Root Cause Investigation of Sub-Synchronous Vibration in a Multi-stage Centrifugal Compressor

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Outline

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- Findings
- Root Cause Analysis
- Modification
- Validation of modification
- Site confirmation test
- Conclusion
- Lesson learnt

Introduction

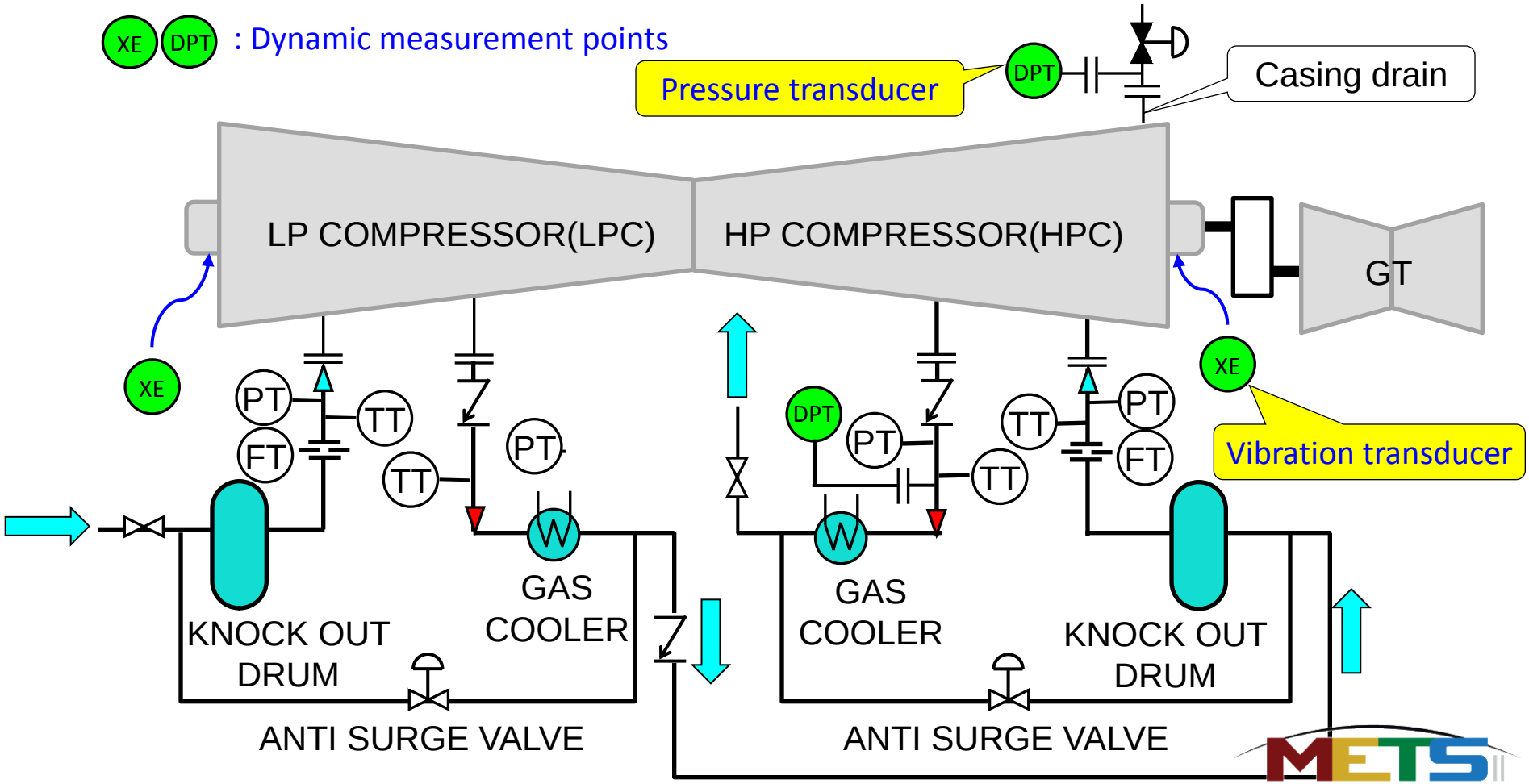
■ During the commercial operation of an eight-stage back to back GT driven centrifugal compressor locates at the end-user's off-shore platform, high level shaft vibration alarm under specific operating conditions was reported from end user.

■ According to the site evaluation test with dynamic measurements, sub-synchronous vibration (SSV) was observed under higher load conditions of high pressure compressor for every operating speed.

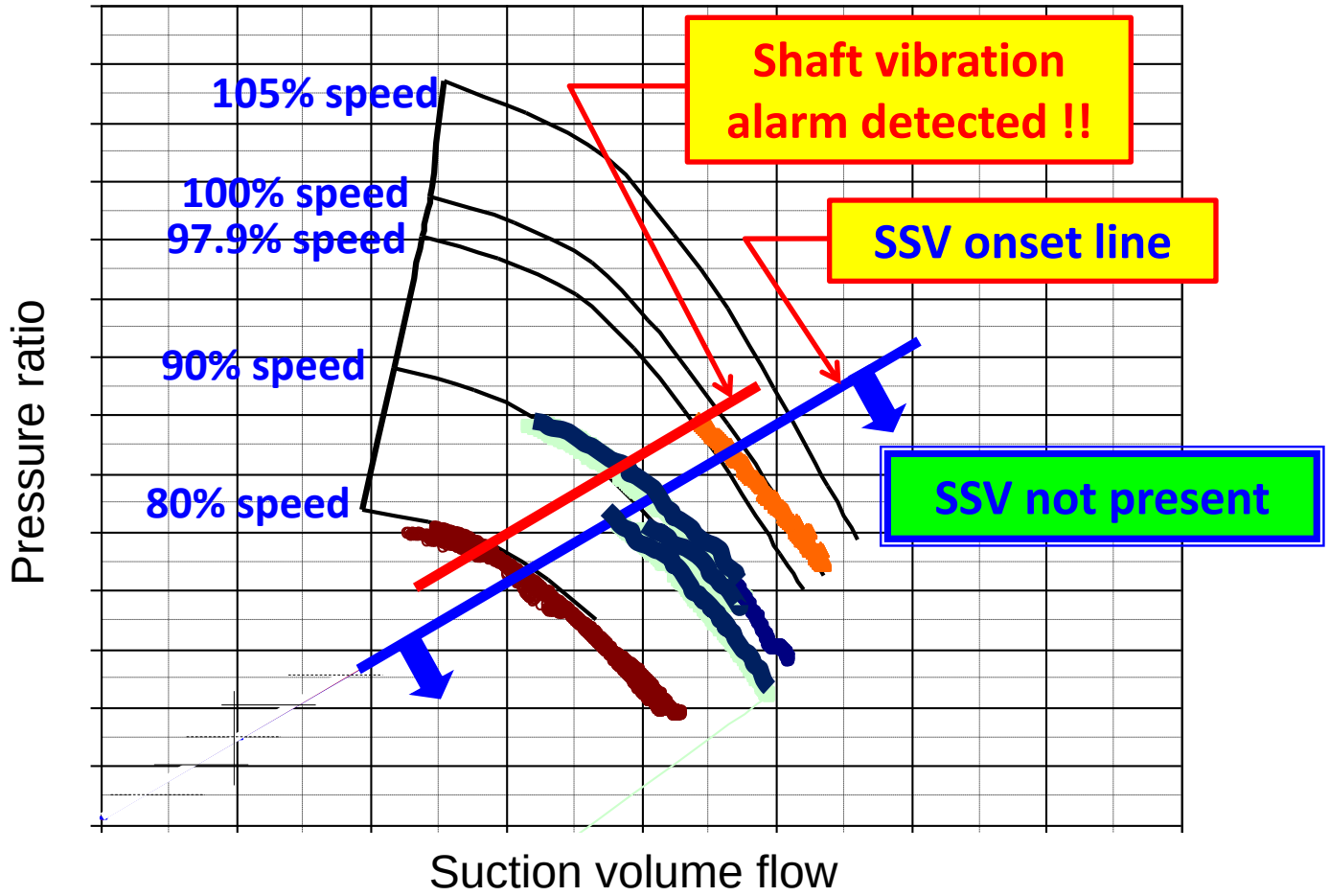
■ This case study features the root cause analysis of SSV problem using large scale unsteady CFD and the final result of site confirmation test after improvement.

Findings (1)
Site Evaluation Test

- *Site evaluation test was conducted to understand the circumstances.*
- *Dynamic measurements of rotor vibration and discharge pressure at HPC casing drain and downstream piping were implemented.*



Findings (2)
Operable Range and Shaft Vibration

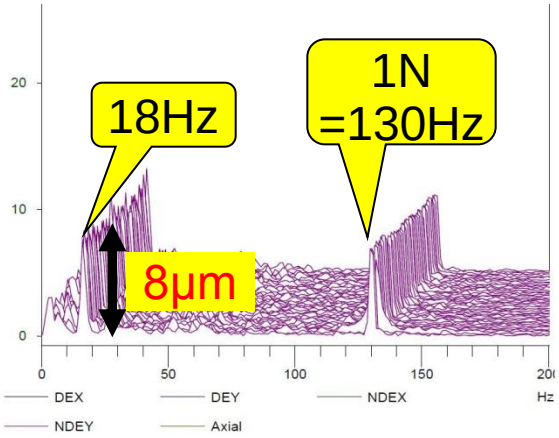


HPC operating map

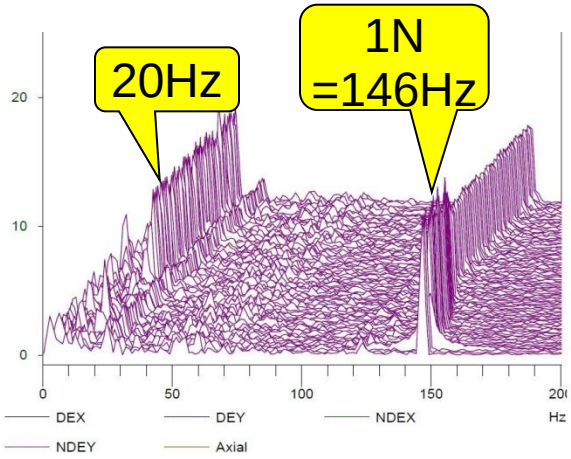
- Operable range was restricted by high level shaft vibration.
- SSV onset points correspond to increase of shaft vibration.

Findings (3)
Sub Synchronous Vibration

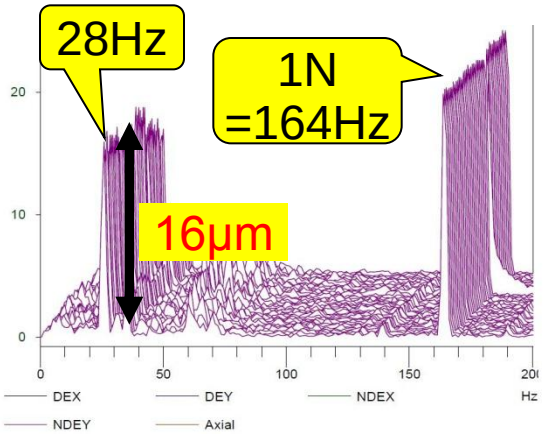
80% speed



90% speed



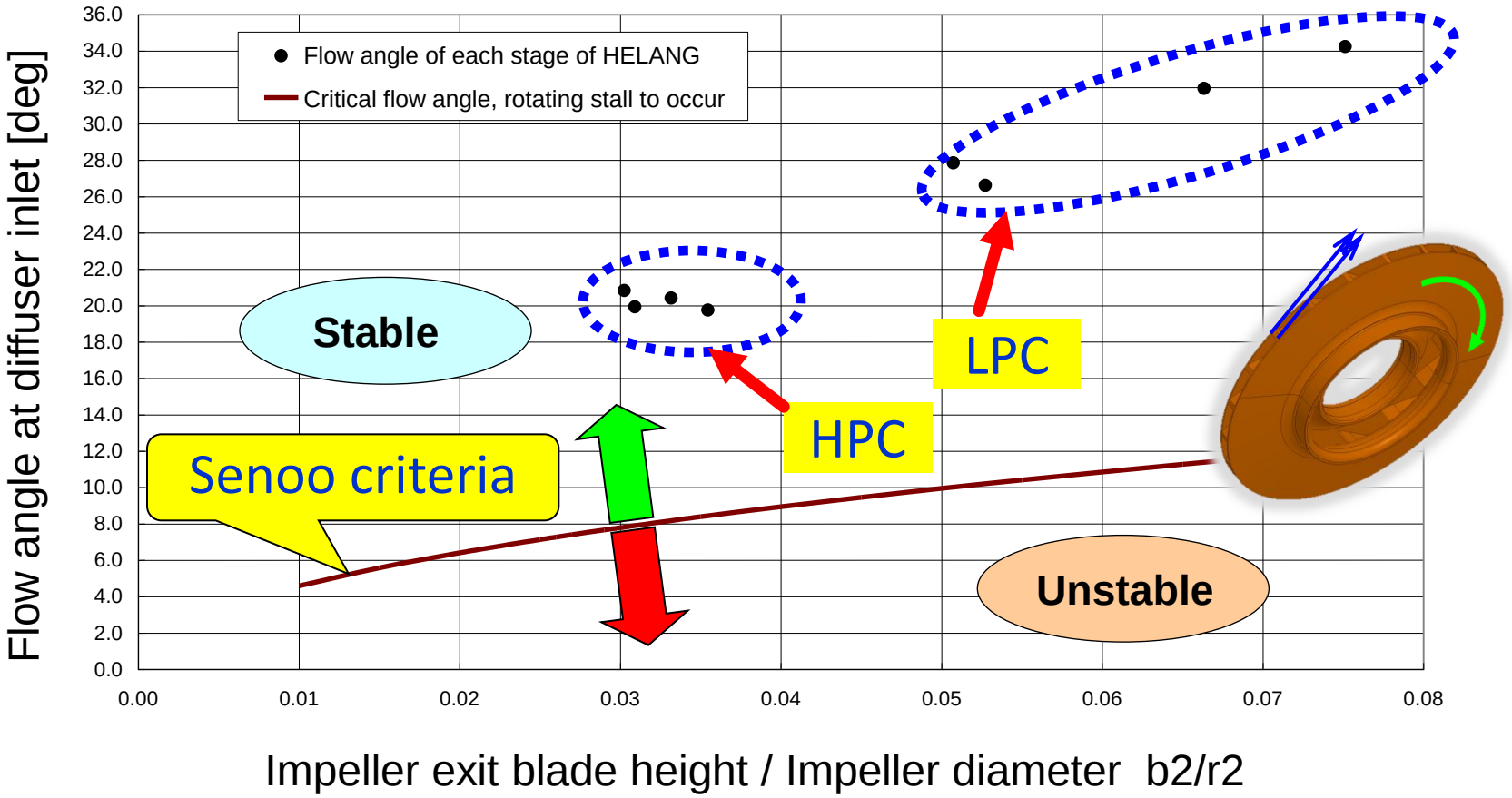
100% speed



Observed radial shaft vibration (Y-NDE)

- SSV around 20~30 Hz were dominantly present. They were approximately 1/6~1/7 times the machine rotational speed.
- Same frequency of discharge pressure fluctuation were also detected at casing drain and down stream piping.
- Is this a typical vaneless diffuser rotating stall ?
  At first we suspected it as the most possible root cause.

Root Cause Analysis (1)
Rotating stall check at vaneless diffuser inlet

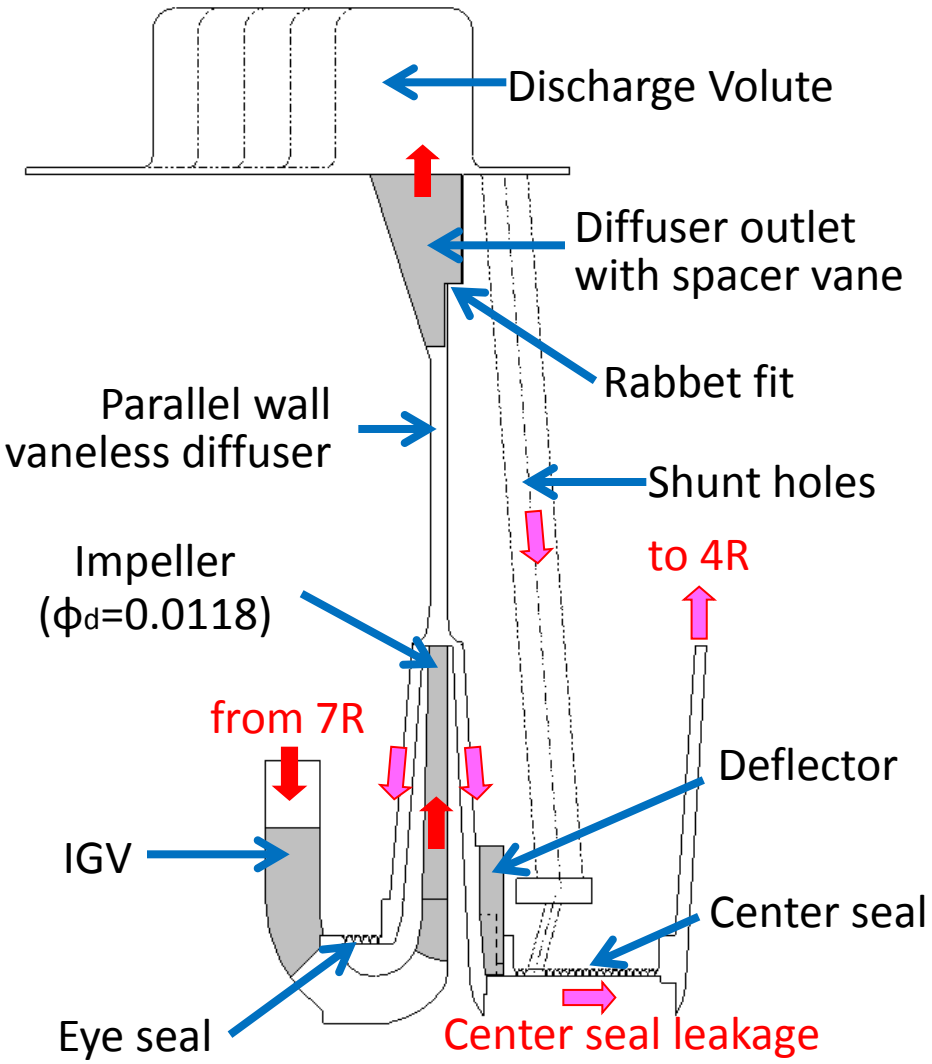


- Rotating stall at diffuser inlet is checked at the design phase based on Senoo criteria. And it was re-confirmed that sufficient acceptable margin were secured.

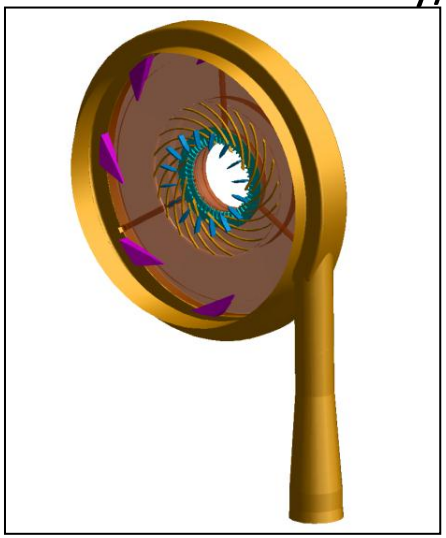
➔ It indicates the root cause is not a rotating stall at diffuser inlet.

Root Cause Analysis (2)
CFD Analysis of 8th stage

- *Large scale unsteady CFD analysis was carried out for the 8th stage.*

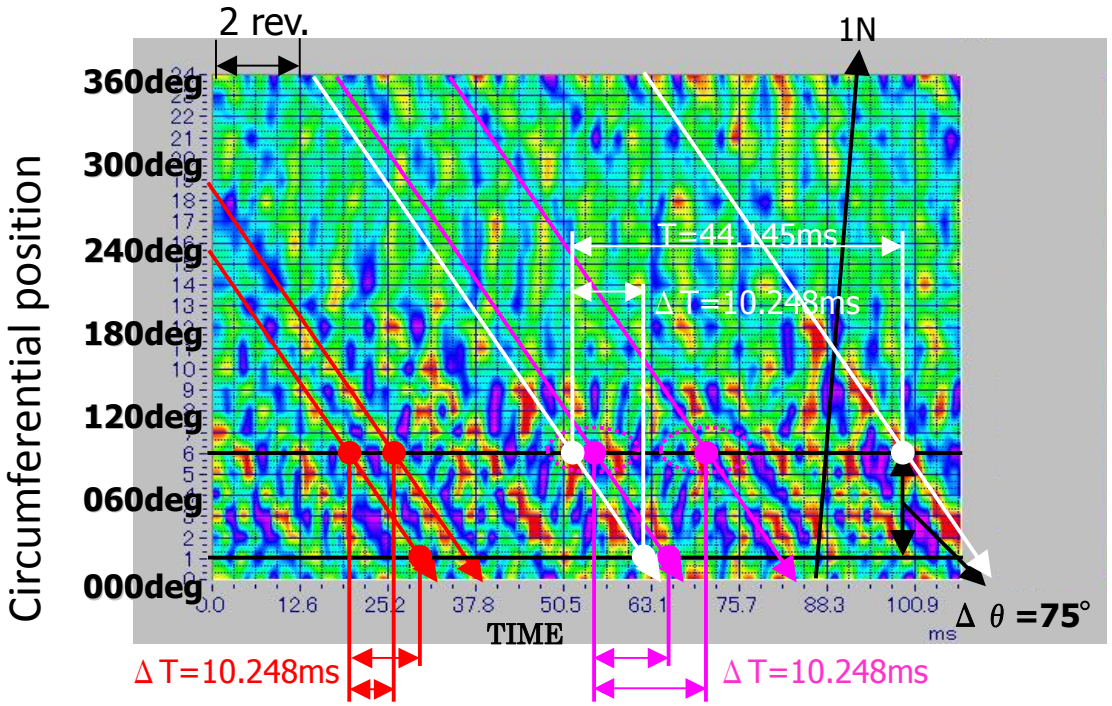


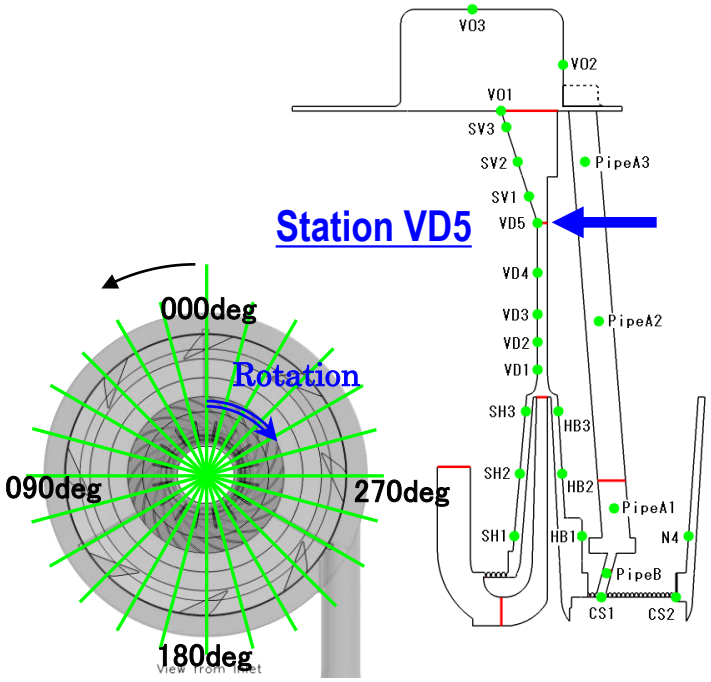
- Number of vane
  - Impeller = 22 w/t splitter
  - IGV = 16
  - Spacer vane = 8
- Number of shunt holes = 3
- Rotating speed =9514 rpm
- Calculation time = 1day/rotation



Birdview from upstream

Root Cause Analysis (4)
Static pressure fluctuation at spacer vane inlet





Time & space distribution of static pressure at spacer vane inlet

$$m=\frac{360}{\Delta\theta}\frac{\Delta T}{T}=\frac{360}{75}\frac{10.248\times10^{-3}}{6.3065\times10^{-3}}=7.8\rightarrow8$$

$$f_0=\frac{1}{T}=\frac{1}{6.3065\times10^{-3}}=159Hz$$

$$f_r=\frac{1}{mT}=\frac{1}{8\times6.3065\times10^{-3}}=$$ 20Hz

$$m=\frac{360}{\Delta\theta}\frac{\Delta T}{T}=\frac{360}{75}\frac{10.248\times10^{-3}}{15.766\times10^{-3}}=3.1\rightarrow3$$

$$f_0=\frac{1}{T}=\frac{1}{15.766\times10^{-3}}=63Hz$$

$$f_r=\frac{1}{mT}=\frac{1}{3\times15.766\times10^{-3}}=$$ 21Hz

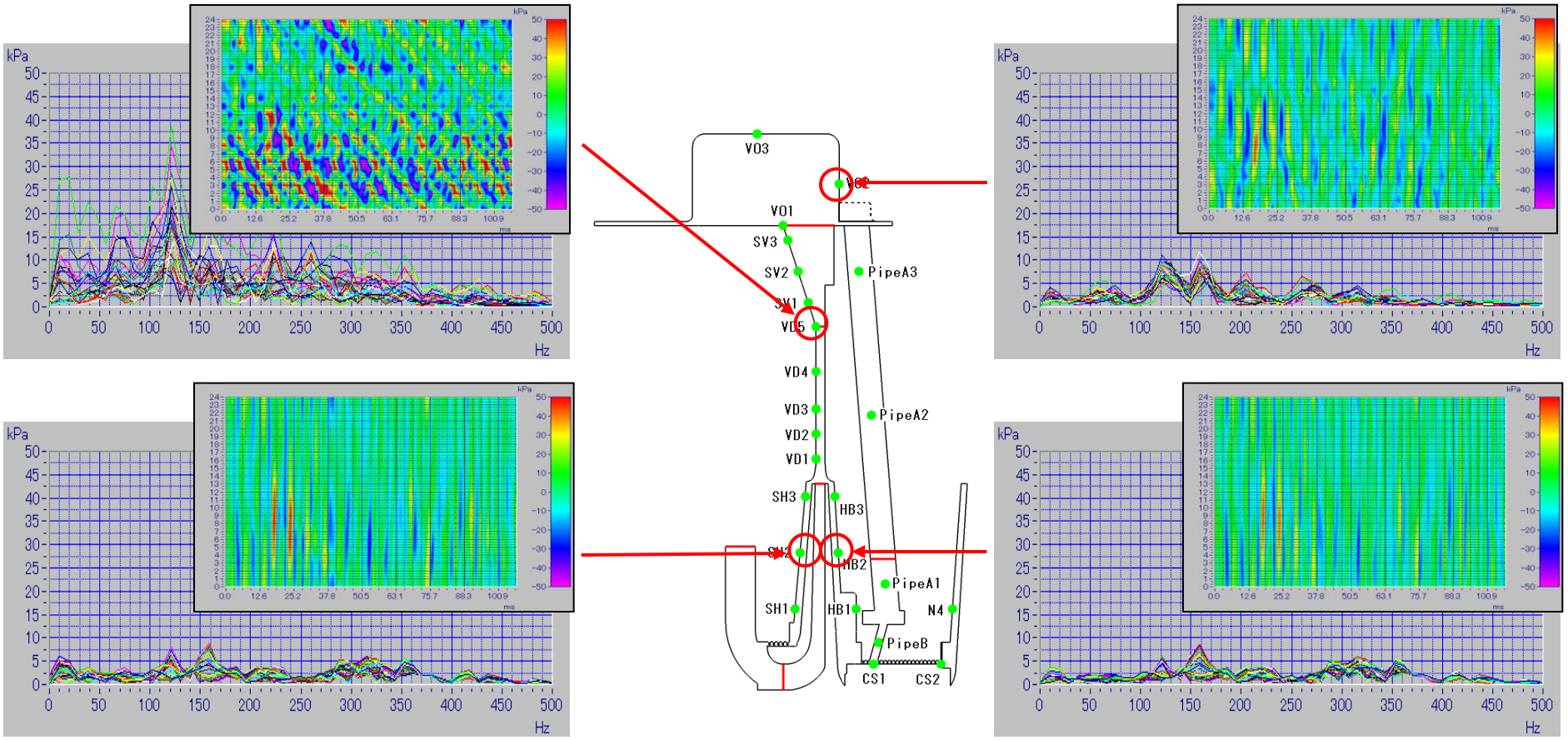
$$m=\frac{360}{\Delta\theta}\frac{\Delta T}{T}=\frac{360}{75}\frac{10.248\times10^{-3}}{44.145\times10^{-3}}=1.1\rightarrow1$$

$$f_0=\frac{1}{T}=\frac{1}{44.145\times10^{-3}}=23Hz$$

$$f_r=\frac{1}{mT}=\frac{1}{1\times44.145\times10^{-3}}=$$ 23Hz

- Close frequency as observed at site test could be simulated.

Root Cause Analysis (5)
Static pressure fluctuation at other stationary region

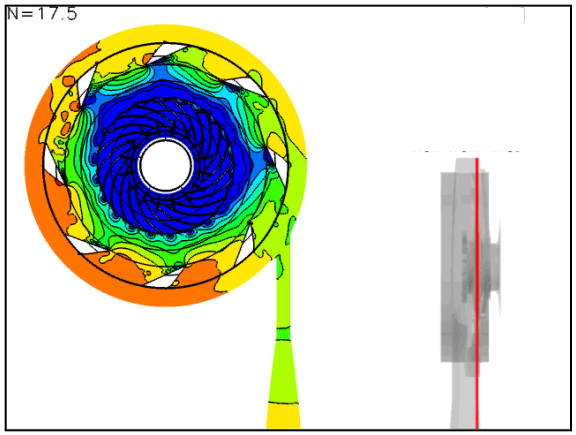


Static pressure time & space distribution & FFT spectra

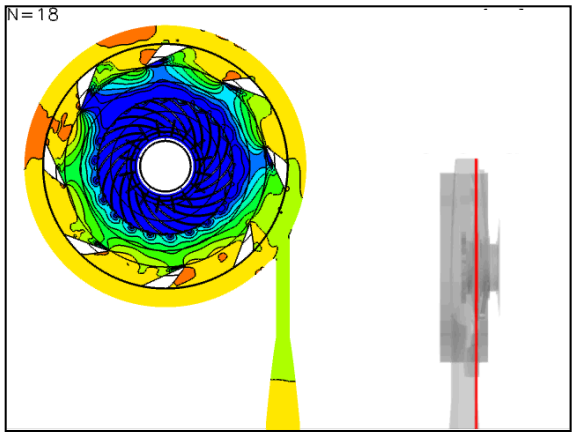
- Strong pressure fluctuation at spacer vane inlet affects to the other stationary region.

Root Cause Analysis (6)

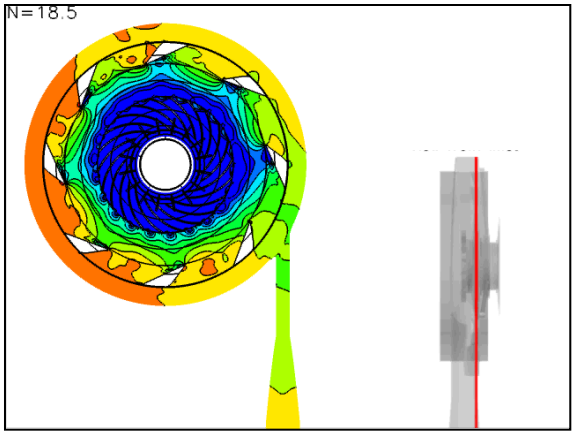
Unsteady pressure distribution across the stationary region



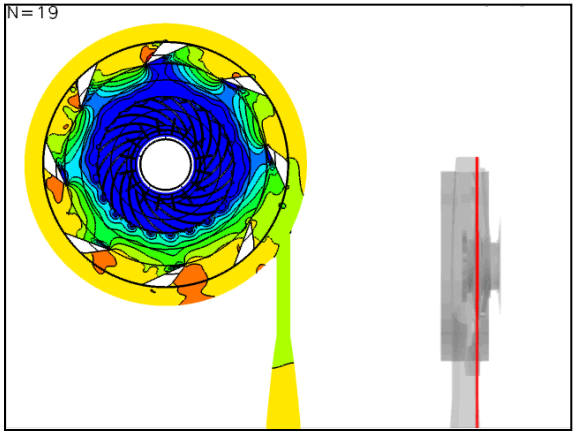
N=17.5TH REVOLUTION



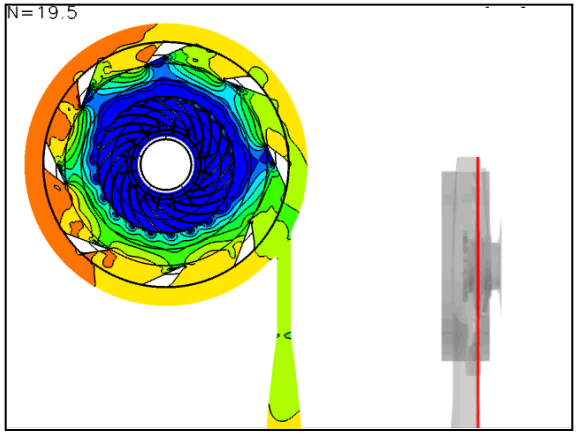
N=18.0TH REVOLUTION



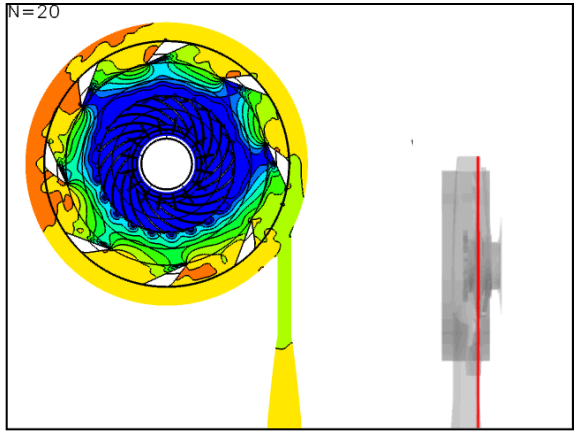
N=18.5TH REVOLUTION



N=19.0TH REVOLUTION



N=19.5TH REVOLUTION



N=20.0TH REVOLUTION

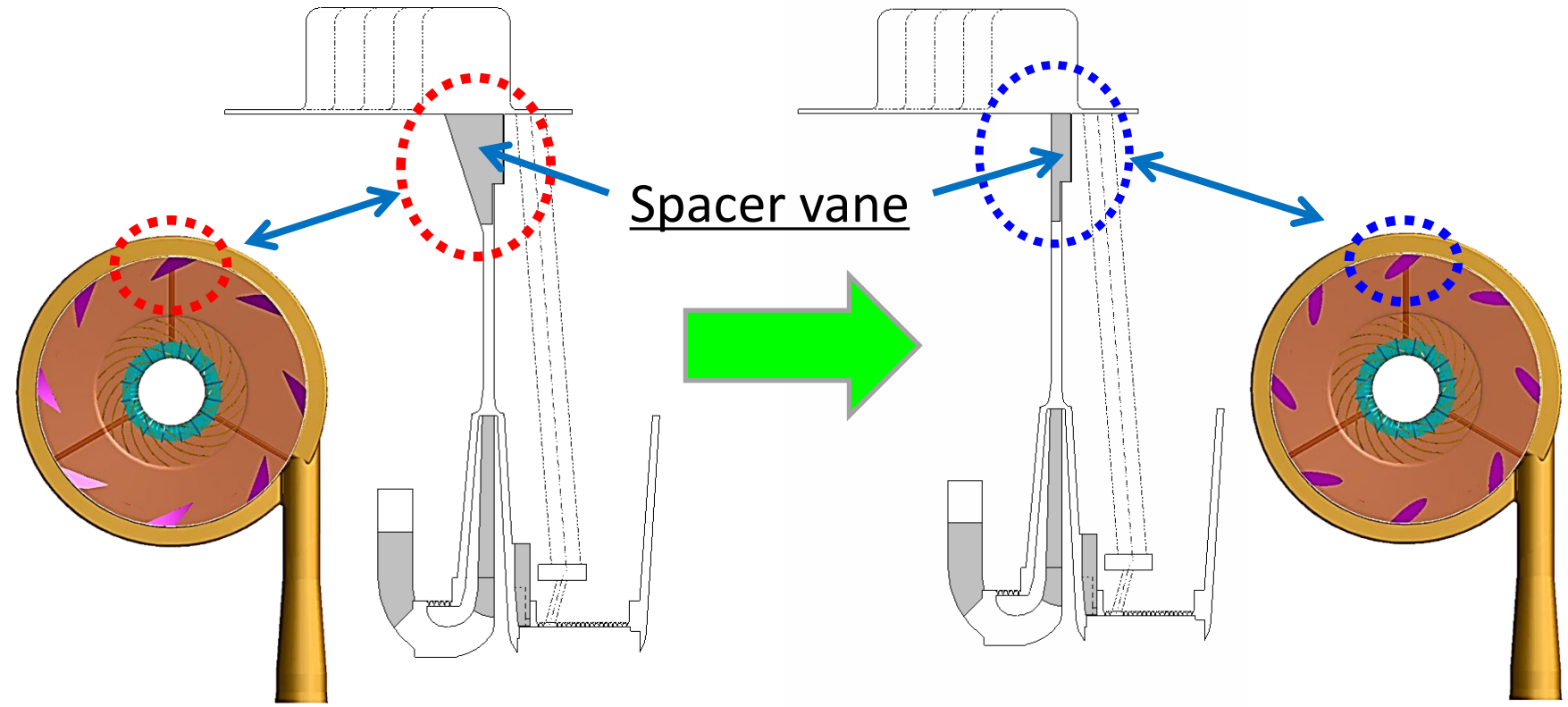
Static pressure distribution

- Periodic pressure fluctuation was shown across the whole stationary region.

Root Cause Analysis
Summary

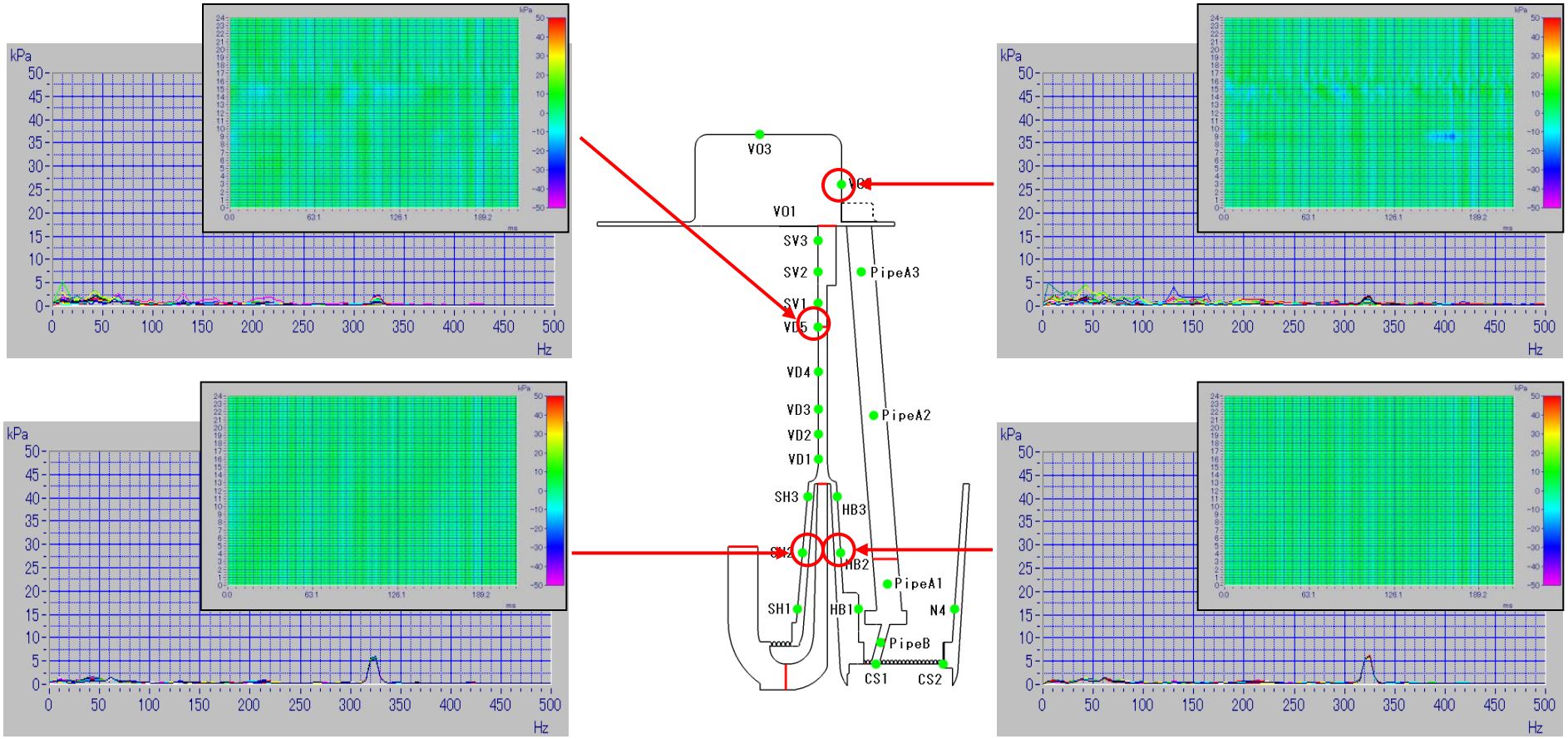
- A large scale unsteady CFD analysis achieved to simulate the sub-synchronous phenomena as close frequency as measured SSV at site test and indicates strong flow fluctuation due to large flow separation at the diffuser outlet with spacer vane at the final stage.
- It was considered that the root cause is complete stall induced from diffuser outlet due to excess flow passage expansion between diffuser outlet and discharge volute at the final stage.
- Therefore, configuration of ‘diffuser outlet with spacer vane’ shall be re-designed.

Modification
Improved diaphragm of 8th stage



- Cross-sectional configuration of diffuser outlet was changed from expanded shape to parallel wall shape
- Spacer vane shape was also changed from cusped to elliptical blunt.

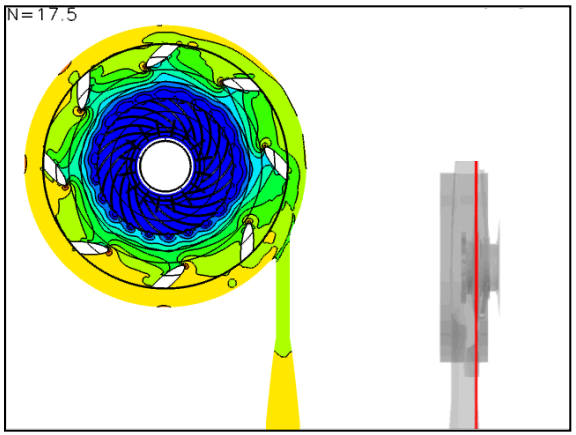
Validation of modification (1)
Static pressure fluctuation at other stationary region



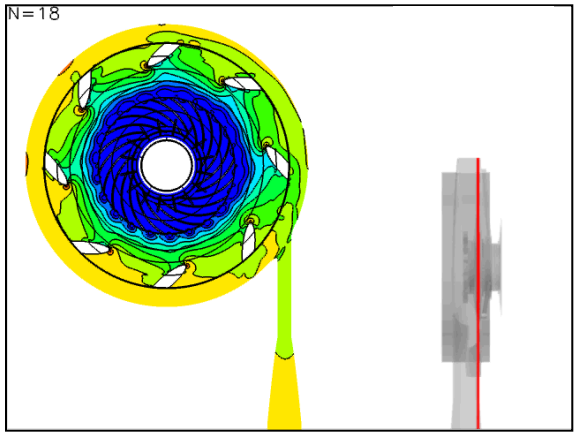
Static pressure time & space distribution & FFT spectra

- Confirmed no presence of noticeable time & space distribution of static pressure at spacer vane inlet and other stationary region.

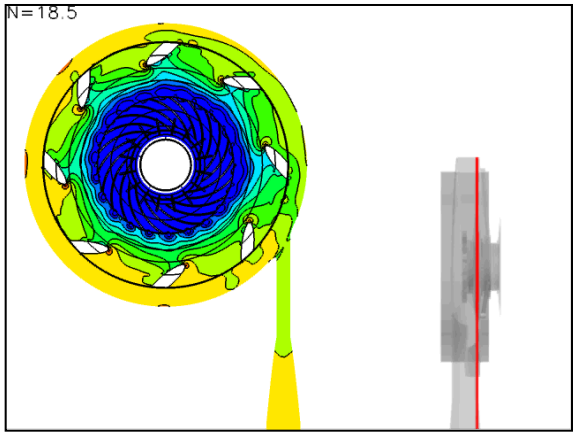
Validation of modification (2)
Flow stability across the stationary region



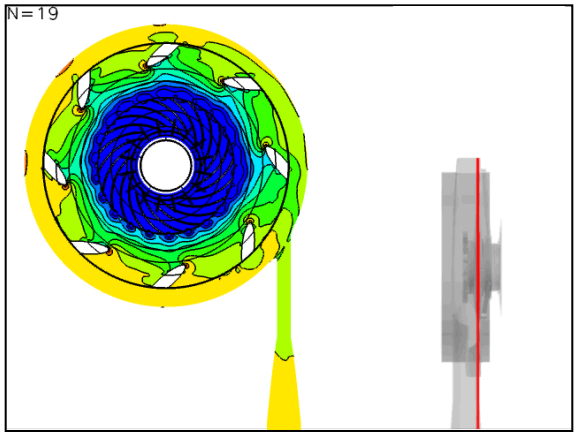
N=17.5TH REVOLUTION



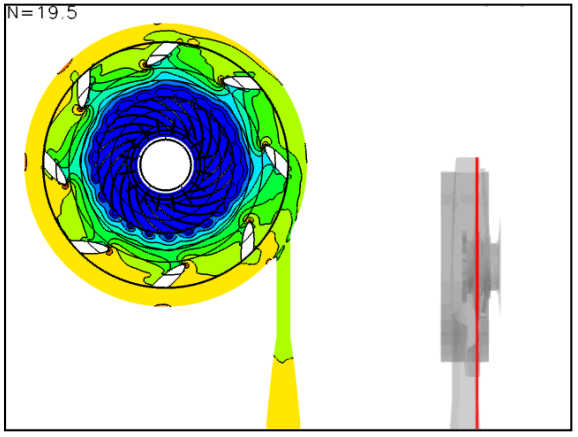
N=18.0TH REVOLUTION



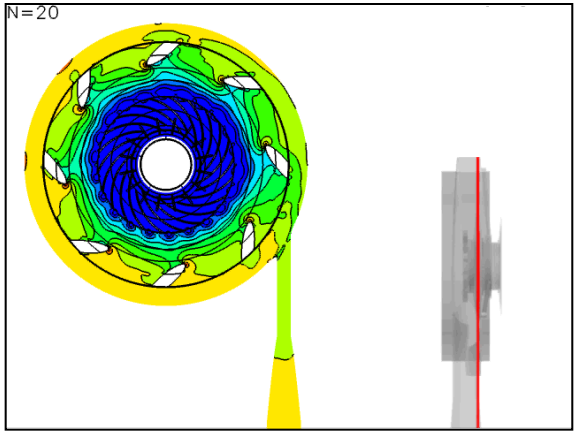
N=18.5TH REVOLUTION



N=19.0TH REVOLUTION



N=19.5TH REVOLUTION

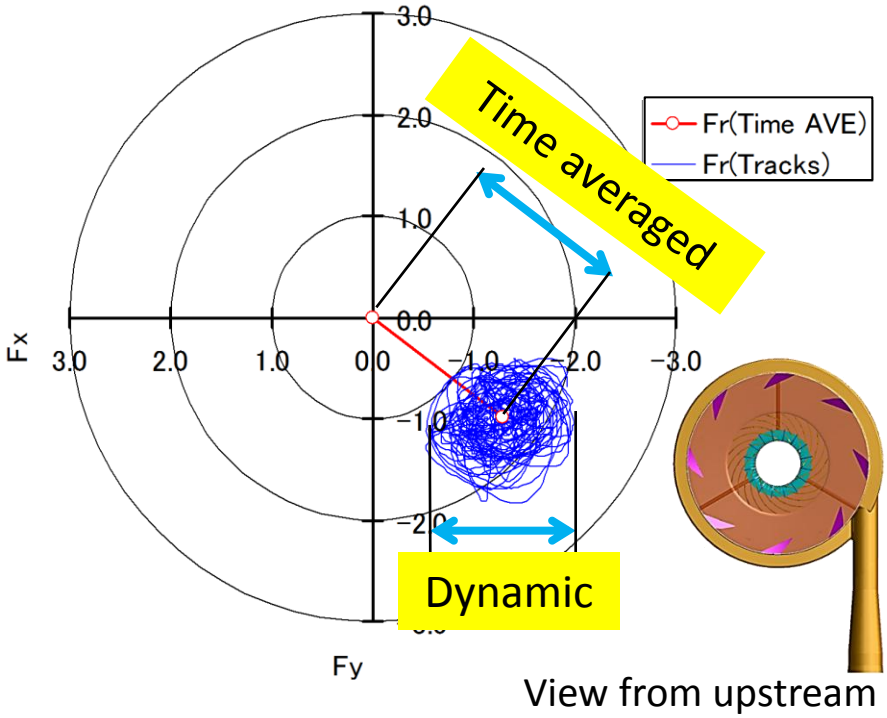


N=20.0TH REVOLUTION

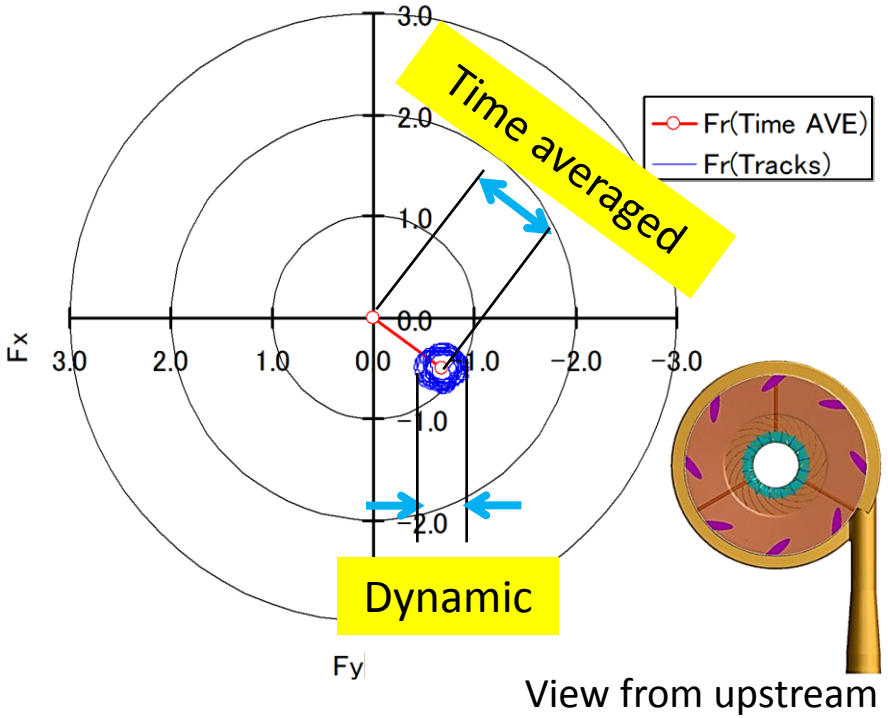
Static pressure distribution

- Pressure fluctuation at the stationary region completely disappear.

Validation of modification (3)
Rotor excitation force



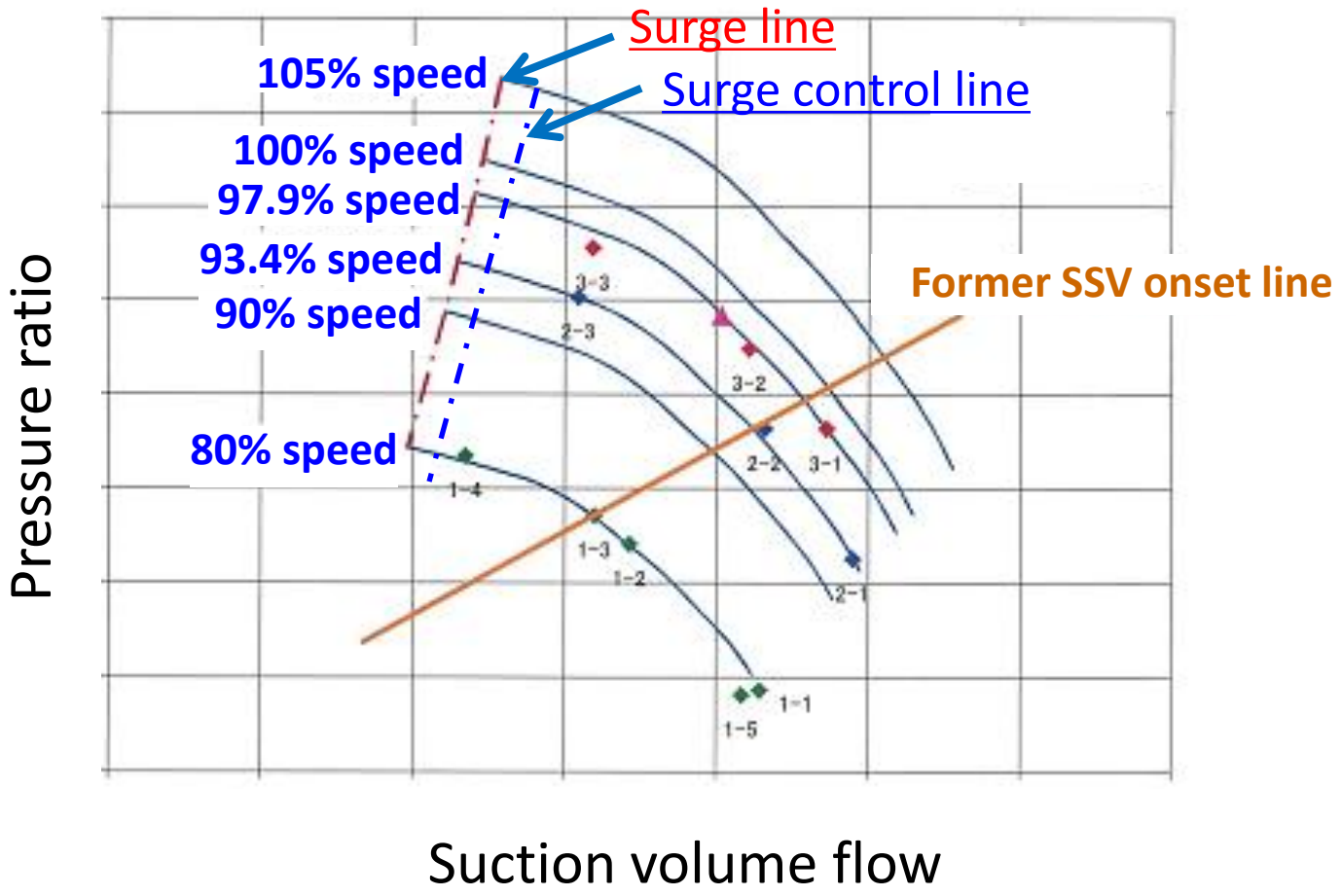
Pre-modified



Modified

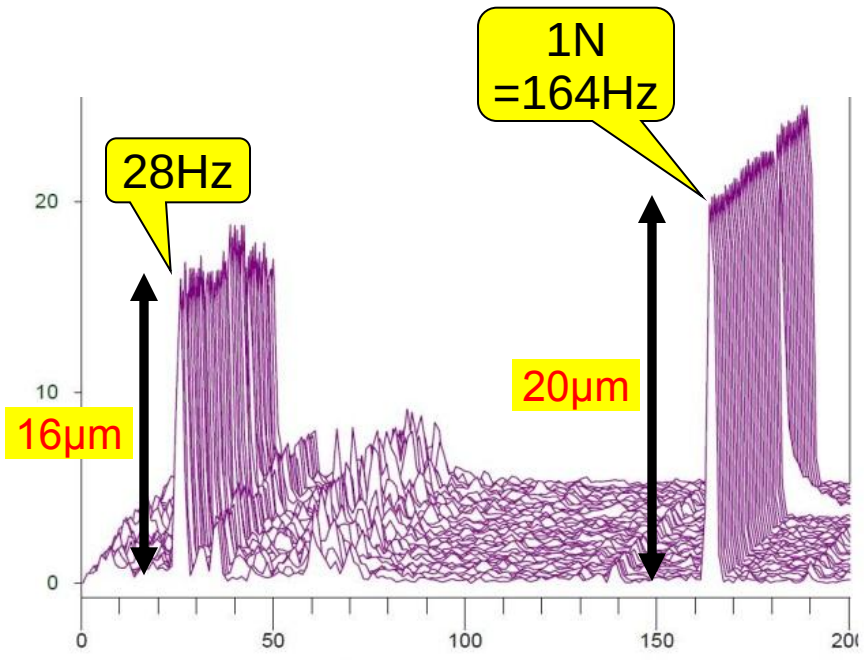
- Rotor excitation force at the stage 8th occurs in the direction of discharge nozzle.
- Excitation force time averaged/dynamic have both decreased in association with modification.

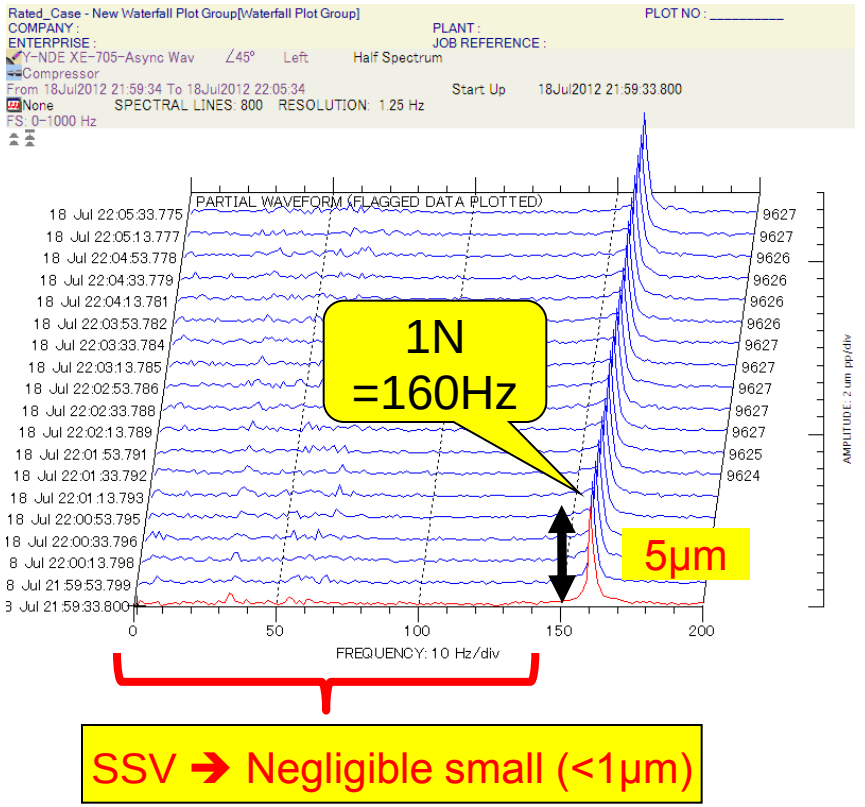
Site confirmation test (1)
Operable range & Shaft vibration



- Confirmed wide operable range is secured as estimated
- Overall vibration is less than 25μm for whole operable range

Site performance test (2)
SSV presence





Pre-modified

Modified

- Confirmed no dominant SSV presence for all operable range.

Conclusion

- With regard to the natural gas export compressor on the off-shore platform which was restricted its operable range due to SSV as 1/7 times the machine rotational speed, a large scale unsteady CFD analysis was carried out in order to investigate the root cause.
- The CFD analysis achieved to simulate those sub-synchronous phenomena. And it was found that the root cause was a typical stall at diffuser outlet due to excess flow passage expansion between diffuser outlet and discharge volute at the final stage.
- Modified stationary flow passage was designed and validated its effectiveness by CFD analysis in the same manner as root cause analysis.
- Modified diaphragm was already installed to the site machine. The followings were confirmed through the site evaluation test.
  * No presence of dominant SSV for whole operable range
  * Operable range is secured as estimated

Lesson & Learnt

- Even the stalls in such a stationary flow passage region apart from the rotor can be the excitation force of shaft vibration especially under high pressure condition.
- Sufficient consideration and care with a broad view shall be taken during the engineering phase.