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RELIABILITY IMPROVEMENT OF PLANT ASSETS THROUGH CONDITION BASED MAINTENANCE: A CASE STUDY

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ABSTRACT

A major part of the energy used in any production process is expended during the maintenance of Plant assets. To ensure plant reliability and equipment availability, a condition-based maintenance policy has been developed in this investigation. This paper describes the application of condition monitoring on a super critical rotary equipment named the Combined Feed Pump in the Cumene unit of Phenol complex in the plant for the case study, which unexpectedly failed to run, so that it requires a large maintenance cost and time for detection and failure analysis for finding out the root cause of the problem for the corrective maintenance action. As the failure of this pump is a critical problem, it was found out that Erosion effect due to Cavitation in pump impeller was the root cause of pump failure. In order to resist Cavitation, some improvements are suggested. It is necessary that, it requires a skilled operation for the confirmation of a complete elimination of the source successfully.

KEYWORDS: Condition Monitoring, Vibration Analysis, Cause and Effect Diagram, Frequency Spectrum Analysis, PDE, PNDE, MDE, MNDE

INTRODUCTION

In a process industry, it is essential that the downtime of equipment be kept to the minimum as any disruption to the production has a cost implication in terms of loss of production, manpower costs, spare parts costs and safety. The mean time between failures and the probability of sudden equipment failures for all plant equipments were more and most of the defects were developed within minutes or hourly or weekly basis, so that the shutdown of these equipments for the corrective maintenance were done in unscheduled time intervals. The overall maintenance costs and the time for maintenance is more during the catastrophic failure of these critical equipments as compared to costs and time related to scheduled shutdowns.

An uninterrupted production process is a key factor for performance and ultimately for a plant's success. All machines involved in a production process are required to work without interruption to guarantee 24/7 operations. This is easy in theory, but there will always be unexpected stops. The target is to reduce them to the minimum, leading to more uptime and more profit for the company. Different approaches and maintenance strategies exist, but not all of them are applicable to every machine and to ensure overall success. It is necessary to analyse different parameters that will clearly show whether a plant is able to introduce and sustain a proper and long-lasting condition-based maintenance programme.

Condition Monitoring

Condition monitoring is the process of determining the condition of machinery while in operation. The key to a successful condition monitoring programme includes knowing what to listen for, how to interpret it, when to put this knowledge to use. Successfully using this programme enables the repair of problem components prior to failure. Condition monitoring not only helps plant personnel reduce the possibility of catastrophic failure, but also allows them to order parts in advance, schedule manpower, and plan other repairs during the downtime. The methodology for a Condition-Based Maintenance Program is shown in Figure 1.

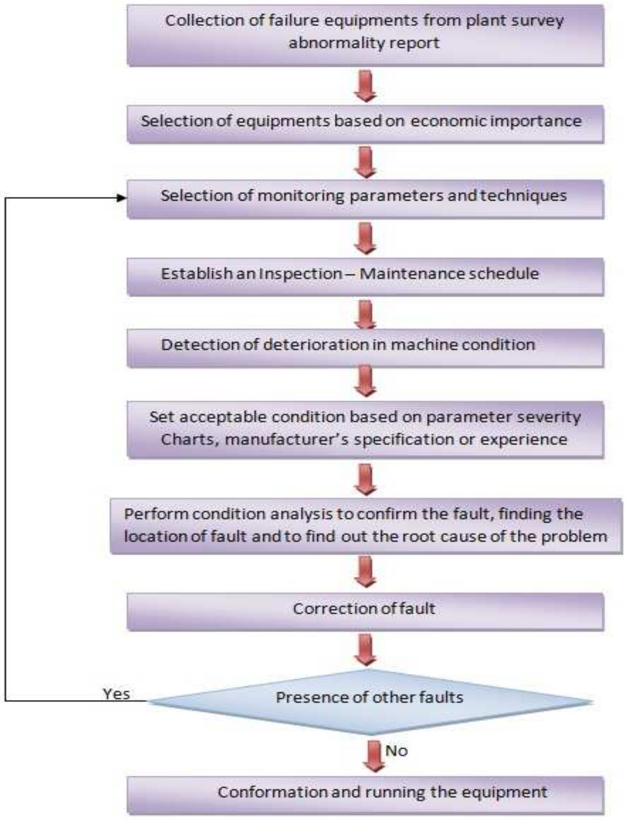


Figure 1: Methodology for Condition-Based Maintenance Program

CASE STUDY

The list of failure equipments collected from plant survey abnormality report taken during the month of August 2013 includes seven equipments due to various reasons like abnormal noise, high power consumption, increased abnormal vibration, low flow rate, high bearing temperature etc. Due to lack of availability of time, the study concentrates only to equipments having high economic importance. So a criticality analysis is done for the calculation of equipment criticality.

Criticality Analysis

Criticality analysis is a tool used to evaluate how equipment failures impact organizational performance in order to systematically rank plant assets for the purpose of work prioritization, material classification, Preventive Maintenance/Predictive Maintenance development and reliability improvement initiatives. In Figure 2, the basic information and algorithm for the calculation of equipments criticality is presented. This figure shows the calculation steps of the equipments. The Equipment Criticality is found out using the following equation.

$$EC = (30*P + 30*S + 25*A + 15*V)/3 \tag{1}$$

where,

EC: Is the equipment criticality

P **:** Is the product

S **:** Is the safety

A **:** Is the equipment stand by

V **:** Is the capital cost.

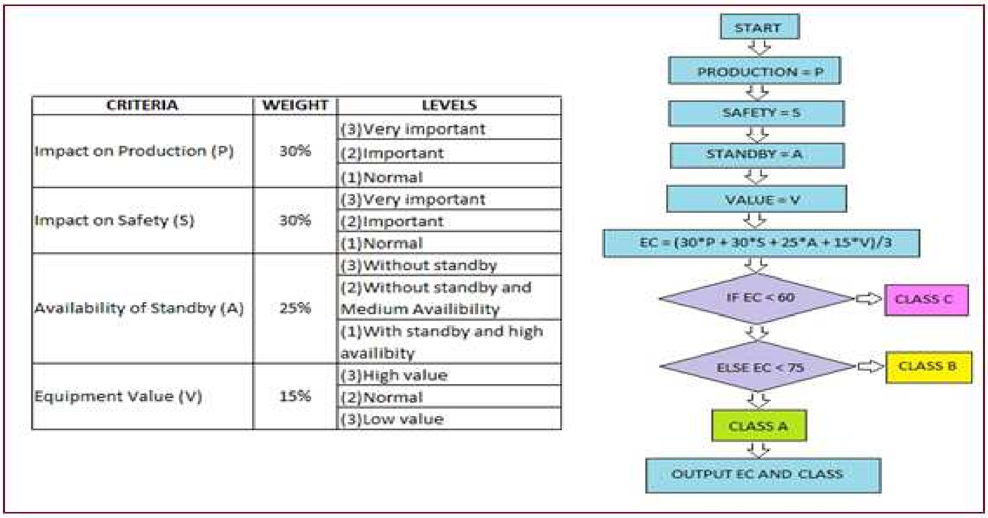


Figure 2: Basic Information and Algorithm for the Calculation of Equipment Criticality

The Class A equipments belongs to Critical, Class B belongs to Semi-Critical and Class C belongs to Non-Critical. Table 1 gives the list of equipments failed during the overall inspection and their criticality index were found out as follows.

Table 1: Criticality Index of Equipments

SL. NO.	EQUIPMENT NUMBER	EQUIPMENT NAME	IMPACT ON PRODUCTION (P)	IMPACT ON SAFETY (S)	AVAILABILITY OF STANDBY (A)	EQUIPMENT VALUE (V)	EQUIPMENT CRITICALITY INDEX (EC)	GROUP
1	BFWP-3	BOILER FEED WATER PUMP 3	1	2	2	3	61.67	CLASS B
2	P 3004-B	EVAPORATOR RECYCLE PUMP	1	2	2	1	51.67	CLASS C
3	P 2005-A	COMBINED FEED PUMP	3	2	3	2	85.00	CLASS A
4	P 3006-B	EVAPORATOR BOTTOM PUMP	1	2	2	2	56.67	CLASS C
5	P 2008-B	BENZENE RECYCLE PUMP	2	2	2	2	66.67	CLASS B
6	CT-F2	COOLING TOWER FAN 2	1	1	3	2	55.00	CLASS C
7	CT-P3	COOLING TOWER PUMP 3	1	1	3	1	50.00	CLASS B

After calculating equipment criticality index, it is observed that only Combined Feed Pump belongs to Critical category. Thus the paper focused on to Condition Monitoring of the critical equipment (Class A equipment) named the

Combined Feed Pump in the Cumene unit of Phenol complex in the plant for the case study, which unexpectedly failed to run, so that it requires a large maintenance cost and time for detection and failure analysis for finding out the root cause of the problem for the corrective maintenance action. It is necessary that, it requires a skilled operation for the confirmation of a complete elimination of the source successfully.

This critical pump discharges the mixture of Propylene, Propane and Benzene to the Cumene Reactor. This pump takes the suction from the bottom of Depropanizer column (Propane and Benzene) and Benzene Recycle column. The propylene feed from the propylene recovery unit after passed through the water wash column enters at Combined Feed discharge line. The Figure 3 gives the specification of this pump.

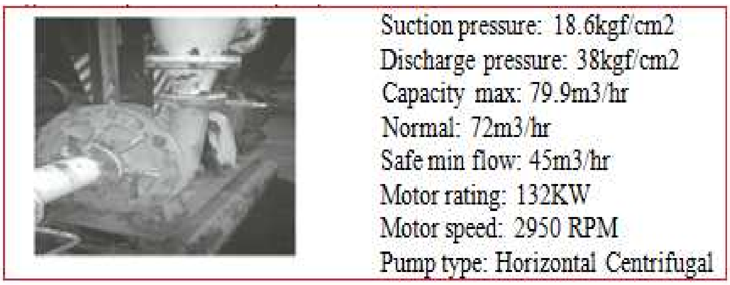


Figure 3: Combined Feed Pump and its Specifications

Pre-Maintenance History

The combined feed pump failed to run unexpectedly by producing a noise level of 94 dB. Due to this reason the equipment has to be closed down for two days which will result in the overall Cumene production loss. The Figure 4 shows the various major causes that may leads to the shutdown of the pump.

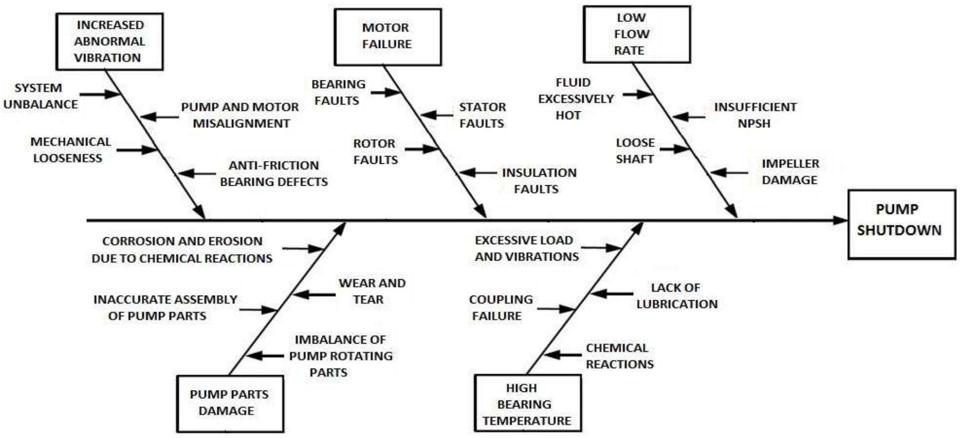


Figure 4: Cause and Effect Diagram of Pump Failure

From the past data of pump's abnormality reports collected from the maintenance department (for last three years) reveals that the cause for maximum times of pump failure was due to increased abnormal vibration. It contributes about 66% (14 times) of overall causes of the failure. It may be due to system unbalance, pump and motor misalignment, mechanical looseness, anti friction bearing defects etc. Second most cause of failure is due to motor failure. It contributes about 19% (4 times) of overall causes of failure. The chance of occurrence of other causes of failure like low flow rate, high bearing temperature and pump parts damage are very small compared to the major causes. The Figure 5 shows the percentage of causes for pump shut down and their Pareto Analysis for finding out the major causes.

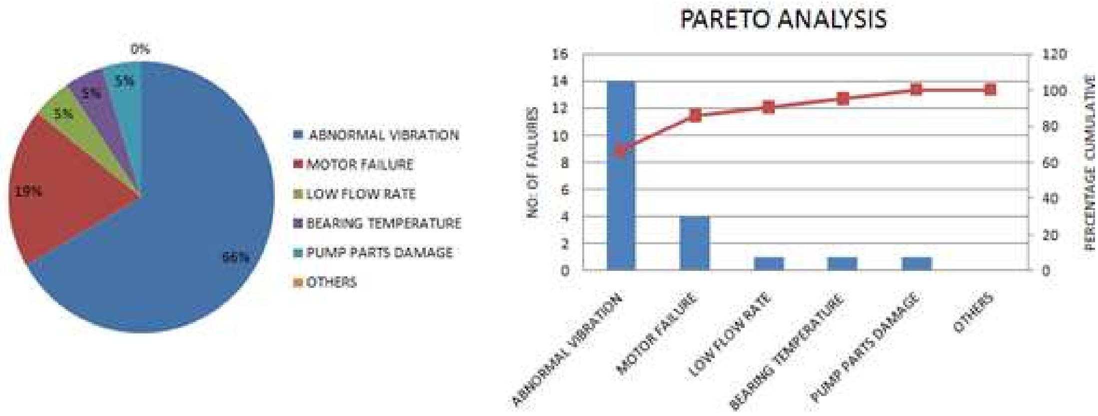


Figure 5: Pareto Analysis

A Pareto Analysis is conducted on the above data and it is interpreted that the major reasons contributed to the failure of combined feed pump were increased abnormal vibration and motor failure (80% contribution). Since the chance for motor failure was ignored due to the conformation from the electrical department and so the study mainly concentrates on avoiding pump's increased abnormal vibration and it has been selected as the major defect. Hence a vibration analysis is needed to carried out for finding out the reasons behind pump vibration. Before shut down the pump it needs to take the RMS velocity readings of vibrations and Shock Pulse Monitoring readings (Spike energy readings) of load carrying bearings in Horizontal, Vertical and Axial directions of Pump Drive End (PDE), Pump Non Dive End (PNDE), Motor Drive End(MDE) and Motor Non Drive End (MNDE) respectively during the critical running of the pump.

Vibration Monitoring and Analysis

Vibration monitoring measures the frequency and amplitude of vibrations. It is known that readings will change as machinery wear sets in. Such readings can be interpreted as indicators of the equipments condition, and timely maintenance actions can be scheduled accordingly. Electrical machines and mechanical reciprocating or rotating machines generate their own vibration signatures during operation. However such complex signals contain a lot of background noise, which makes it difficult or even impossible to extract useful, precise information by simply measuring the overall signal. To capture useful condition monitoring data, vibration should be measured at carefully chosen points and directions. Vibration monitoring usually involves the attachment of a transducer to a machine to record its vibration level. Transducers for the measurement of vibrations employ electromagnetic electrodynamics, capacitive, piezoelectric, or strain gauge principles, out of these piezoelectric accelerometers is most widely used since the recent past.

Vibration analysis is a non-destructive technique which helps detection of machine problems by measuring vibration. Vibration analysis has been proven to be the most successful predictive tool when used on rotating equipment, both in increasing equipment availability and reliability. In order to maximize the finite life associated with rolling element bearings and optimize equipment production life, excessive wear caused by misalignment, unbalance, and resonance must be minimized. The presence of trained vibration specialists with equipment to conduct analysis will form the basis of a strong vibration program. There are literally hundreds of specific mechanical and operational problems that can result in excessive machinery vibration. However, since each type of problem generates vibration in a unique way, a thorough study of the resultant vibration characteristics can go a long way in reducing the number of possibilities hopefully to a single cause. The cause and effect diagram of increased abnormal pump vibration is shown in Figure 6.

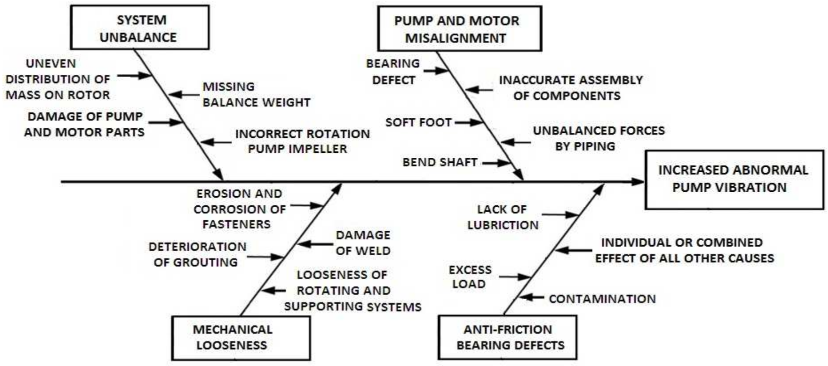


Figure 6: Cause and Effect Diagram of Increased Abnormal Pump Vibration

Most problems generate vibration with frequencies that are exactly related to the rotating speed of trip in trouble. These frequencies may be exactly 1 x RPM or multiples (harmonics) of 1 x RPM such as 2x, 3x, 4x, etc. In addition, some problem's may cause vibration frequencies that are exact sub harmonics of 1 x RPM such as 1/2x, 1/3x or 1/4 x RPM. In any event, the Fast Fourier Transform analysis data can identify the machine component with the problem based on the direct relationship between the measured vibration frequency and the rotating speed of the various machine elements.

The machine component that has the problem is usually the one with the highest amplitude of vibration. The following chart lists the most common vibration frequencies and their relation to machine rotating speed (RPM), along with the common causes for each frequency.

Table 2: Vibration Trouble Shooting Chart Based on Frequency

Frequency in Terms of RPM	Most Likely causes	Other possible causes & Remarks
lx RPM	Unbalance	1) Eccentric journals, gears or pulleys 2) Misalignment or bent shaft if high axial vibration
2 x RPM	Mechanical looseness	1) Misalignment if high axial vibration 2) Reciprocating force
3 x RPM	Misalignment	1) Usually a combination of misalignment and excessive 2) Axial clearance (looseness).
Less than lx RPM	Oil Whirl(Less than1/2 x RPM)	1) Bad drive belts 2) Background vibration 3) Sub-harmonic resonance
Many Times RPM (Harmonically Related Freq.)	Bad Gears, Aerodynamic Forces, Hydraulic forces, Mechanical Looseness, Reciprocating Forces	1) Gear teeth times RPM of bad gear 2) May occur at 2, 3, 4 and sometimes higher harmonics
High Frequency (Not Harmonically Related)	Bad Anti-Friction bearing	1) Cavitation, recirculation and flow turbulence causes random high frequency vibration 2) Improper lubrication of journal bearings 3) Rubbing
Synchronous (A.0 line frequency)	Electrical Problems	1) Common electrical problems include broken rotor bars, eccentric rotor, and unbalanced phases in poly phase Systems, unequal air gap.
2xSynch.Frequency	Torque Pulses	Rare as a problem unless resonance is excited

Relatively high amplitudes of axial vibration are normally the result of

- Misalignment of couplings
- Misalignment of bearings
- Misalignment of pulleys or sheaves on belt drives
- Bent shafts

The Table 2 shows the Vibration severity chart as per ISO 2372. Since Combined Feed Pump is a class III machine and the limits of this class is found out from the standard.

Table 3: Vibration Severity as per ISO 2372

The vibration readings taken at different measuring locations before rectification are shown in Table 3. From the table, it is clear that some readings are in ALARM limit or UNACCEPTABLE limit according to the vibration severity range (in accordance with ISO 2372), we can conclude that the reason for the pump failure is increased abnormal vibration. (Since combined feed pump is a class III machine according to ISO 2372). We want to find the causes, which leads to the pump vibration.

Table 4: Vibration Data Sheet of Combined Feed Pump before Rectification (Taken on 30/08/2013)

Measuring Locations	Vibration Velocity Readings in Horizontal Direction (in mm/sec)	Vibration Velocity Readings inVertical Direction (in mm/sec)	Vibration Velocity Readings in Axial Direction (in mm/sec)
Pump Drive End (PDE)	10.41	3.28	4.83
Pump Non Drive End (PNDE)	4.51	1.39	1.32
Motor Drive End (MDE)	4.34	5.25	7.28
Motor Non Driv End (MNDE)	4.97	5.97	7.13

The following figures (Figure 4 to Figure 15) shows the different Frequency Spectrums showing the frequency-vibration velocity relations monitored at different bearing locations of pump-motor system respectively.

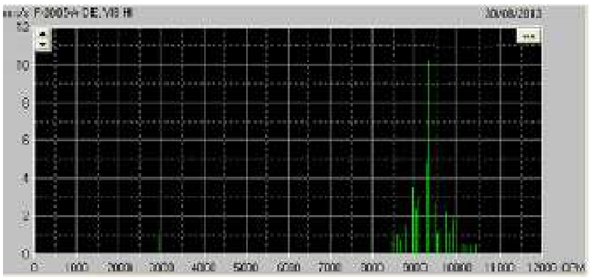


Figure 7: Frequency Spectrum PDE Hor. Direction

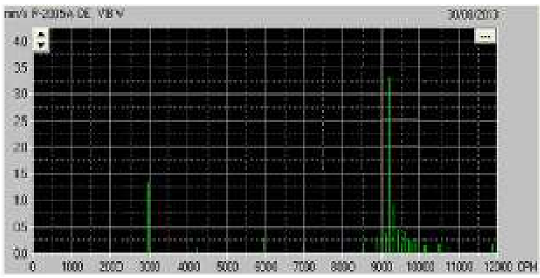


Figure 8: Frequency Spectrum PDE Ver. Direction

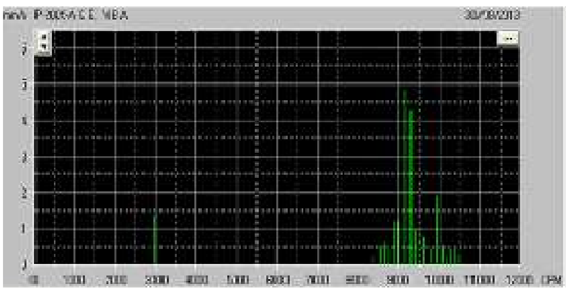


Figure 9: Frequency Spectrum PDE Axial Direction

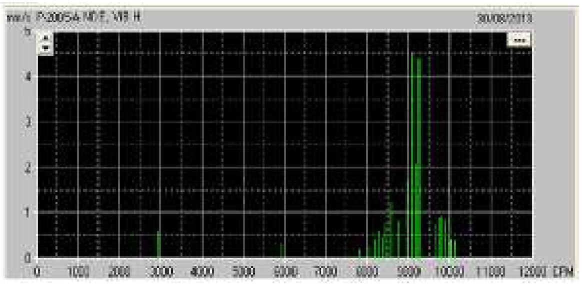


Figure 10: Frequency Spectrum PNDE Hor. Direction

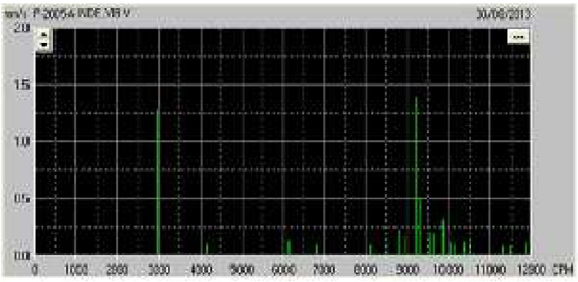


Figure 11: Frequency Spectrum PNDE Ver. Direction

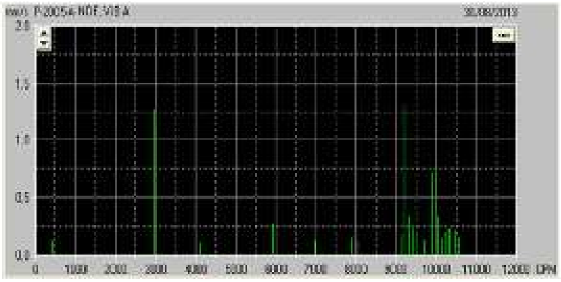


Figure 12: Frequency Spectrum PNDE Axial Direction

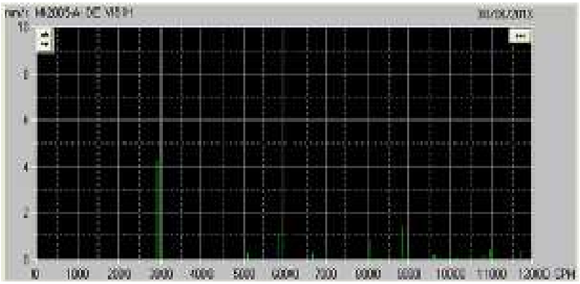


Figure 13: Frequency Spectrum MDE Hor. Direction

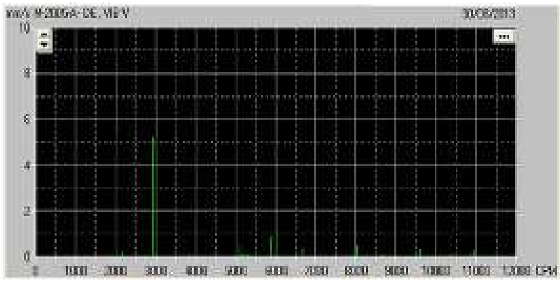


Figure 14: Frequency Spectrum MDE Ver. Direction

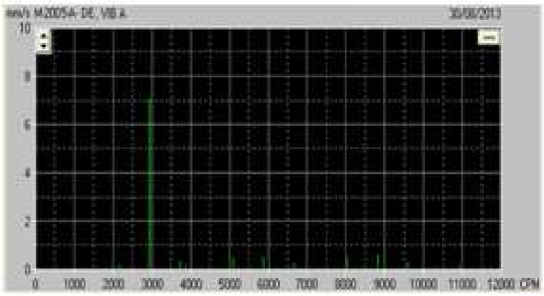


Figure 15: Frequency Spectrum MDE Axial Direction

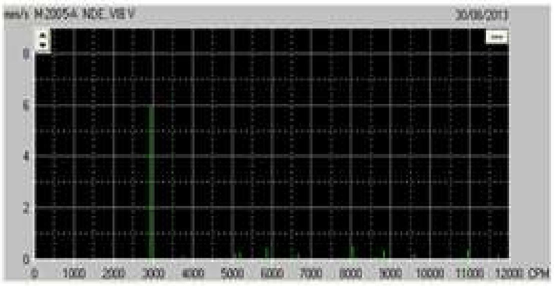


Figure 16: Frequency Spectrum MNDE Hor. Direction

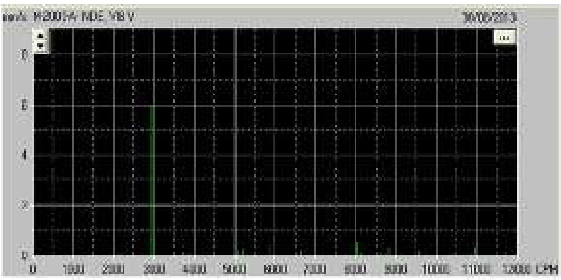


Figure 17: Frequency Spectrum MNDE Ver. Direction

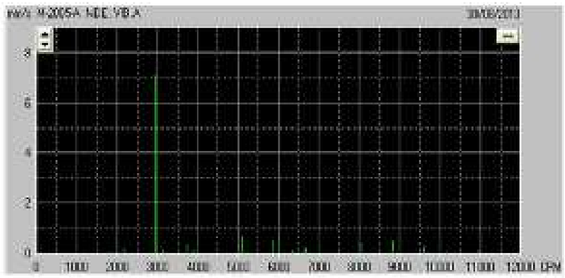


Figure 18: Frequency Spectrum MNDE Axial Direction

Observations from the Frequency Spectrums

By observing the trend and the spectrums obtained, the interpretation is that the there is severe misalignment between motor and pump. In PDE, the horizontal velocity readings (10.41 mm/sec) are in ALARM limit and vibration frequency of 3*rpm is dominant, which indicates misalignment. In vertical direction, the velocity readings (3.28 mm/sec) are in SATISFACTORY limit and vibration frequency of 3*rpm is dominant, which also indicates misalignment. In axial direction, the velocity readings (4.83 mm/sec) are in ALARM limit and vibration frequency of 3*rpm is dominant, which also indicates misalignment. Also high frequencies (not harmonically related) at three directions indicates some severe Bearing damage. Other reasons for high frequency vibrations may be Cavitation, Flow turbulence or recirculation of flowing fluid. For conformation it needs further analysis. In PNDE, the horizontal velocity readings (4.51 mm/sec) are in ALARM limit and vibration frequency of 3*rpm is dominant, which also indicates misalignment. In MDE and MNDE, high amplitudes at axial direction in 1*rpm is dominant, which also indicates severe misalignment.

For finding the root cause for pump and motor misalignment, further analysis is needed. Thus the factors that lead to system misalignment were studied through brainstorming and the major causes found out are bearing defect, bent shaft, soft foot, unbalanced forces by piping etc., which were shown in the following cause and effect diagram.

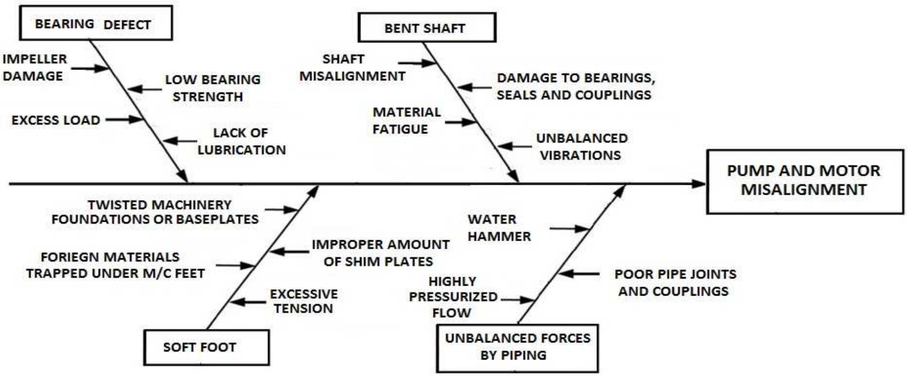
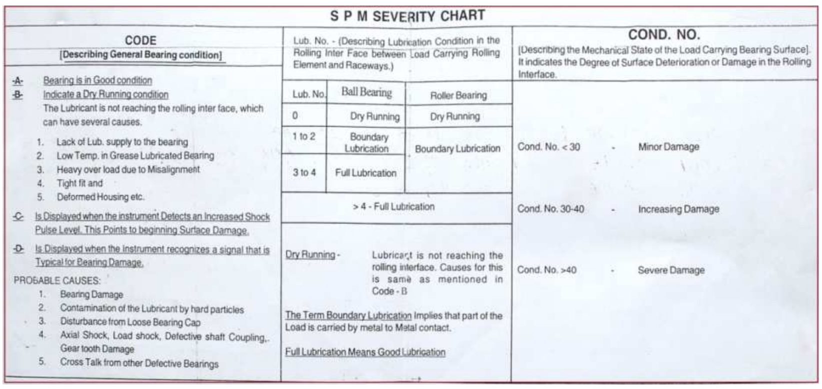


Figure 19: Cause and Effect Diagram for Pump and Motor Misalignment

Through an effective visual monitoring the factors like bent shaft, soft foot and unbalanced forces by piping were ignored and the study mainly concentrates on to the bearing defect. The Shock Pulse Monitoring method is used to assess the operating condition of rolling element bearings. Shock Pulses are a special type of vibration that can be clearly distinguished from ordinary machine vibrations.

The SPM Method

SPM is an abbreviation for the Shock Pulse Method, which is a patented technique for using signals from rotating rolling bearings as the basis for efficient condition monitoring of machines. The SPM Method detects development of a mechanical shock wave caused by the impact between two masses. At the instantaneous moment of impact, molecular contact occurs and a compression (shock) wave develops in each mass. The SPM Method is based on the events occurring in the mass during the extremely short time period after the first particles of the colliding bodies come in contact. The following figure shows the SPM severity chart.


S P M SEVERITY CHART

CODE
[Describing General Bearing condition]

-A- Bearing is in Good condition
-B- Indicate a Dry Running condition
The Lubricant is not reaching the rolling inter face, which can have several causes.
1. Lack of Lub. supply to the bearing
2. Low Temp. in Grease Lubricated Bearing
3. Heavy over load due to Misalignment
4. Tight fit and
5. Deformed Housing etc.

-C- Is Displayed when the instrument Detects an Increased Shock Pulse Level. This Points to beginning Surface Damage.

-D- Is Displayed when the Instrument recognizes a signal that is Typical for Bearing Damage.

PROBABLE CAUSES:
1. Bearing Damage
2. Contamination of the Lubricant by hard particles
3. Disturbance from Loose Bearing Cap
4. Axial Shock, Load shock, Defective shaft Coupling,. Gear tooth Damage
5. Cross Talk from other Defective Bearings

Lub. No. - (Describing Lubrication Condition in the Rolling Inter Face between Load Carrying Rolling Element and Raceways.)

Lub. No	Ball Bearing	Roller Bearing
0	Dry Running	Dry Running
1 to 2	Boundary Lubrication	Boundary Lubrication
3 to 4	Full Lubrication	

> 4 - Full Lubrication

Dry Running - Lubricant is not reaching the rolling interface. Causes for this is same as mentioned in Code - B

The Term Boundary Lubrication Implies that part of the Load is carried by metal to Metal contact.

Full Lubrication Means Good Lubrication

COND. NO.
[Describing the Mechanical State of the Load Carrying Bearing Surface]. It indicates the Degree of Surface Deterioration or Damage in the Rolling Interface.

Cond. No. < 30 - Minor Damage
Cond. No. 30-40 - Increasing Damage
Cond. No. >40 - Severe Damage

Figure 20: SPM Severity Chart

The following table gives the SPM readings taken at different bearing locations of Pump - Motor system.

Table 5: SPM Readings at Different Bearing Locations

Measuring Locations	LUB. NO	COND. NO	CODE
PDE	2	56	D
PNDE	2	32	B
MDE	2	35	B
MNDE	4	25	A

Observations from SPM Readings

From the SPM readings, it is observed that, in PDE, the CODE is D which indicates a signal that is typical for bearing damage and COND NO of 56 indicates a high degree of surface deterioration or damage in the rolling interface. But the LUB NO of 2 indicates a boundary lubrication. So that it is interpreted that the cause for severe bearing damage in PDE is not the lack of lubrication. There may be some other reasons which lead to the severe bearing damage. But for the other measuring locations, the CODE observed is A or B, which indicates the bearing is in good running condition and the COND NO indicates minor damage. So it is interpreted that strong bearing failure found out only in PDE, which is the root cause for system misalignment, which leads to the system increased abnormal vibration. The vibrations generated at the other measuring locations are after effects and are transferred from the PDE.

Next we want to find the root cause for severe bearing damage in PDE. Pump was taken for maintenance and during this section, a severe bearing damage was observed. In order to find out the root cause of this problem, through a panel of experts and by analyzing the past maintenance records, some major factors were found out which leads to the bearing defect. The following figure shows the cause and effect diagram for bearing defect.

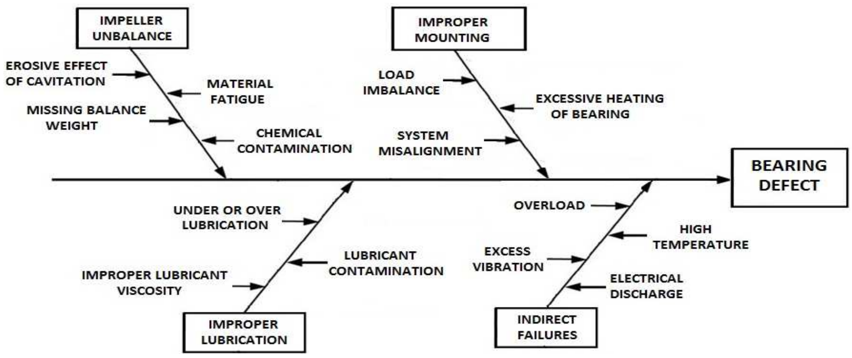


Figure 21: Cause and Effect Diagram for Bearing Defect

By an effective monitoring and expert discussion, the causes like improper mounting, improper lubrication and indirect failures were avoided and the only cause left is impeller unbalance. So the pump was isolated and decoupled from the motor at the site and then it was shifted to maintenance workshop for overhauling. On dismantling the pump, it was observed some severe material removal in the pump's impeller surface. The shape of the cavities generated implies an erosive effect occurred due to Cavitation and so it is finalized as the root cause of the pump failure.

Cavitation

Cavitation is a phenomenon that occurs when vapour bubbles form and move along the vane of an impeller. As these vapour bubbles move along the impeller vane, the pressure around the bubbles begins to increase. When a point is reached where the pressure on the outside of the bubble is greater than the pressure inside the bubble, the bubble collapses as shown in Figure 18. The process is not an explode, but rather an implode. This collapsing bubble isn't alone, but is surrounded by hundreds of other bubbles collapsing at approximately the same point on each impeller vane. The phenomenon of the formation and subsequent collapse of these vapour bubbles, known as Cavitation, has several effects on a centrifugal pump.

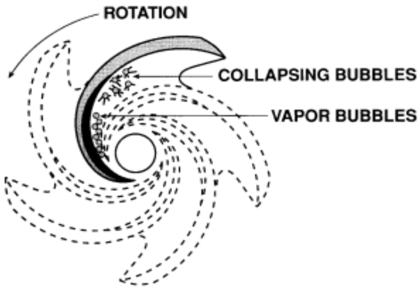


Figure 22: Cavitation Effect

The collapsing bubbles make a distinctive noise, which has been described as a growling sound leads to severe vibration and resulted in impeller damage. The photograph of damaged impeller due to cavitational erosion is shown in Figure 18.

Figure 23: Impeller Damage Due to Cavitional Erosion

Recommendations to Resist Cavitation

The solution to pump impeller Cavitation lies in finding a material that can withstand high pressures, bear harsh environments, and be machinable. At present, no readily available alloy can do that cost effectively. Thus the only tangible way to salvage the pump is to protect it with a sacrificial material that is readily available, easy to use, and cost-effective. Technological advances in industrial protective coatings and repair composite materials have made it possible to repair pumps suffering from Cavitation, rather than simply replacing them. Cavitation-Resistant (CR) Elastomers can retain adhesion under long-term immersion, dissipate energy created under high-intensity Cavitation, and provide outstanding resistance to corrosion and other forms of erosion.

Cost Saved by Preventing Catastrophic Failure of Combined Feed Pump

- Costs calculated if catastrophic failure occurs (due to impeller damage)

  = cost of impeller + cost of production loss for 2 hours + labour cost + spare part cost

  = 22000 + (2*(9355*3.75)) + 2000 +2500

  = Rs 96662.5/- (approx)

- Costs involved during scheduled shutdown

  = cost of 1 liter of CR Elastomer (for two coatings on pump impeller and casing) + cost of production loss + labour cost + spare part cost

  = 3500 + 0 + 5000 + 2500

  =Rs 11000 /- (approx)

  Total costs saved = (A) – (B)

  = 96662.5 – 11000

  = Rs 85662.5/- (approx)

CONCLUSIONS

By using an effective condition monitoring system, it was found out that the combined feed pump failure was mostly due to erosion effect by Cavitation in the pump impeller. It is recommended that Cavitation Resistant Elastomers provide outstanding resistance to corrosion and other forms of erosion and ensures better life to impeller and thus the improve the reliability of pump. In an industry with well applied and managed condition monitoring system, we can have many benefits like prolonged machine life, minimized unscheduled down time, elimination of unnecessary overhauls, more efficient operation, increase machinery safety and improve quality performance.

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