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Detection of Stall Region during Testing of Compressor

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***ABSTRACT** - Most of the algorithms for anti surge control for industrial centrifugal compressor work on the data taken from various process parameters . In recent years , some more works have been done to co- relate the compressor stall / surge with machinery vibrations. These features have been applied in some compressor control PLC as well. Compressor stalls are aerodynamic stalls which can result to reduced compression efficiency or complete breakdown in compression. Stall is normally a precursor to surge which cause radial vibration at certain frequencies .Pure surge, on the other hand, is an axisymmetric oscillation of the mass row along the axial length of the compressor. It is more severe than rotating stall and may cause severe damage to compressor. For high speed , high pressure centrifugal compressor, it is imprative to conduct a ASME PTC10 type 1 test before equipment is towed out. For high pressure centrifugal compressor, aerodyanmics induced vibration may lead to Resizing diffuser and return channelleading to enormous delay if issue is not identified at OEM (Original equipment manufacturer) test bench itself .This paper provides a road map to draw a surge limit line and locating stall region in compressor map which can help deriving a Real Surge Precursor Algorithm based on vibration and dynmaic pressure analysis at OEM works . These can be used also as a part of diagnostic tool to identify the real source of sub synchronous vibration.*

***Keywords** – Subsynchronous Vibration , Dyanmic pressure transducer, Axial excursion , low / high pass filter.*

I. Introduction

When the pressure ratio across a centrifugal compressor exceeds the maximum pressure ratio that can be produced for that gas and impeller speed, the flow will suddenly reverse through the compressor.If the condition that has temporarily created a higher than designed pressure ratio across the compressor is not changed , the flow reversal will repeat. At this point, the compressor shall be in surge.

Incipient surge occurs when the flow through the impeller is not sufficient to fill the impeller flow passage. Boundary layer separation occurs on the trailing side of the vanes. Stall cells are formed in the separation area and when they reach the impeller exit, it moves in a counter-rotation direction to another flow passage. Some of the times rotating stall occur just before the time of surge. Incipient surge is a flow disturbance in the blade passage of the impeller when the flow is very low, but still "going forward". If there is not enough gas flow to fully fill the blade passages in the impeller, boundary layer separation occurs on the trailing side of the blade. When the boundary layer separates, eddy currents form. The shearing energy that creates the eddy currents becomes velocity energy in the eddy currents. These eddy currents escape the blade passage and move radially outward into the diffuser. Once in the diffuser, they fall behind the impeller and move back into one of the following blade passages. When they land in one of the blade passages, they impart their energy into that passage as a pressure pulse. This pulse acts normal to the shaft.

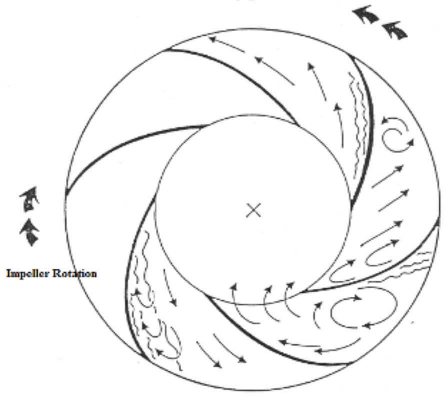

Fig -1 – Flow separation and Stall Cell Propagation in Centrifugal Compressor Impeller

To avoid compressor instability due to stall, OEM maintains Seeno- Kinoshita / Nishida –Kobayshi criterion during design stage; but still in some cases , compressor can demonstrate high sub synchronous vibration. Hence the drawing a stall line at test bed is important to avoid unexpected Rotor / Blade vibration at site particularly for High Pressure Compressor

II. Pulsations In Terms Of Machinery Vibration

In rotating stall condition, a radial pulsation is produced that acts orthogonally of the axis of Rotation of compressor rotor . The pulsation across the impeller due to a rotating stall in a stage can be expressed as approximately: □P ≈ □**U/ 20** where ρ is the density of the gas and U is the impeller tip speed. The exciting frequency of the pulsation are transgressed into radial asynchronous vibration which normally happens at 0.3 - 0.7 X of RPM . This is mostly combined with a Noisy signal and generally cascaded by lubrication related troubles like whirl (0.43-0.47X RPM) or structrual resonance related issues.

Surge propagates axially in gas flow path whereas Rotating stall propagates circumferentially at some fraction of rotating speed. Most of time, common belief is that both occurs together with vibration point of view.

Common belief is that Rotating stall corresponds to frequency signal usually half of rotor frequency. The radial substnchronous vibrations are the effect of Dynamic pressure pulsations that occur during incipient surge which are basically function of the gas density and impeller tip speed squared. The magnitude of the pressure pulsation cause low amplitde vibration due to various damping effects in Rotor Bearing system. Most of the time it is found that frequency of such pulsation are quite close to 1^{st} critical speed of rotor which makes it quite difficult to detect .

The cyclic changes of the pressure difference across the compressor during surge , causes pressure pulses acting in the axial direction. These pressure pulses cause the thrust forces on the rotor to reverse. The thrust reversals, if large enough, can lead to a failure of the thrust bearings, and excessive axial displacement. The high pressure centrifugal compressor do have comparatively lighter rotors .Repeated thrust reversals of sufficient magnitude can damage the thrust bearing, inter-stage seals, shaft-end seals and shaft sleeves.

Noticing an audible squeal during compressor mapping at site , Machinery Vibration trends were taken from event log from diagnostic system . It was observed that time interval of squeal sound and Rotor axial movement trend had some distinct relationship. This excursion was detectable as RPM of rotor was quite low , Compressor was at recycle mode at low suction pressure .Further investigation concluded the reason of squeal noise as obstruction in Recycle line gas path.

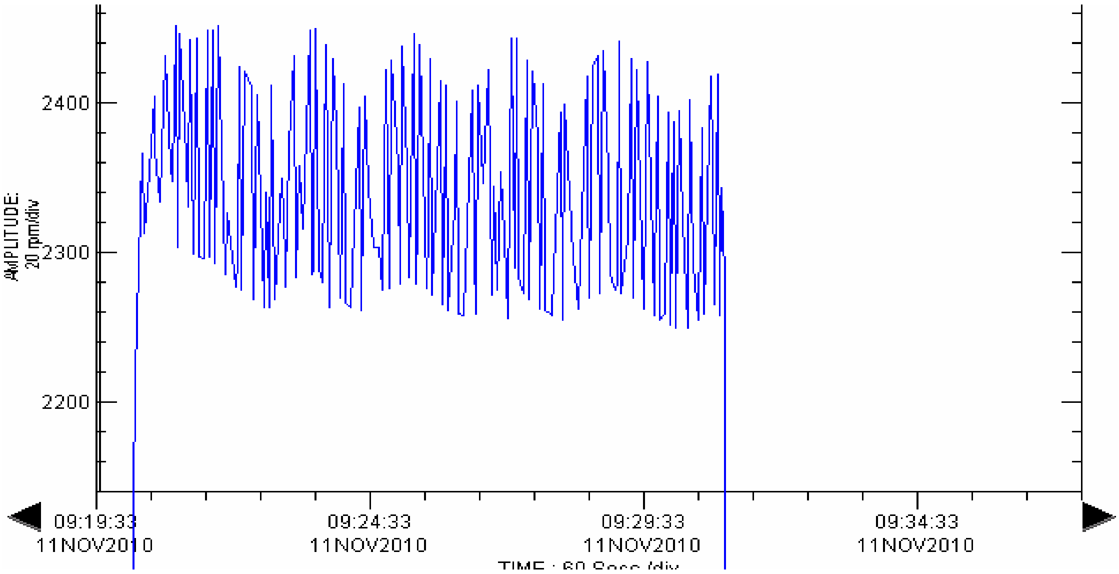

Fig-2 Axial Excursion reading during low level pressure pulstaion in loop

It was evidient that Pressure Fluctuation during surge shall cause axial excursion as above observation. In addition Gear Box Pinion radial vibration fluctuation was observed because of fluctuation of load resulting change in dynamic stiffness of pinion bearing.

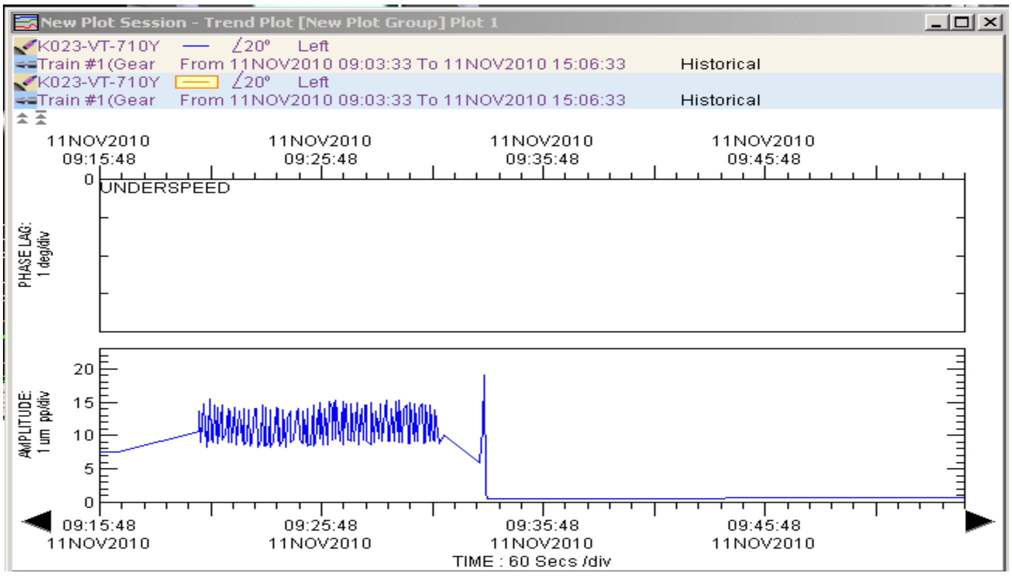

Fig-3 Hunting in pinion vibration readings

The onset of surge / machine stall is accompanied by a low frequency asynchronous vibration which are detected only when the surge energy is quite high .If the Compressor train is driven with a speed increasing gear box , the pinion being the lightest part of system may demonstrate some excitation in low frequency regime and a spectrum can easily reveal the symptom .

Above findings have led to explore a possibility to diagnose such event during field commissioning and a road map to mark up stall region based on possibility to measure the dynamic pressure fluctuations at penultimate impeller stage and prepare a proper prediction algorithm. This write up provides a simplified approach to draw a stage stall or final stage surge line during PTC type 1 test for extremely critical rated Compressor based on measured sub synchronous vibration at Vendor works.

Proposed Road Map - Method to detect stall

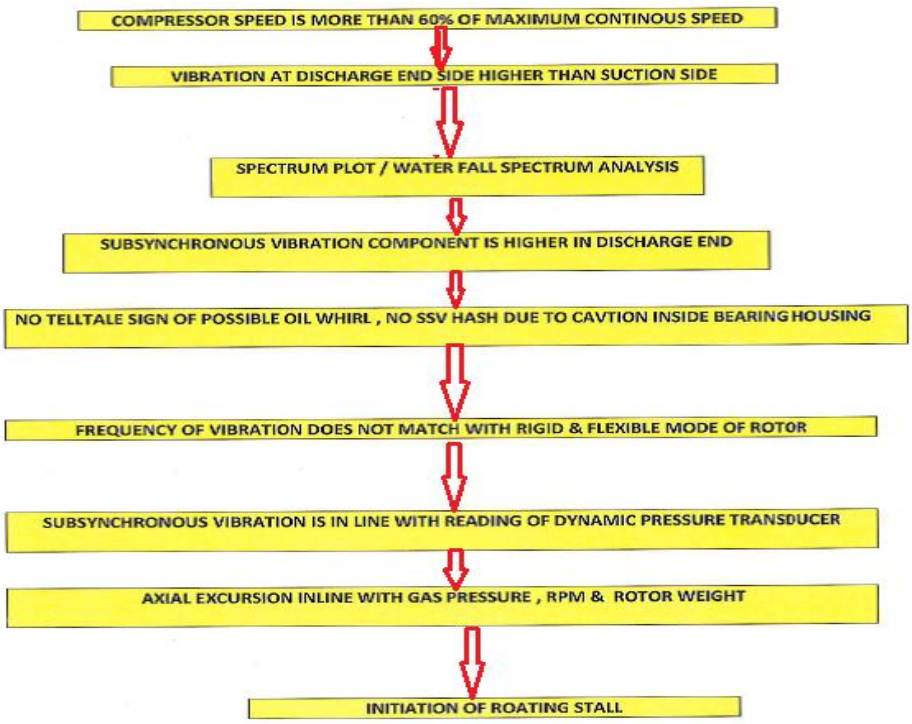

Fig 4 Flow chart to detect rotating stall.

To realize the proposed road map it requires a microprocessor with a good scanning time with a logic box , a counter , Low and High pass filters with Vibration diagnostic tools and signal booster /charge amplifier to amplify gear box casing / compressor casing vibration.
Z1 & Z2 = axial displacement measured by dual proximity probes preferably with a signal booster.
Z0 = difference between Z1 & Z2. This value shall be accompanied with a timerto estimate the severity of rotor excursion.
Process parameter – monitor Ps/Pd and compare to standard ratio from performance curve for reference .
Machine parameter – Rotor weight and RPM .

The logic box shall initiate an alarm for an incipient surge if number of rotor axial shift is more than Z0 micron exceeds predetermined count of A in 2 seconds . Axial position transducers shall be measuring element . The value of 2 seconds is based on numerous vendor experience that compressor can withstand a surge for 2 seconds with surge event counting of 2.
During ASME PTC 10 type 1 test , it is possible to deferentiate the SubSynchronous Vibration and its contributors (Precursor of rotating stall and structural resonance) . Structural Resonance can be detected by loop in shaft polar plot . Structural Resonance can be found in only one opertaing frequency while Compressor is tested at 70% to 105% of value corresponding to rated speed .Hence the element of structural resonance can be eliminated.

In ASME PTC10 type 1 test , compressor is tested from right side of curve to left side by throttling the flow at constant pressiure and at particular speed line . During the PTC 10 Type 1 test , the compressor is tested from 70% to 105% of operating speed range . Dynamic pressure transmitters fixed in stage drain ports can capture the pressure oscialltion with charge amplifier and data aqusition system which shall transform to FFT spectrum .. In addition , a transducer can be installed on compressor casing nearest to discharge side of the compressor to capture low frequency low amplitude vibration .

A schematic of compressor instrumentation in addition to API 670 is shown below where casing vibration transducer (shown in Red) is placed on discharge side and dynamic pressure transmitters (shown in Blue) are placed in compressor stage drain point opening .

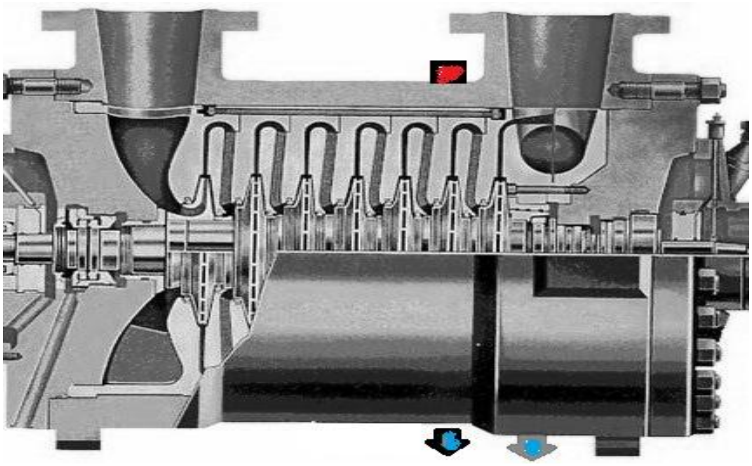

Fig 5- schematic of compressor instrumentation

Before carrying out the ASME PTC 10 test , mechanical run test as per API 617 standard is to be carried out to ensure rotor dynamic integrity of compressor . During testing of 1st unit of compressor as per PTC 10 Type 1 , with throttling the flow towrads the left side of curve radial vibrations are measured along with FFT spectra of pressure pulsation in return channel of impeller stages closest to discharge.

While the compressor is operating near to left side of estimated curve drawn by design software , Pressure Fluctuation during Rotating Stall at last stage impeller of compressor might showup higher vibration amplitude with a comapartively dominant sub synchronous descrete peak. When the sub synchrounous peak is detected it is important to rule out stuctural related resoannce issue which can be diagnosed in shaft polar plot and subsequently carrying out the test in other speeds drawn in map . There may be a miniscule rise in casing velocity as well which can further processed by using a signal booster .

All three (X-Yshaft displacement , Casing vibration and Dynamic pressure pulsation) spectrums shall be compared and a corelation shall be drawn which can later used as comparator in logic box.

Axial excursion occurs in rotor during flow reversals while machine is in complete rotating stall / surge . Besides axial excursion of rotor , radial vibrations also occur but energy level of such vibration are quite small to detect as main cause of surge / rotating stall in stage of compressor unless a special type of device and signal processor is to be used .

Aerodynamically induced sub synchronous vibration amplitudes are normally discrete function of flow and speed but a direct function of pressure .Such aerodynamically induced vibration are below 20% of operational frequency and indicative to diffuser induced rotating stall .

III. Instrumentation

Measurement and monitoring of radial vibration with low amplitude at low frequency calls for a very accurate band pass filter . Calibrating very low frequency accelerometer is difficult task .Hence during compressor operation it is quite difficult to pin point onset of surge with the increase of asynchronous vibration as a tool. Hence dynamic pressure transmitter shall be used to detect Rotating stall .

If the unit uses a speed increaser gear box , a low frequency accelerometer and shaft displacement probes can pick up the vibration as pinion is the lightest part in transmission train. It must use Piezoelectric transducer , which shall be capable of overcoming monitor noise shall be less sensitive to strain.

The rotor excursion during surge is dependant on dynamic pulsation of machine which then is a function of gas density and Square of rotor peripheral speed . These axail vibration shall occur at low freuqency hence low pass filtering may be used .

Notes on required Teansducers and sensors

The ability to measure small pressure fluctuations at high static pressure levels is a unique characteristic of piezoelectric pressure sensors. With integrated amplified output, the transducers are well-suited for continuous operation in hostile environments and in field test applications across long cables. Special low-noise cable and charge amplifiers are not required if proper Peizoelectric transducers are used. These sensors are ideal for virtually all dynamic pressure applications with high temperatures range and hence suitable to be used at high temperature gas paths of last stages of compressors.

Although piezoelectric pressure sensors are primarily recommended for dynamic pressure measurements, some quartz pressure sensors have long discharge time constants that extend low-frequency capability to permit static calibration and measurement of quasi-static pressures over a period of a few seconds.

The transducer signal can be doubled and then each signal can be processed with a pre-configured with low pass and high pass filter which can detect diffuser and impeller stall properly.

Solid state construction of a piezoelectric pressure transducer provides a wide linear measuring range which confidently provides calibrations at 100% and 10% of full scale output for most models.

It is worthy to note that gas turbines also use dyanmic pressure transmitters to measure conmbustor rumbles .

Two modes the monitor can be programmed to return measurements in units:

- peak-to-peak dynamic pressure
- rms dynamic pressure

Piezoelectric (PE) pressure transducers with low impedence voltage signal are well-suited for dynamic pressure measurements. They are available in high-impedance charge output and, more commonly, Integrated Circuit Piezoelectric designs. They are fabricated from natural piezoelectric quartz, natural tourmaline, or artificially polarized, manmade ferroelectric ceramics. PE sensors operate over a wide temperature range and have a wide linear dynamic range, ultra high-frequency response. They are small, have flush diaphragms, and provide a clean, high-voltage output.

If low amplitude vibrations are to be measured on casing with accelerometer near the electronic noise floor of sensor signal corruption can occur .Pizoceramic transducers are far better than quartz accelerometers in terms of signal to noise ratio. It is advisable to use pizo velocity sensors.

Dynamic pressure transducers are ideal for measuring pressure transients or dynamic pressure pulsations in gases. With their wide dynamic range, they can measure pressure events with rise times as fast as 5 µs, frequencies to hundreds of kHz, and pressure levels down to fractions of Bar. Using pure synthetic quartz crystals under high compressive preload, these transducers produce a clean, low-impedance voltage signal.

Due deligence with a good background knowledge of field instrument application is necessary to select transducers & sensors for required use.

Machinery protection from Surge / stall can be implemented by continuously comparing monitored parameters against configured alarm setpoints based on measurements at Vendor works. Essential machine information for both operations and maintenance personnel is required to initiate corrective action .

Each channel typically conditions its input signal into various parameters called “proportional values”. Alert and danger setpoints can be configured for each active proportional value.

Diaphragm type pressure transmitter fixed at individual drains can provide performance insight stage wise basis .The proper mounting of such trasnmitter with signal booster / charge amplifier can greatly mitigate attenuation of pressure pulsation signal.

A dedicated peizoelectric sensor can be mounted nera the dischange end casing with predetermined frequency range to detect diffuser / impeller rotating stall with Signal booster.

Bsaed on operating map of compressor generated by sizing and estimation tools amd how close the surge line is close to operating point , casing / individual drains can be decided.

Dynamic pressure sensor connected to change amplifier to DAQ system and then to proper enveloping by High Pass / Low Pass filters to FFT analyzer.A properly programmed software canconfigure the bandpass corner frequencies, along with an additional notch filter, if needed.

Water fall spectrum of pulstaion with RPM and time and water fall spectrum vibration with RPM and time can be a good comparative tool for benchmarking.

A comparator can further be provided in software to compare the surge precursors with predetermined base liane data as drawn during ASME PTC 10 test.

IV. Conclusion

The above proposal is effective only during machine operation as during start up trip multipliers are applied . Different compressors surge at different rates, and even the same compressor will surge at different rates in different applications. While actual surge rates are determined experimentally, still, it is to be noted that Surge duration varies with flow rate / downstream volume, severity of axial excursion is based on rotor weight the damping of rotor vibration is based on Compressor casing to Rotor mass ratio.

The proposed scheme based on flow chart avoids Human error to interpret Surge with maximum extent. All data required for mapping and analysis can be taken from VMS(Vibration Monitoring System)Rack directly with RS232 communication .The proposed system is cheaper and can be used at various sites & test beds with a laptop having the program.

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