Condition Based Maintenance: A Study of Condition Monitoring Techniques

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Abstract - Study on condition-based maintenance (CBM) spans disciplines and introduces a wide range of concepts. On the source of statistical analysis of the papers published in major maintenance-related journals, the development of the field of CBM in the recent past is examined. Consequently, the objective of the research paper is to study the tools used in Condition Based Maintenance. The CBM fields start in the 1940s with primary efforts due to the railway companies in the western part of US. Now a day, CBM has developed into a truly worldwide discipline involving such fields as economics, management, insurance, maintenance, and production. This paper also discusses the monitoring techniques used in CBM. Large number of articles on general surveys, and specific applications in industries are reviewed. It is wished that this article will contribute to the additional advancement of CBM research.

Keywords – ***Mutual fund industry, evaluation, growth perspective, emerging trends***.

1. Introduction

It has been observed that one third of all maintenance costs is wasted as the result of unnecessary or improperly carried out maintenance. Maintenance of plant equipment based on its perceived condition is a more cost effective strategy than either maintenance based on time or usage hours. Maintenance after the breakdown incurs interruption to production or service, more maintenance activity and extra spares usage. Planned preventive maintenance can result in unnecessary maintenance activity and downtime and in excessive spares usage, whilst being ineffective in preventing breakdown.

In condition based maintenance (CBM) the equipment is maintained when measurements indicate an incipient failure. The condition of the machine may be determined continuously or at regular intervals by monitoring vibration, wear debris, temperature and performance parameters. Any change in any of these parameters would mean a change in the condition or health of the machine. Following conditions should be satisfied before implementing a condition based maintenance programme:

- The existence of failures, which do not occur at regular intervals.
- These failures are either a safety hazard or incur significant costs in lost
- Production, breakdown maintenance labor and materials.
- A monitoring method exists that can give sufficient advance warning of the impending

failure for the maintenance/production system to act to avoid failure.

- The monitoring and corrective maintenance costs less than the lost production and breakdown maintenance including associated overheads.
- The monitoring method is compatible with the existing company procedures and workforce attitudes and expertise.

Condition based maintenance should not be looked at as a substitute for more traditional maintenance management methods. It is, however, a valuable addition to a comprehensive, total plant maintenance management programme.

. CONDITION MONITORING TECHNIQUES

a) Visual Monitoring

Optical techniques are used to enhance the powers of the naked eye. The three main ways in which this is done are: magnification, providing access, and freezing or slowing movement.

Magnification can be provided by a magnifying glass, telescope or microscope

- Binoculars are widely used to inspect remote equipment such as smoke or fume stacks, walls, roofs, steam traps, switchgear and other electrical equipment.
- Hand held microscopes are valuable for onsite inspection of wear surfaces or debris.

Access can be provided to the insides of plant machines or vessels by light probes, boroscopes and video images copes.

- The simplest light probe is a torch which can be used in conjunction with mirrors on sticks to illuminate and observe dark internal parts of units
- Boroscopes are cause to built devices of small diameter (0.2-0.6") designed to illuminate and view the inaccessible component. There are both rigid and flexible versions with heads capable of illuminating and viewing any different magnifications and angles to the bore
- Motion analyzes allow the high and low speed analysis of visual events. A tiny video camera mounted at the head captures the image, transmitting it electronically to video monitor and motion analysis system.

Comparison can be made between these techniques as follows:

	Rigid Boroscopes	Flexible Boroscopes	Motion analyzes
Resolution	Excellent	Fair	Fair
Access- through hole	Excellent	Excellent	Fair
- straight tube	OK	Excellent	Fair
- bent tube	No	OK	OK
- tortuous path	No	Fair	OK
Light intensity	High	Fair	Fair
Viewing sensitivity	Good	Fair	High

Timed viewing becomes necessary with moving components to freeze or slow the motion. The three types of instrument used are stroboscope, photographic camera and video camera.

- The stroboscope illuminate the component with a short duration pulsed light at a selectable frequency, which can be triggered by the movement of the component. This appears to freeze the motion so that the component can be observed by eye or by any of the instruments described. Off-tuning the strobe frequency causes the component to appear to move slowly. This technique enables an off-load inspection to be carried out on-load, e.g. the condition of belt drives may be examined this way

- The camera systems are used to slow and record components in motion. Photographic systems can operate up to 1000 frames/sec giving a slowing by a factor of 50. The video systems operate normally to the same frame frequency and exceptionally to12000 frames/s, but there is more flexibility in replay since single frames can be played back.

Storing the information obtained by any of the optical techniques can readily be carried out using video recorders, which then permit computer analysis.

Visual monitoring techniques can be used on or off load, providing visibility to remote, small or moving components.

b) Temperature Monitoring

Temperatures of the mechanical or structural components of a unit are monitored to ensure that they remain within permitted limits, or that deterioration is detected.

Location of the measurement is critical to both the application and the choice of technique. Measurements made at a surface are more difficult than that those made within a fluid or a solid, because the sharp discontinuity in the temperature profile that occurs in the convective boundary layer is sensitive to the presence of the temperature sensor. Sensors for surface measurement are therefore restricted to thin devices such as thermal label indicators which alter the profile only slightly whilst maintaining good thermal contact.

For immersed and in-body temperature measurement use:

- Liquid expansion sensors such as mercury or alcohol in glass or metal
- Bimetallic expansion sensors
- Thermorcouple, thermistor or platinum resistance sensors.

For surface temperature measurement:

- Self-adhesive thermal labels, which respond to temperature rise by changing colors are cheap and ideal. They contain up to 8 bands each changing at a different temperature. Reversible and non-reversible versions exist. The non- reversible are ideal for routine monitoring
- Temperature paints and crayons work the same way but are not so convenient to use
- Thermocouple sensors designed for surface contact are most convenient and come with a variety of hand-size indicators, but suffer from systematic error due to interference with the heat flow and non-repeatability caused by poor conductive contact
- Non-contact infrared temperature measurement devices sense the infra-red radiations from the surface and deduce from this the surface temperature. Metal surfaces should be painted or otherwise covered with a non-metallic surface. Hand-held, non-contact temperature meters are very convenient and reasonably priced.

Scanning thermographic cameras are now widely available to present a temperature pattern on a two dimensional display. These are appropriate when the monitoring is used to detect a localized hot or cold spot, e.g. a breakdown in lagging or a failed electronic component. Instruments range from simple monochrome systems having the size of a dictionary to shoulder mounted systems with video output and disc data storage.

Typical temperature rises in a working system involving electrical installations as given by Agema are :

Minor problem, 1ºC-10ºC
Problem, 10ºC-35ºC
Serious problem, 35ºC-75ºC
Critical problem > 75ºC

Display of absolute temperature (and hence colors portrayed) depends on the emissivity, ambient temperature and object distance. All of these can be compensated for in advanced systems. Following are the examples of different changes in colors with decreasing temperature :

A			**B**
Red Orange	Strong thermal radiation	Higher temperature	White Yellow
Yellow	Average thermal radiation	Average temperature	Orange
Green			Red
Blue Indigo	Low thermal radiation	Lower temperature	Purple Blue
Violet			Indigo

- c) Lube Oil Monitoring
- A used sample of oil consists of :
- The base oil and its additives which provide the lubricating and cooling properties of the lubricant
- The contaminants in the form of solids, liquids and gases, which get carried away by the lubricant as it circulates through the system. Mechanical deterioration is primarily indicated by the presence and type of wear debris. Table shows relationship between wear characteristics and particle features.

Relationship between wear characteristics and particle Features

Wear Characteristics	**Wear particle feature**
Severity	Quantity (concentration) Size Morphology
Rate	Quantity Size Morphology
Type	Size Morphology
Source	Composition

Lubricant condition

Lubricant is monitored to determine its effectiveness and hence allow change on condition. Table explains the oil properties, which can be monitored. Table gives pollutants and their effect on lubricating oil. The major modes of failure and their associated monitoring techniques are shown in Table

Pollutants and their effects on lubricating oil

Lubricant Property	Pollutants influencing changes in properties
Acidity	Oxidation products, sulphurous products
Alkalinity	Possible additives
Ash	Base mineral constituents
Flash point	Fuel dilution
Insolubles	Carbonaceous products; dust wear products; corrosion products; additive degeneration products -
Specific gravity	All
Viscosity	Fuel dilution, water oxidation products

Wear debris

Wear debris monitoring is concerned with the condition of the primary wearing components of machinery, and is achieved by monitoring and analyzing the wear particles that are washed away by the fluid. The quantity and size of wear debris generated indicates an increasing trend in abnormal conditions. The major wear debris monitoring techniques are shown in table. All these techniques can be operated off-line with the sample being collected on or off load condition.

Major wear debris monitoring techniques used

Technique	Off/on-line	Particle	Quantify	Size/ Morphology
Spectrometric oil analysis	Off	<10μ m	Sample sent to laboratory to obtain ppm of elements	No
Magnetic plugs	On	>100μ m	Debris meter	Yes
Filter	Of f /On	>5μ m	Debris tester	Yes

Ferrography	Of f /on	1µm<< 200µm	Direct reader Ferrograph	Analytical Ferrograph

Some of the oil sampling methods used are:

- Through sampling value

- By suction sampling

- Through drain stream

- Through magnetic chip detector housing

The sampling frequency depends on:

- Function – i.e. importance of the machinery
- Age– time since overhaul
- Operating schedule, loading characteristics of the machine
- Safety considerations
- Rapidity of failure from defect initiation
- New equipment with possible infant mortality requires frequent sampling

During sampling following precautions are recommended :

- ➢ The sampling container must be absolutely clean, showing no visible trace of dirt, water, or other matter; it should be discarded after use
- ➢ Extreme care is necessary during sample withdrawal to ensure that no foreign contaminants are introduced; if the sample is taken by gravity flow, the first few milliliters should be discarded before filling the sample bottle
- ➢ Sampling must be done during operation or shortly after shut down of the machinery while the lubricant is at normal operating temperature, and before particulate settling can occur
- ➢ A complete identification with following information must accompany the sample

_ Machine or system identification

_ Date of sampling

_ Total operating hours

_ Hours since last lubricant or fluid change

_ Hours since last filter change

_ Lubricant or fluid type, and addition since last sample

_ Person to be informed of the results of the analysis

Transformer oil

The common modes of failure on transformers can be detected early on by monitoring the gases dissolved in the oil. The ratios of specific hydrocarbons created by overheating and arcing lead to diagnosis.

Common modes of failure are inter-turn shorts, overheating of the insulation, integral switchgear high resistance or arcing.

Table gives guidelines for possible diagnosis in case of diesel engine, gearbox and hydraulic system based on common contaminants present. Some of the equipment manufacturers provide guidelines of the contaminants limits allowed for their equipment.

Common contaminants and possible diagnosis	
Symptom	**Diagnosis**
Diesel Engine Silicon, iron, chromium, aluminum	Damage to the air filter, cracks or absence of clips on the air manifold system allowing the ingress of abrasive silicon dust and subsequent damage to the cylinder liner/piston/piston ring
Sodium, copper, lead	Coolant leak with damage to the main bearings or the ingress of salt through the air manifold
Chromium	Bore polishing and damage to the piston rings
Copper	Material leeching from the oil cooler
Copper and lead	Main bearing damage
High viscosity	Degradation of the lubricant through oxidation and nitration, or high soot loading, or incorrect lubri- cant top up
Low viscosity	Fuel dilution (low flash point) or incorrect lubricant
Low total base number	Lubricant degradation
Low total acid number	Lubricant degradation
High oxidation (infrared)	Lubricant degradation
High nitration (infrared)	Lubricant degradation
Gearbox Silicon, iron	Abrasive wear resulting from ingress of dust
Iron, chromium, nickel	Wear of bearing material (rolling element)
Low viscosity	Wrong lubricant
High viscosity	Lubricant degradation or wrong lubricant
Hydraulic system Silicon, iron	Abrasive wear resulting from ingress of dust
Increasing total acid number	Lubricant degradation
Low or high viscosity	Wrong lubricant

d) Vibration Monitoring

Vibration monitoring is based on the concept that provided the operating conditions have not been changed; an increase in vibration is an indication of an impending failure. The greater the increase in vibration level the greater is the deterioration. A machine vibrates when the frame, having mass and elasticity, is subjected to periodical forces. The forces may be produced by components attached directly to the frame; they may be developed by reaction forces or transmitted to the frame from rotor via the bearings. Forces transmitted the rotor may be centrifugal due to unbalance or they may be impulsive such as are caused by teeth meshing in a gear train or by fluid striking an impeller blade. Knowing the machine details (such as shaft speed, number of gear teeth, number of impeller blade, etc.), it is possible to calculate the frequency at which vibration will be produced by a particular component. By comparing a list of such frequencies with the frequencies at which an increased vibration is detected it is possible to identify the source of the increase.

Thus a vibration monitoring system should provide:

a) A measure of the increase in vibration level to indicate the urgency of the need for attention

b) A measure of the frequency at which the increase occurs to permit a diagnosis of the problem and

c) Phase shift in vibration is also a useful parameter in diagnosing machine problems

Identification of causes of vibration	
Cause	**Identification**
Unbalance	Major component of the vibration is at shaft RPM
	Major component at 1× RPM usual 2&3 × RPM sometimes
Damaged rolling element bearing	Major components at ball/roller speeds
Oil Whirl	Major component at approximately half the shaft speed
Damaged or worn gears	Tooth meshing frequency predominates
Reciprocating forces	1st, 2nd & higher orders of shaft speed
Mechanical looseness	Major component at 2 × shaft speed
Bad belt drivers	1, 2, 3 & 4 × RPM of belts

Thus, vibration is a useful tool to detect the presence of mechanical trouble in its early stages of development. Different problems cause vibration in uniquely different ways. This is clearly shown in vibration identification Chart in Table Close inspection of this chart reveals that the key to identifying each trouble is primarily the frequency at which the vibration occurs.

Vibration monitoring systems

Any of the following three types of the monitoring system can be used :

Periodic manual monitoring

Automatic surveillance and

Continuous monitoring systems

The selection of appropriate monitoring system depends upon the cost of downtime and the criticality of the machine. When selecting a monitoring system it is essential to take into consideration the details of each individual machine to be monitored. The important factors influencing the selection are:

Application of machine

Continuous or intermittent operation

Machine type

Speed (driver and driven units)

Type of drive

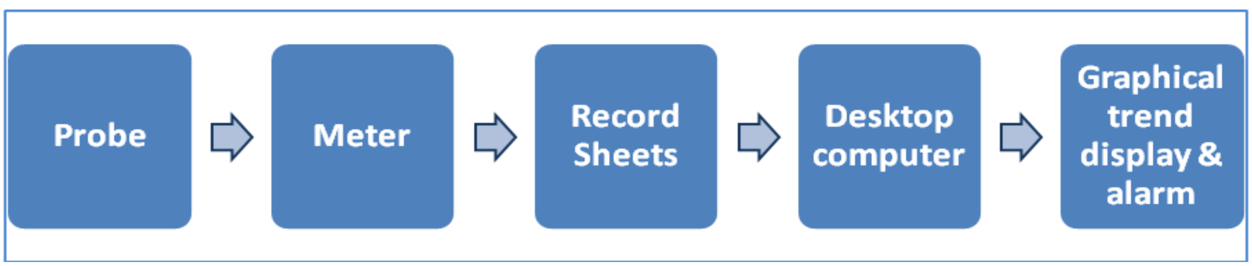
Type of transmission

Bearings and

Machine operating environment

Periodic manual monitoring

This is the routine on-site manual measurement of machinery vibration levels, taken at set intervals. Its principal purpose is to detect and plot changes in those levels, which may indicate the onset of a problem. To ascertain the cause of an increase in the vibration level a vibration analyzer, measuring amplitude, frequency and phase, is used for diagnostic purpose. Figure 16.4 shows a manual monitoring system.



Manual Measurement Recording & computer storage & analysis type off-line system

Periodic manual monitoring has now been automated through the development of the microprocessor based data collector. It is used in conjunction with a personal computer, suitable software and printer to generate hard copy reports.

The automatic data collector is portable, hand-held and battery operated. It is microprocessor controlled and programmed from the host computer. LCD display guides the operator through a measurement route indicating all the required information such as machine type, test point, measurement direction, units of measurement, alarm level and machine speed.

The majority of measurements taken would be overall vibration levels. However, certain critical machines with complex vibration signature can benefit from amplitude Vs frequency spectra checks. To capture such vibration spectra the data collector requires an on-board FFT analysis capability.

Upon completion of a measurement route, the data collector is off-loaded to the computer, which with user-friendly software enables the maintenance manager to generate a wide range of text and graphic reports. The advantages of such a system are:

Periodic readings are taken in a controlled and disciplined manner

Operator error is reduced to a minimum as there is no requirement for selecting the range and unit of measurement

Manual transcription errors are eliminated

Frequency band trending offers considerable advantages compared to just trending overall vibration levels

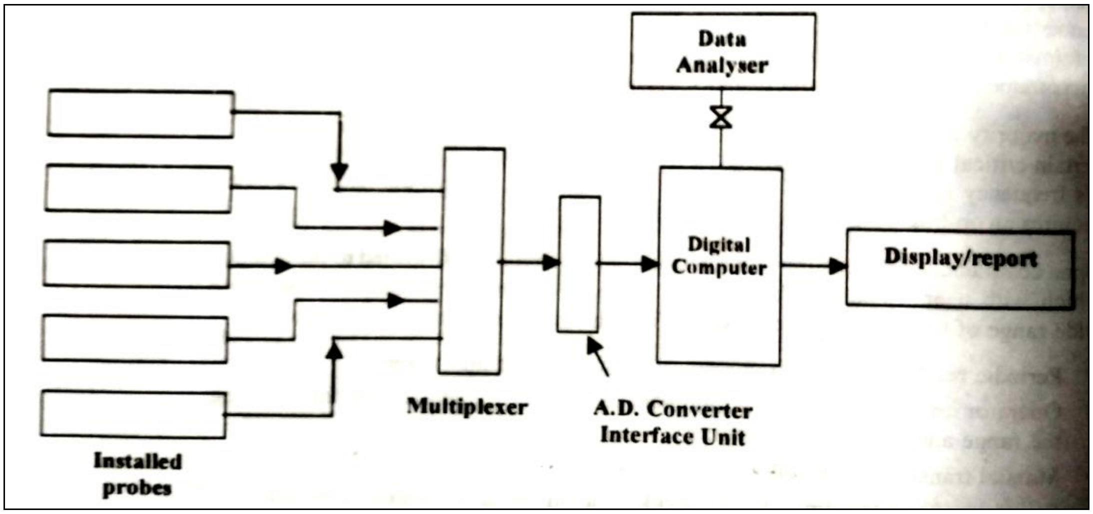
Automatic generation of alarm reports, trend graphs and machinery vibration signatures.

Automatic surveillance

A typical system consists of an array of transducers permanently mounted on machinery wired to multiplexers and controlled by commercially available personal computers, which are programmed to automatically scan and collect both vibration and process data. The sensors are interrogated at pre-progammed intervals, simultaneously measuring displacement, velocity, acceleration, and spike energy from any one transducer.

When a problem area is identified, the system automatically increases its sampling rate until such time as the offending machine is corrected. In addition, spectra capture via FFT analysis can be automatically performed for detailed assessment of machinery faults. It being an on-line, system operating personnel can see all dynamic data at a glance.

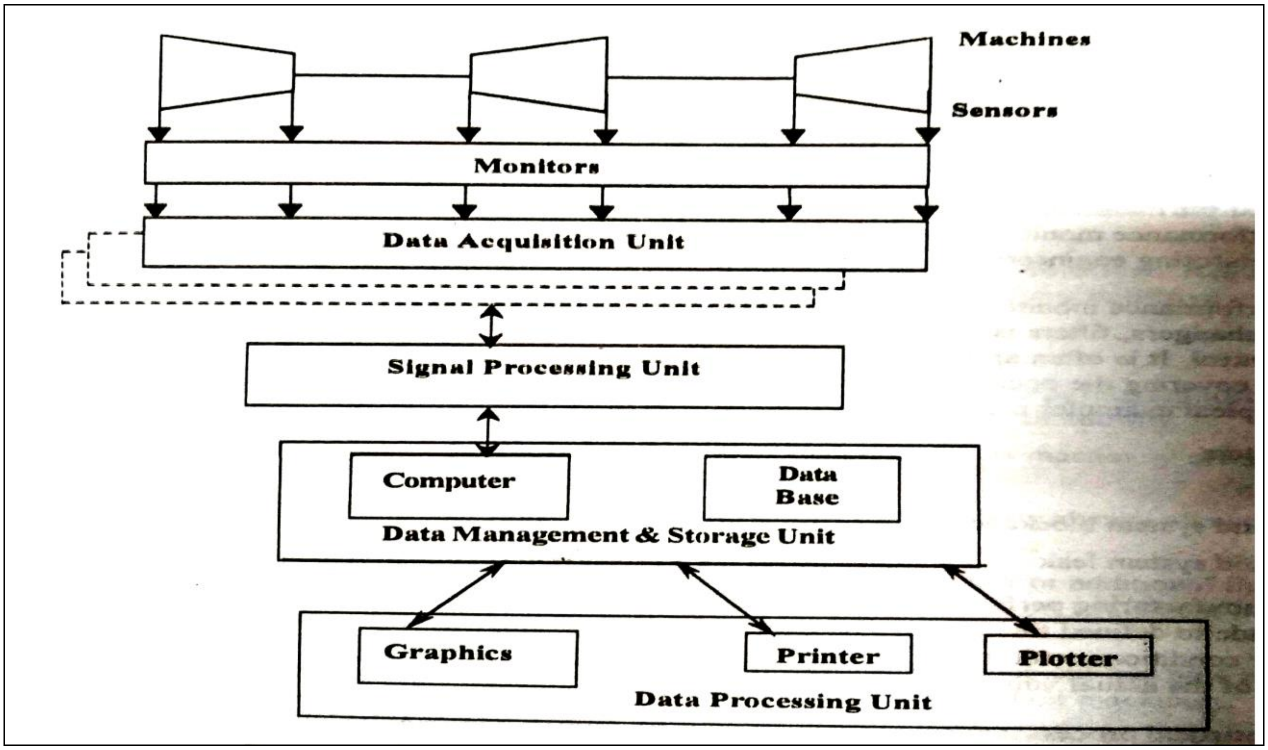
Unlike continuous monitoring system, where a signal conditioning card is required for each channel of measurement, in this system only one signal conditioning card per measured vibration parameter is needed, which can be applied to as many as sixty channels. It is very cost effective option for protecting a large number of strategic rotating machines. Bellow figure shows an on-line computer based condition monitoring system.



i) Continuous monitoring

Continuous monitoring is intended for the on-line continuous protection of critical machinery. It incorporates all the key features of periodic manual monitoring and automatic surveillance in one self-contained unit. Transducers are hard-wired to a microprocessor based plant information center, which is located in the process control room or near to a high concentration of machines in the plant.

It provides the operator with comprehensive machine and plant performance data and enables engineers to make objective maintenance decisions based on historical machinery trends. A plant information center continuously monitors vibration amplitude, axial position, temperature, thrust, speed, bearing /gear condition, together with inputs from virtually any other process parameter that requires monitoring. The visual display unit can simultaneously present upto 30 channels of information with a vertical bar showing as a percent of the alarm set point. In the event of an alarm an FFT spectrum analysis automatically captures the vibration spectrum so that it can be compared with stored baseline signatures to identify a particular machinery problem. Alarm events and operator acknowledgements are automatically stored for retrieval purposes at a latter date. To assist in evaluating a machine's condition, various maintenance reports are possible. These include long-range trend reports based on 52 weekly averages, fourteen-day, 24 hours or even one minute trends. It gives the added protection of continuous monitoring with automatic warning an machine shutdown facilities. The details of a typical on-line computer based system is shown in bellow Figure



Due to complexities of integrated process plants most situations will require a combination of periodic manual monitoring, automatic surveillance and continuous monitoring systems. These can be integrated to provide the maintenance manager with comprehensive machine and process information at a single data terminal.

Performance Monitoring

Most machines, which are involved in industrial production have as their main function the transportation or transformation of energy or materials. The monitoring of their performance usually involves measurement of their output or sometimes relationships between their input and output.

The performance of a plant unit is a useful measure of its condition, for prognosis and need for maintenance action. The variety of units and their functions means that performance monitoring techniques are limited only by the innovation of condition monitoring engineers.

Performance monitoring of process units such as pumps, fans, boilers, heat exchangers, filters is readily carried out using information necessary for process control. It is often appropriate to use independent sensors since the monitoring may be covering the operation of the control sensors as well as the controlled unit.

Typical examples are:

Filters	differential pressure rise
Fan	pressure, flow and power decrease
Fluid system blockage	pressure increase, flow and power decrease
Fluid system leak	pressure decrease, flow and power increase

Conclusion

Condition based maintenance in a valuable addition to a comprehensive, total plant maintenance programme. Under this programme the equipment is maintenance when measurements indicate an incipient failure. The condition of machine is determined continuously or at regular intervals by visual, temperature, wear debris, vibration and performance monitoring. Implementing condition-based maintenance involves identification of plant machines, selection of critical machines, selection of monitoring techniques, setting up of a systematic monitoring program, setting up of an information and data recording system, training of manpower and setting up of appropriate maintenance schedule. Application of condition-based maintenance is recommended if the benefits obtained from avoided costs by its implementation are able to offset the investment costs required to implement it. As a general guide for a typical industrial plant a reasonable level of initial investment in condition monitoring is about 1% of the total capital value of the plant, which is being monitored. In case the plant has some special safety requirement, an initial investment of the order of 5% of the total value is likely to be more appropriate.

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