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Reliability and condition monitoring of rotary equipment: A case study on BB2 API610 centrifugal pump

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Abstract
Vibration analysis is one of the powerful tool used in condition monitoring of machinery. Through the years a variety of methods was developed to monitor the operation and onset of failures cost effectively. This analysis helps in early detection of faults and failures and thus reduces the losses in industry. This increases the operation and working efficiency of the machinery. Specific aspects to consider while doing vibration measurements are the placement of the probe, type of the probe to be used, operating frequency range etc. This information is relevant in predictive maintenance point of view to establish which component requires replacement and continuous running of plant without breakdown. Once the measurements are taken the method and the technique to analyse the problems are discussed in this paper using a case study. In this work the importance of vibration analysis in an industry is highlighted with a case study. The work was done at BPCL Kochi refinery. This work gives an overview of how vibration analysis can be used to monitor the operation of pumps.

Keywords: Robot, ROS, ARM

I. Introduction

Reliability and condition monitoring are the two main terms which is associated with the machine life. The term reliability is the measure of probability that a machine will perform its intended function for a given specified state of condition. In simple we can analyze reliability of a unit: as the number of components and more the system is complex, its reliability decreases. This means that a system which is simple and is having few components will have higher reliability than complex one.

Reliability is an important factor when we go to industries. For an industry, the number of units working describes its performance. Every unit in an industry is prone to different type of failures which arrests its functioning that will lead to shut down of the unit. That's why industries will have stand by and running components in units that are more prone to failures. This increases reliability of unit.

Maintenance and periodic monitoring is the way by which number of failures of a particular unit can be reduced. There are different type of maintenance. Among them condition monitoring in predictive maintenance is the prime part we deal in this paper. Condition monitoring or CM is the process of monitoring a parameter of condition in machinery (vibration, temperature etc.), in order to identify a significant change which is indicative of a developing fault. The use of condition monitoring permits maintenance to be scheduled, or other actions to be taken to prevent damages and avoid its consequences. Condition monitoring contains a distinctive benefit in this conditions that might shorten normal lifetime can be addressed before they grow to be a serious failure. Condition monitoring techniques are usually used on rotating equipment, auxiliary systems and other machinery (compressors, pumps, electrical motors, combustion engines, and presses), whereas periodic examination using non-destructive testing (NDT) techniques and fit for service (FFS) analysis area unit used for static plant equipment like steam boilers, piping and heat exchangers. Various tools used for monitoring are vibration, temperature, noise, smell, power consumption, oil quality etc. In this paper vibration is the tool which is used for monitoring. This paper also explains about vibration analysis and how it is interpreted.

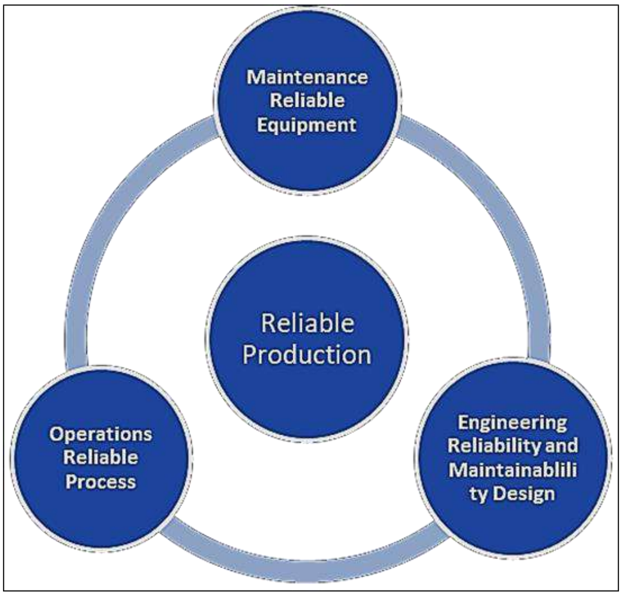

Fig 1: Reliability and Maintenance

1. Importance of condition monitoring

Condition Monitoring System (CMS) is an essential part of any industrial maintenance system which is needed for reliability, safety and efficiency. CMS system is the best part of future maintenance system which will use advanced technology and semiconductor devices for vibration analysis to predict the failure or proactively work to avoid failure. Improving vibrational analysis and conditional monitoring can influence day today functioning of every industrial unit. Also this section of maintenance have a lot of research options in other areas apart from industrial sector.

2. Condition monitoring

Condition monitoring is the method of monitoring the condition of equipment and machinery, which are running condition in respective plants. It is also known as predictive maintenance or condition monitoring. The use of conditional monitoring allows maintenance to be scheduled, or other actions to be taken to avoid the consequences of failure, before the failure occurs. Nevertheless a deviation from a reference value (e.g. temperature or vibration behavior) must occur to identify impending damages. Predictive maintenance does not predict failures but it only helps in predicting the time of failure.

The failure has already commenced and condition monitoring systems can only measure the deterioration of the condition, it is typically much more effective than allowing the machinery to fail. Serviceable machinery includes rotary equipment and stationary plant such as boilers and heat exchangers. They are flexible in detail, and can be adapted to the existing maintenance system.

Vibration analysis is one of the most important condition monitoring techniques that are applied in real life. Most of the defects encountered in rotating machinery give rise to distinct vibration pattern and hence most of false can be identified using vibration signature analysis technique. The tools generally used for condition monitoring are temperature, vibration, oil quality, power consumption and output quality. There are two types of signals encountered in condition monitoring. They are primary and secondary signals. Primary signals are used to access performance of machine and secondary signals mainly give information about different defects which causes vibrations. Analyzing these signals are inevitable in condition monitoring.

Secondary signals shows vibration, sound, leakage and friction wears.

3.1 Condition monitoring techniques

There are different techniques which are used in condition monitoring to analyze the machines and for collection of data to obtain information about the condition of different components of machine. They are:

- Performance monitoring
- Visual monitoring
- Leakage monitoring
- Temperature monitoring
- Vibration & Lubricant monitoring
- Corrosion monitoring

For the techniques mentioned above, we have to use certain electronic equipments to receive data from machines. The equipments commonly used to obtain vibration data from machines are:

- Stroboscope
- CSI 2130 Machinery Health Analyzer
- Pyrometer

A stroboscope also known as a strobe is an instrument used to make a cyclically moving object appear to be slow-moving, or stationary. It consists of either a rotating disk with slots or holes or a lamp such as a flashtube which produces brief repetitive flashes of light. Usually the rate of the stroboscope is adjustable to different frequencies. When a rotating or vibrating object is observed with the stroboscope at its vibration frequency (or a submultiples of it), it appears stationary. Thus stroboscopes are also used to measure frequency.

Fig 2

CSI 2130 Machinery Analyzer also called Vibration analyzer can quickly and accurately identify developing fault in rotating machinery, and then arrive to the root cause of the problem. Simple to use, the CSI 2130 allows maintenance personnel to monitor more machines in less time and focus their effort to analyze and develop action plan for pre- failure corrections. Detecting imbalance and misalignment is simple with most data collectors, but the CSI 2130 can also detect developing fault on bearings and gears. Pyrometer, device for measuring relatively high temperatures, such as are encountered in furnaces. Most pyrometers work by measuring radiation from the body whose temperature is to be measured. Radiation devices have the advantage of not having to touch the material being measured. Optical pyrometers, for example, measure the temperature of incandescent bodies by comparing them visually with a calibrated incandescent filament that can be adjusted in temperature.

Fig 3: CSI 2130 machinery health analyzer

3. Vibration analysis

Vibration can be defined simply as the cyclic or oscillating motion of a machine or machine component from its initial position of rest. Every equipment whether it is static or rotating vibrates during its operation in certain frequencies which may be its natural frequencies or frequency level which may be a combination of natural frequencies of various components they may comprise the equipment. The vibration level will be disturbed or increased when the operating forces experienced by the equipment gets disturbed or unbalanced. The importance of vibration of a machine is that, usually every machine will develop a problem accompanied by increased levels of vibration. The most common problems that produce vibration are:

- Unbalance of rotating parts
- Misalignment of shaft, coupling and bearing.
- Bent shaft
- Eccentric shaft
- Torque variations
- Looseness
- Rubbing
- Resonance, etc.

3.1 Vibration monitoring

Vibration can be defined simply as the cyclic or oscillating motion of a machine or machine component from its initial position of rest. Every equipment whether it is static or rotating vibrates during its operation in certain frequencies which may be its natural frequencies or frequency level which may be a combination of natural frequencies of various components they may comprise the equipment. The vibration level will be disturbed or increased when the operating forces experienced by the equipment gets disturbed or unbalanced. They are:

- Mass of system
- Exciting force, in our case external force caused by unbalance or misalignment
- Damping characteristics
- Stiffness of system

The main purpose of vibration monitoring is to establish the running condition of machinery in a fashion which is object as well as scientific. Vibration can be monitored normally by a general purpose transducer which is installed at the pump or motor bearings or other vibrating components. By the vibration characteristics of a machine we can understand the health condition of the machine. This information can be used in detecting any problems that might be developing in the machine. In industries it is very important to avoid as many faults as possible for the continuous running of plants. By vibration monitoring we can rectify some problems in advance like:

- Severe machine damage increasing maintenance cost
- High power consumption
- Machine unavailability

Compromise in the quality of end products. Machine vibration is very complex. Sometimes overall level of the vibration is only indication of operating condition of a machine. Since the amplitude is not occurring at just one frequency, it is very difficult to locate any specific fault from this. Therefore it is essential to determine the individual amplitudes and frequencies for the identification of fault. A plot of amplitudes and frequencies of all the vibrating components of the machine is known as vibration signature and these signatures are the characteristics of a machine. Any change in such signature indicates impending failure at its location.

Vibration analysis is considered as a very effective method for detecting machine faults and diagnosing the nature and sensitivity of the fault. A skilled person can point out the causes of rough machinery condition by using a vibration analyzer. Some problems, like rotor imbalance and misalignment make up a great proportion of mechanical deficiencies, which can be identified by vibration analysis and further it is rectified. The steps followed by an analyst for vibration analysis of a machine can be summarized as:

- Define the problem
- Determine the machine history
- Determine machine specifications
- Visual inspection
- Obtaining FFT spectrums.

4. Fast fourier transforms

Baron Jean Baptist Joseph Fourier established that any periodic function (which includes machinery vibration signal) can be represented mathematically as a series of sine's and cosines. In other words, it is possible to take a vibration time wave form, whether simple or complex, and mathematically calculates vibration frequencies present along with their amplitude. The process is called a "Fourier transform". Digital vibration analyzer and data collectors actually include a computer chip programmed to perform the FTT function. Most vibration analysis instruments today utilize a Fast Fourier Transform (FTT) which is special case of the generalized Discrete Fourier Transform and converts the vibration signal from its time domain representation to its equivalent frequency domain representation.

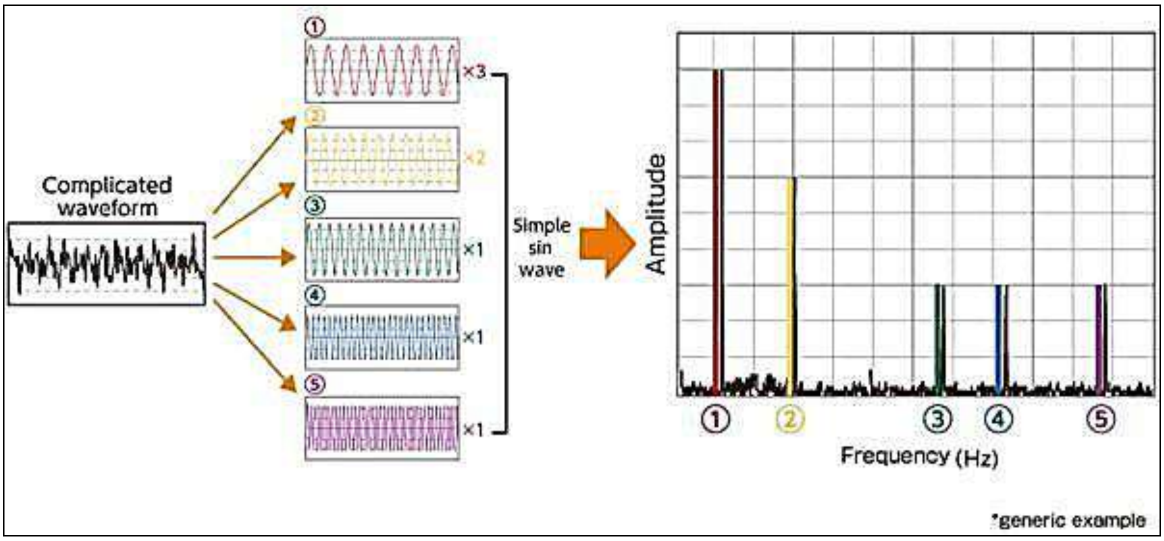

Fig 4: Complex waveform transformed to spectrum using FFT

In order to get vibration data from machines we need devices that can convert mechanical vibrations into electric signals. They are called transducers. Commonly used transducers for vibration analysis are:

- Accelerometer
- PZT Actuators.
- FFT Analyzer
- Vibration Hologram, etc.

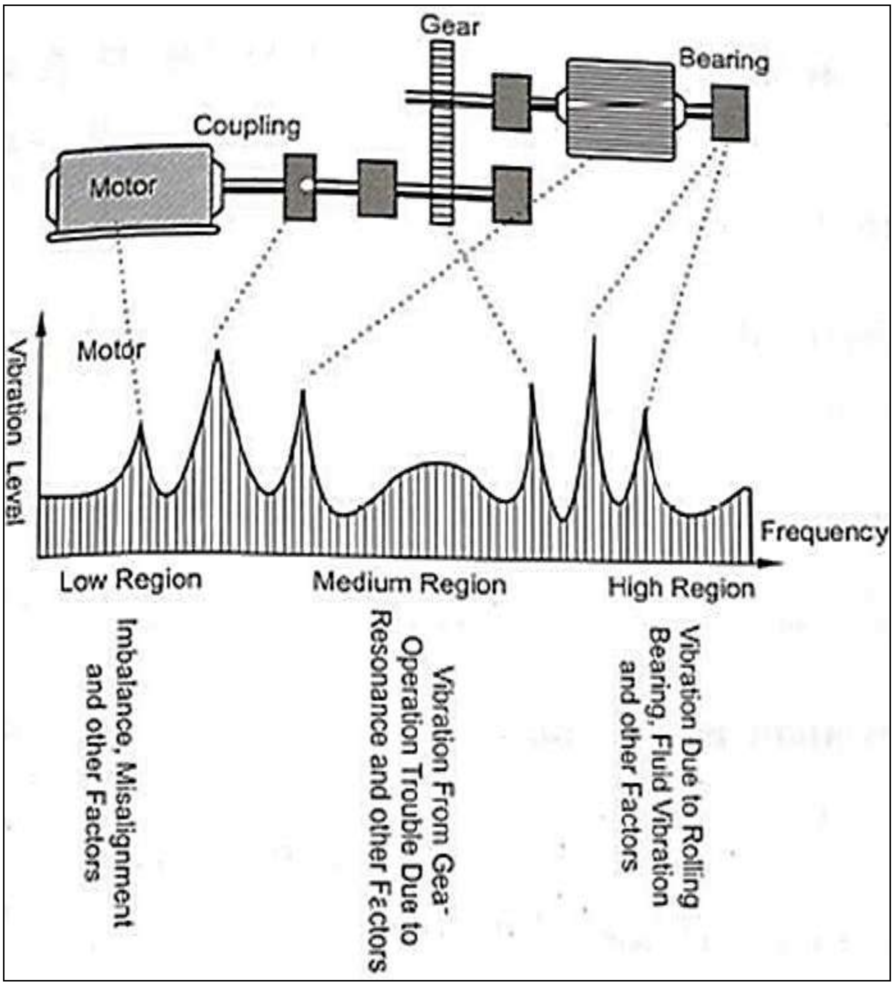

Fig 5: FFT Analysis and spectrum

5. Fast fourier analysis

The vibration spectrum can be explained by means of an example. Consider the time waveform in the figure, which has a frequency of 10 Hz (We can count ten complete cycles during one second) and amplitude of 5 mm (The units of the amplitude could be any unit related to vibration, e.g. displacement, velocity or acceleration).

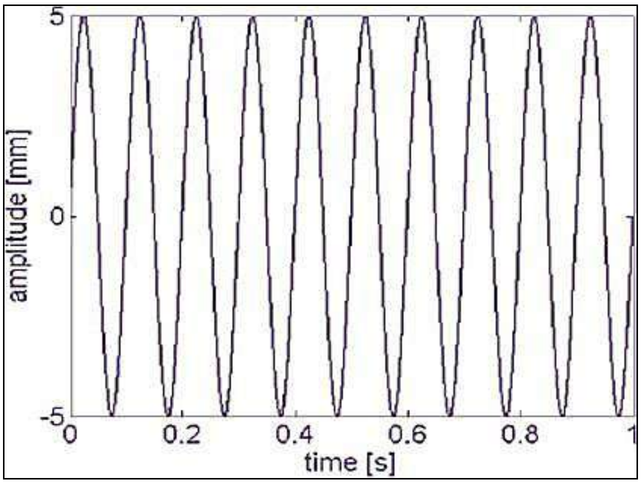

Fig 6

The time waveform is a plot of time vs. amplitude, and is referred to as the time domain. The time domain signal can be converted into a frequency domain representation, which is in fact the spectrum. The spectrum is a plot of frequency vs. amplitude. The FFT for the time waveform from above figure is plotted in figure below. We can understand from this plot that the frequency content of the signal is 10 Hz, and that its amplitude at 10 Hz is 5 mm.

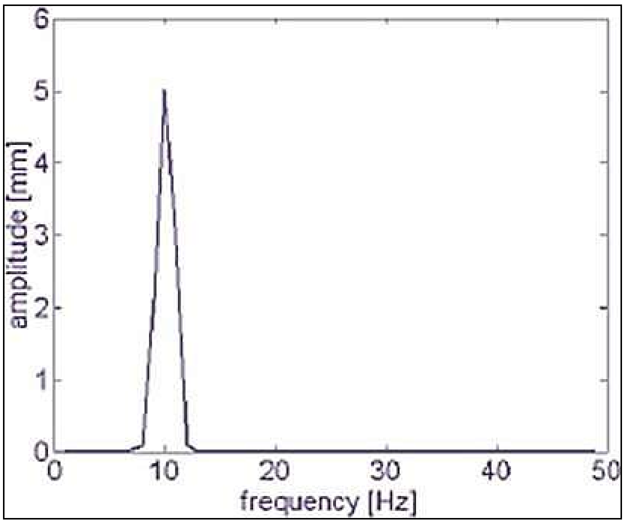

Fig 7

What if our time waveform has more than one frequency present? So let's see another example. Consider the waveforms in figure below. In the top graph we have our 10 Hz waveform, called S1. The second waveform is a 25 Hz waveform with amplitude 2 mm, which we can call S2. The third waveform, plotted at the bottom, is S1+S2, which gives a much more complex waveform.

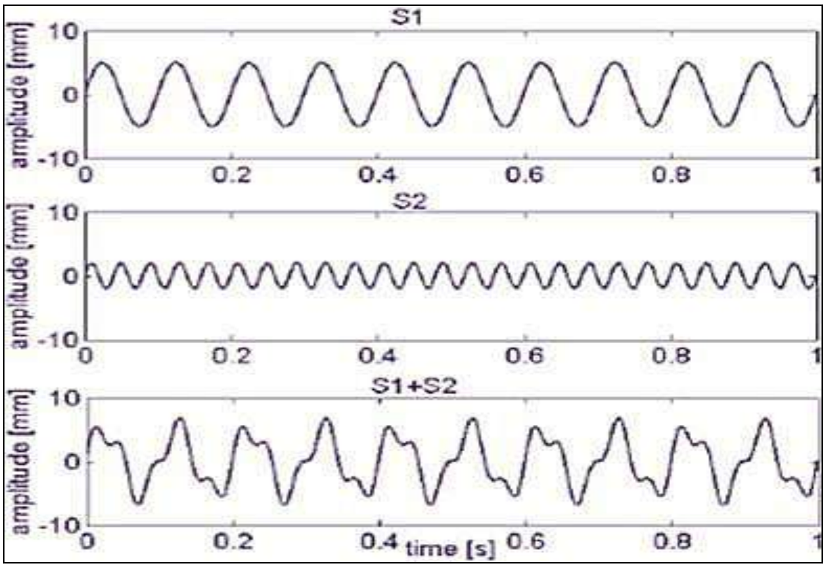

Fig 8

Now study the FFT for S1+S2, shown in figure below. We can see two peaks in spectrum, namely a 5 mm peak at 10 Hz, and a 2 mm peak at 25 Hz. Thus, by only looking at the spectrum, we can characterize our S1+S2 waveform much better than by examining the waveform from figure above. The frequency spectrum is hence much easier to interpret and gives us information that is often impossible to observe by just looking at the time waveform.

6. Machine problems analyzed from vibration spectrum

There are some most commonly occurring machine problems which are easily identified by vibration analysis in condition monitoring. These machine problems are identified by their order in the spectrum and by industrial experience. They are explained briefly.

Imbalance

Unbalance of rotating machine parts is the easiest problem to pinpoint with certainty. It is due to the non- coincident of center of mass with center of rotation. In majority of the cases the data from an unbalanced condition can be seen.

- Vibration frequency = lx RPM of the unbalanced part.
- The amplitude is proportional to amount of unbalance.
- The amplitude of vibration in horizontal and axial readings is greater than vertical reading (for couplings). Generally the ratios are; Horizontal: axial: vertical=5:4:1
- Eccentric journals, pulleys, bent shaft, etc. can also add to imbalance.

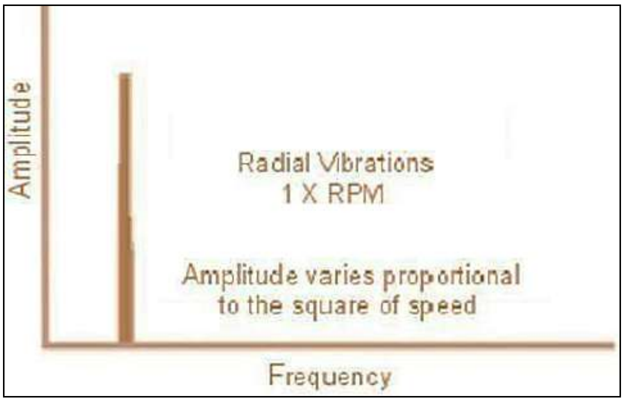

Fig 6: Vibration due to imbalance

Misalignment of parts

Although machines may be well aligned initially, several factors can affect alignment.

- The vibration frequency is lx RPM; also 2x RPM and 3x RPM if the misalignment is severe.
- The amplitude of vibration is proportional to misalignment.
- The amplitude of vibration is high in axial as well as the radial direction. This can be reduced by aligning the parts at operating temperature.

There are three types of misalignment; Offset, Angular, and combination misalignments. Each of these show different spectrum indications. Offset shows at 2x rpm, Angular at 1x and Combination at 1x, 2x, and 3x rpms.

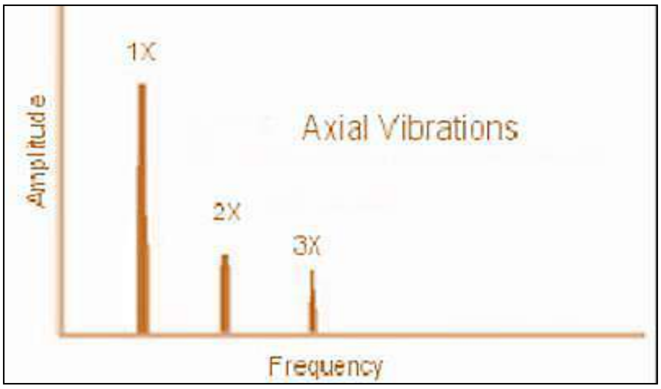

Fig 7: Angular misalignment

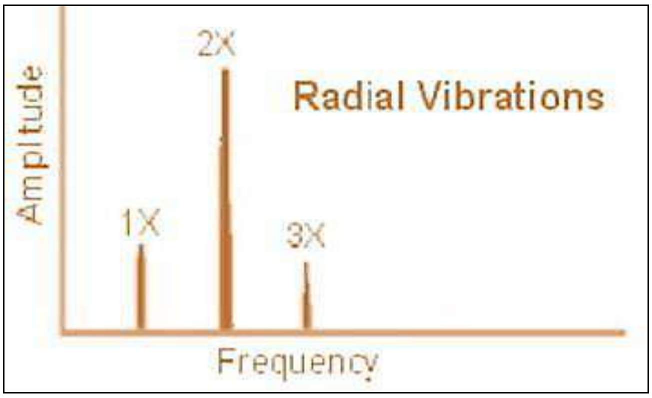

Fig 8: Parallel misalignment

Electric Faults

Common causes of electric faults can be:

- Rotor not round
- Eccentric armature journals
- Rotor and stator misaligned
- Elliptical stator bore
- Open or shorted windings
- Shorted rotor iron

The frequency of vibration resulting from electrical problems will be 1 x RPM. They generally respond to the amount of load placed on the motor as the load changes amplitude readings also changed.

Vibration due to rubbing

Rubbing between stationary and rotating components of a machine will generate vibration at 1x rpm, 2x rpm and higher frequencies. Continuous friction because of rubbing will excite high frequency resonance in other parts of the machine and probably the amplitude and phase readings will be very unstable.

Bearing failure

When a rolling component bearing develops flows within the raceways and or rolling component, there are literally variety of vibration frequency characteristics that result relying up on the extent deterioration. therefore distinguishing these characteristic frequencies can't only help to verify that a bearing is certainly failing, However it can even provide some indication of extent of degradation because the rolling bearing parts deteriorates, the spike energy increase to higher level and eventually the rolling bearing component fails. For a journal bearing, spike energy is nil.

Cavitation

Cavitation causes random, high-frequency broadband energy, which is sometimes superimposed with the blade pass frequency harmonics. Each collapse of a bubble creates a kind of impact, which generate high- frequency random vibrations, as shown in figure below. Cavitation are often quite damaging to internal pump elements if left uncorrected. It is usually liable for the erosion of impeller vanes. Measurements to observe cavitation are typically not taken on bearing housings, however rather on the suction piping or pump casing.

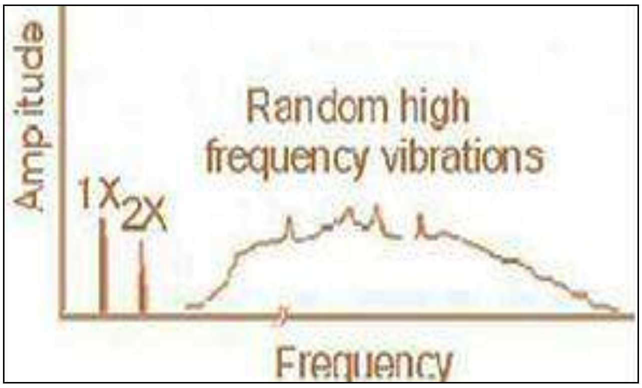

Fig 9: Vibration due to cavitation

Vibration due to bent shaft

When a bent shaft is encountered with a pump, the vibrations within the radial as well as within the axial direction are high. Axial vibrations could also be more than the radial vibrations. The spectrum can commonly have 1×

and 2× parts, as shown in figure below.

- If the amplitude of 1× rpm is supreme, then the bend will be near the shaft center.
- If the amplitude of 2× rpm is supreme, then the bend will be near the shaft end.

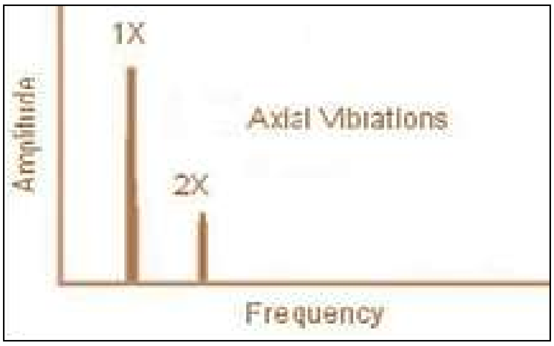

Fig 10: Vibration due to bent shaft

7. Case Study: condition monitoring & vibration analysis on BB2 API610 centrifugal pump (IDP105B) in Bharat petroleum corporation Ltd (BPCL) India-KR

In order to explain the importance of vibration analysis and for understanding the principles practically, the analysis was done on a pump. The pump is a '*between bearing*' pump which was used to pump Heavy Coker Gas Oil (HCGO), which is an inflammable gas. Usually the readings of vibration on each pump in the refinery was taking in a gap of 10 days. As a result by using a software (In our case AMS suite by Emerson process management), there will be a general trend generated, so that any variation in this shows the problems in the pump.

Readings are taken on both motor and pump side i.e. both inboard and outboard of pump and motor.

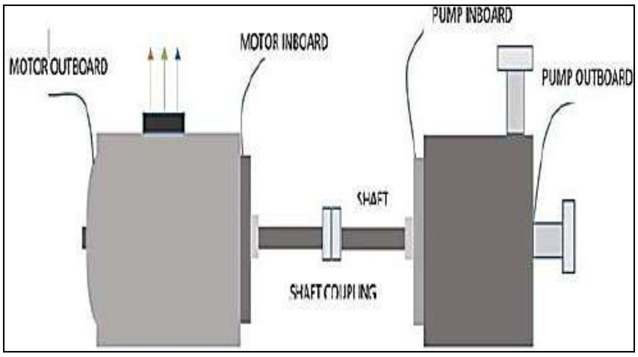

Fig 11: Vibration reading positions

The vibration of the pump inboard and outboard measured using accelerometer and vibration analyzer is dumbed in to the system. The system has an AMS suite software by EMERSON process management for analyzing the complex waveform read from pump. The waveform will be converted to corresponding spectrum using Fast Fourier Transform. The software itself assigns upper warning, fault and alert limits using vibration analysis findings. Various trends and spectrum of the pump taken at different dates are given below.

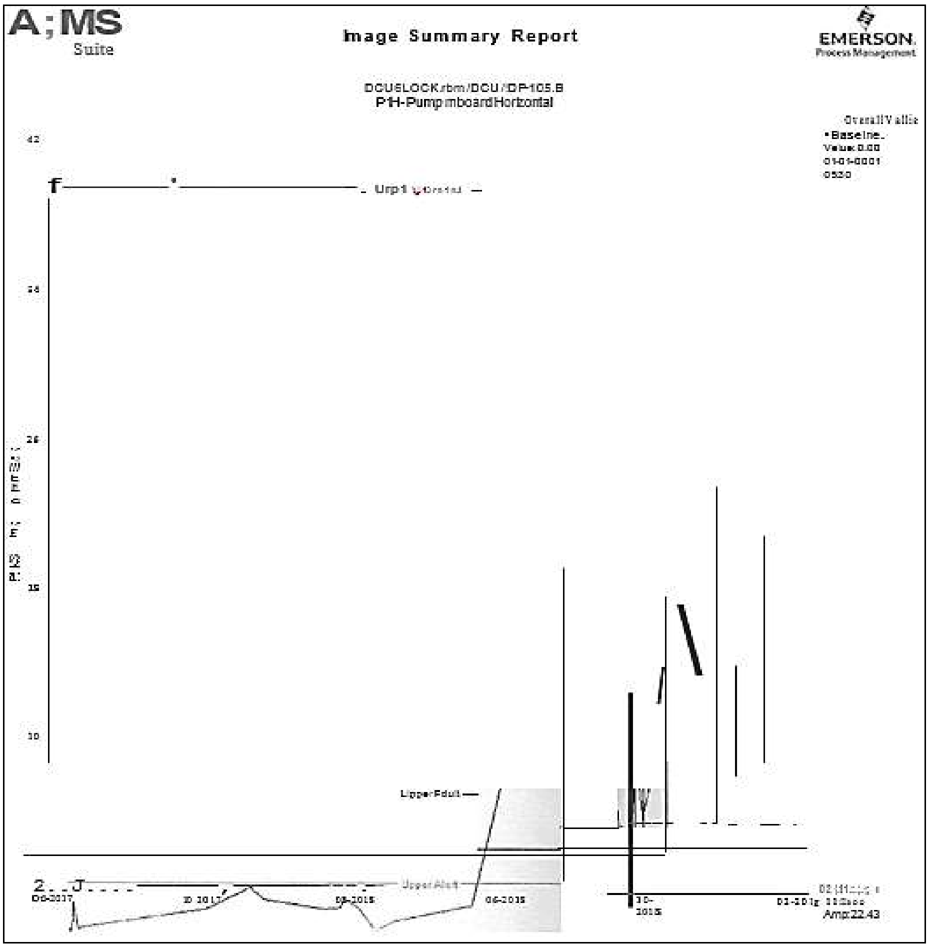

Fig 12

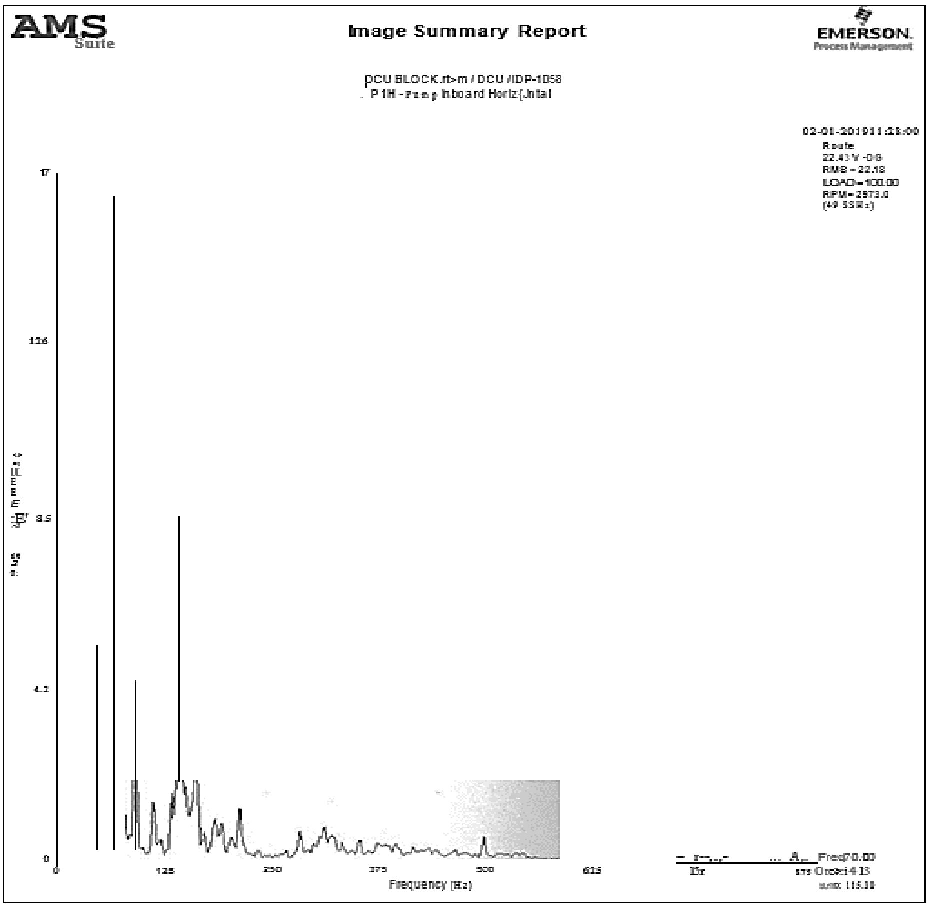

Fig 13

Initially the values were taken at lower resolution so the amplitude was in range of 1x, so the pump was overhauled. When overhauled, it was found that the wearing rings in impeller was damaged. Due to this there was rubbing in impeller. So the wearing rings were changed and oil change was done. After that the pump was energized and carried out the testing, but still the problem of vibration exists. As the general trend is increasing above critical limits set, motor side was also checked. As any problems in motor like electrical faults, bearing problems and frequency change can be transferred to pump through shaft and couplings. The readings from motor was normal. Then the resolution of the equipment was increased. It was found that the amplitude is in the range of 1.4x. This can be due to some external factors. So the history of pump maintenance was checked. Various activities like oil flash, replacement of side bearings was done. It was also noticed that due to leakage in discharge line maintenance activities are done. So a detailed study of that was done. On checking it was found that instead of spectacle blind during maintenance the team used ordinary blind in between the flanges. Due to this activity strain was developed in pipe. In order to make sure the discharge line was separated by giving a cut in between them. When separated the axis of both pipe were different. So the root cause for the vibration was pipe strain. So both pipes were corrected and welded and was energized. But still vibration continues this time it was found that the support which is given got disturbed due to thermal expansion. So a support which can overcome this was designed. When there is thermal expansion the pipe itself has to align itself. Since rolling friction is less than sliding friction a movable bearing pad was given at the bottom of the support so once energized it can overcome strain which is developed. Thus the problem was solved.

8. Conclusions

The root cause of the excess vibration of the IDP105-B can be the pipe strain caused as result of thermal expansion. It can be also caused by increased nozzle load by the working fluid due to the pipe strain. Since pipe strain can be the root cause, the pipe is cut and alignment in flanges where corrected. This pipe strain caused some effects in pipe supports which caused further abnormalities in spectrum. By suitable level arrangements and support corrects we can rectify those issues too.

Through vibration analysis a tool of condition monitoring the problems in IDP105-B centrifugal pump were recognized and necessary repair works were done. This helped in preventing any future unexpected vibrations resulting in failure of the equipment which would have adversely affected the working of the entire plant substantially bringing down its productivity. All the process helped in increasing the mean time between failures (MTBF) of the given centrifugal pump in DCU. Sometimes such a failure of pump due to seal leakage or any leakage in pipe can cause large economical and human power loss. It also affects the safety of workers and surrounding habitation of people.

This project highlights the importance of vibration analysis and condition monitoring in a large scale 24/7 industry like BPCL-KR. Also we practically found that some of the theories on vibration analysis and condition monitoring obtained correct findings which lead to predict causes before overhauling the pump. It really helps in successfully identifying a fault and rectify it before a failure.

9. Acknowledgements
The preparation of this paper required a lot of guidance and assistance from many people during our study and we are extremely fortunate to have got all this along the completion of our project. Whatever we have done is only due to such guidance and we could never forget to thank them. We would like to thank Dr. Kurian Antony, Associate Professor, Department of Mechanical Engineering, MITS, Kochi and Mr. K Raghavan, Deputy General Manager, Maintenance, BPCL-KR who gave us the opportunity to do this project at BPCL-KR. We owe our profound gratitude to Mr. Raman R., Chief Manager, Maintenance, BPCL-KR who guided us throughout the entire study and preparation and also to others who took keen interest in our work and helped and guided us all along. We would also like to thank Mr. Monish and Mr. Shiek Sahed, Engineers in Reliability Center and Mr. Sajeev K Joseph and Mr. Deepak Aravind, Engineers in Area 5 Maintenance Section for giving us their valuable time and information about conditional monitoring and production units to prepare the project. We are also thankful to our friends, parents, and everyone who supported us.

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