FEM Analysis for rotor thermal bending

Thermal bending of the rotor could be caused by the rust, due to the uneven heat transfer from impeller.



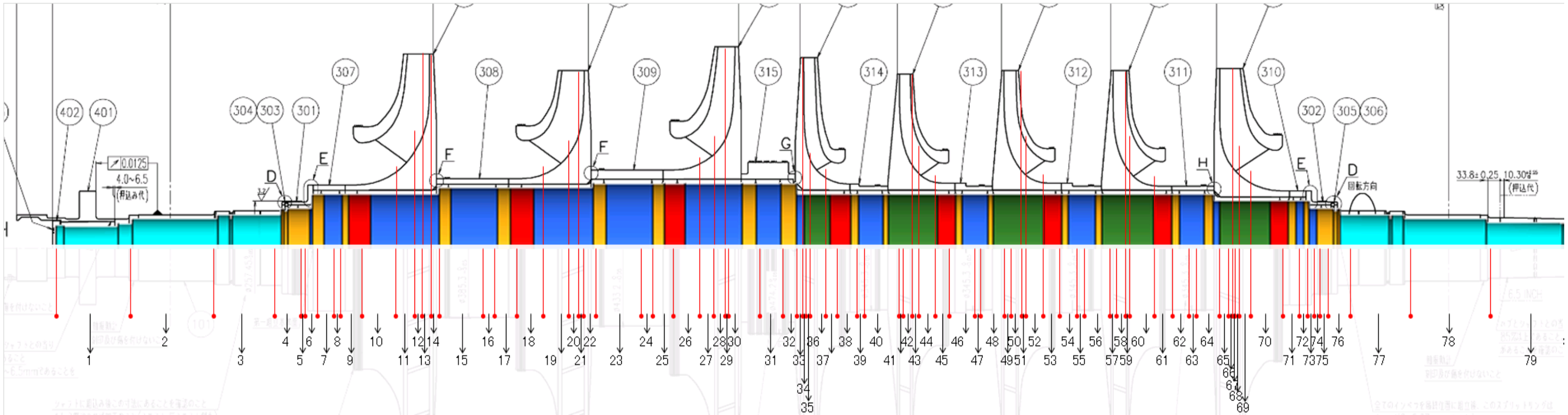


FEM Analysis for rotor thermal bending

Item	Analysis conditoin
Objects	Shaft
Analysis type	Steady thermal analysis
Assumptions	・N2 operating condition of each stage was considered (Pressure, temperature, velocity). ・Thermal transfer coefficients for each parts are shown on right table.

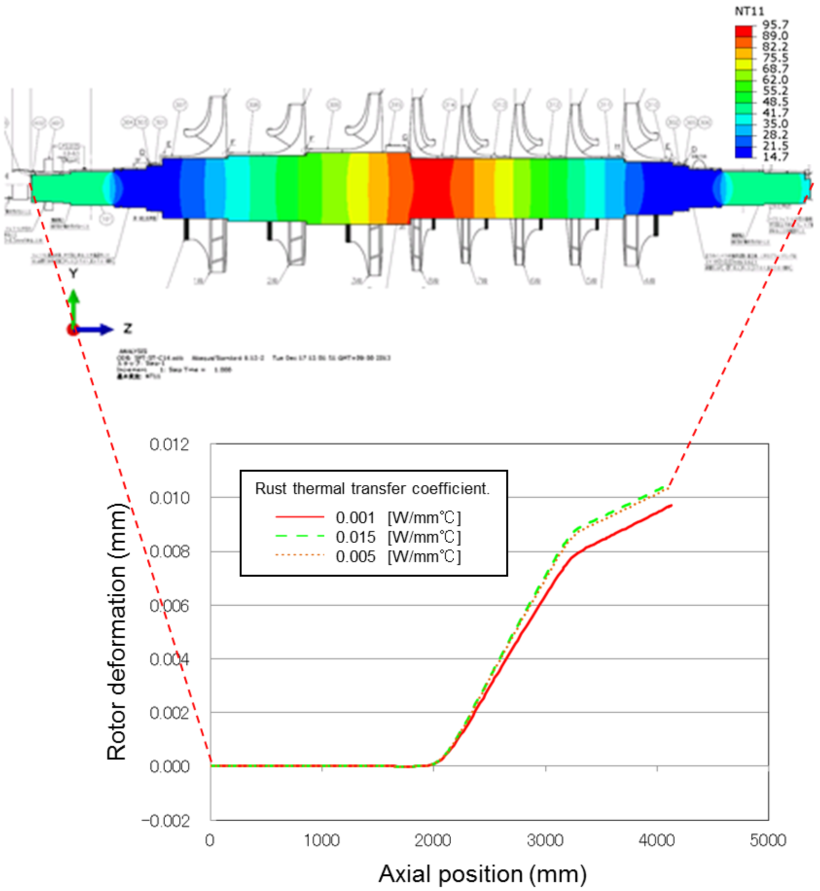
Parts	Thermal transfer coefficient.	Unit
Carbon steel	0.036	W/mm℃
Stainless steel	0.025	W/mm℃
Air	2.28E-05	W/mm℃
Rust	0.001-0.015	W/mm℃

Thermal boundary condition



FEM Analysis for rotor thermal bending

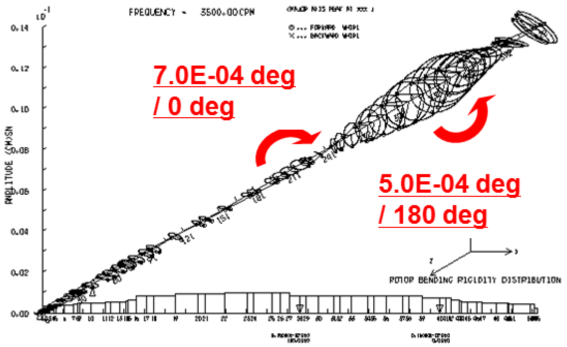
Temperature distribution of rotor

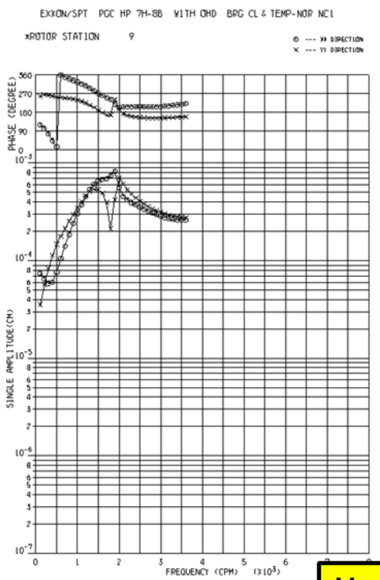


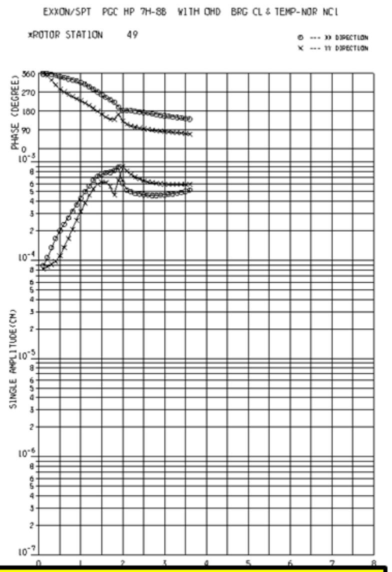
Rotor thermal bending analysis was performed based on N2 operating condition.

Effect of thermal transfer coefficient difference was confirmed by the analysis.

Lateral analysis for rotor thermal bending







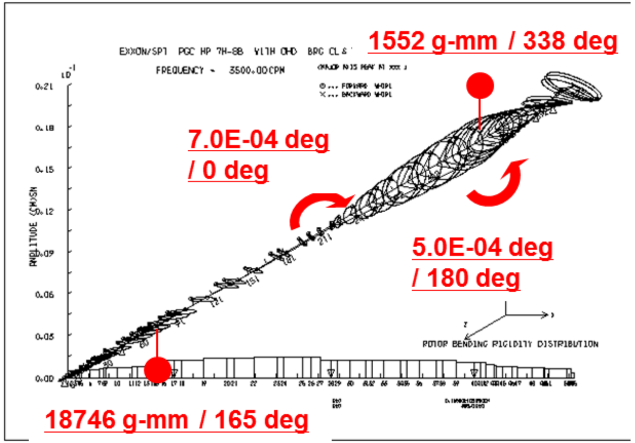
Only rotor thermal bending is considered in this analysis.

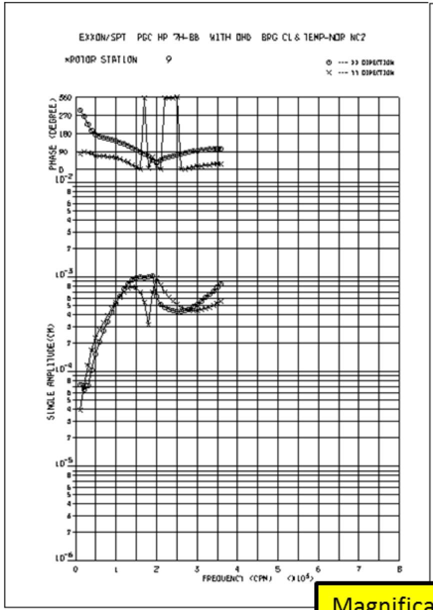
Magnification factor of almost 2 between DE and NDE, almost matched with site observation

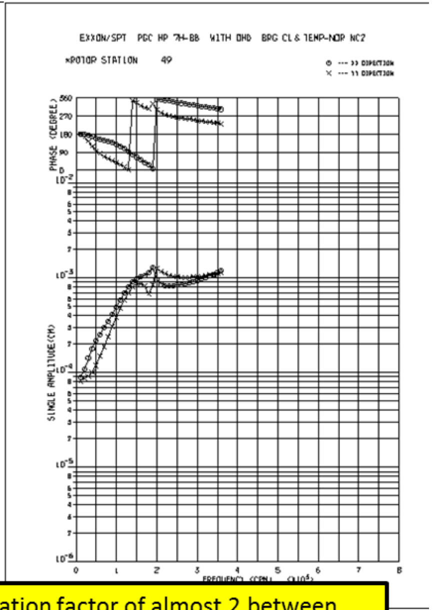
Vibration amplitude (at 3500 rpm)

	TH side H [μmp-p]	TH side V [μmp-p]	N-TH side H [μmp-p]	N-TH side V [μmp-p]
Site operation	34	33	72	49
Analysis considering rotor bending due to the rust	6	6	12	10

Lateral analysis for rotor thermal bending







Thermal bending and residual unbalance were considered in this analysis.

Magnification factor of almost 2 between DE and NDE, almost matched with site observation

Vibration amplitude (at 3500 rpm)

	TH side H [μm^{p-p}]	TH side V [μm^{p-p}]	N-TH side H [μm^{p-p}]	N-TH side V [μm^{p-p}]
Site operation	34	33	72	49
Analysis considering rotor bending due to the rust	16	11	21	20

Conclusion

- ✓ Low Speed Balance and High Speed Balance check result were not conclusive and did not point to any specific abnormality.
- ✓ FEM analysis for impeller gripping force was performed and it was confirmed that the gripping force is adequate.
- ✓ Strong correlation with operating conditions (operating pressure and temperature) and shaft vibration level was observed. Vibration level was increased during constant speed operation. Vibration phase was not so much changed.
- ✓ Rust observed around HP section. (4th to 8th impeller). Lateral analysis to include effect of uneven heat transfer conducted. The results matched actual rotor observations, magnification factor of almost 2 between DE and NDE.
- ✓ **Thermal bending of the rotor in dynamic condition (due to rust between impeller and shaft) resulted in high amplification of vibrations.**

The root cause of abnormal phenomenon observed at site operation could be investigated thoroughly via a close relationship & support between end user and manufacturer.