Condition Monitoring and Fault Diagnosis of Machines by Using Vibration Analysis

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Abstract: Condition Monitoring of rotating machinery are used to monitor the status of critical operating major components such as the shafts, bearing, gearbox, generator, misalignment of parts. Faults can thus be detected while components are operational and appropriate actions can be planned in time to prevent failure of components. This work contains study of various monitoring techniques which are used to monitor the machine with the objective of improving the reliability of given system and also the techniques are categorized with system application. Finally this study focused on one case study of rotating shaft to examine the vibration characteristics of shaft using vibration monitoring technique. It helps to understand the behaviour of fatigue crack initiation and propagation in a Pre-cracked high carbon steel shaft which be monitored using a vibration based condition health monitoring method. Future work is based on the identifying functional requirement of machine and the monitoring technique can be analyzed to maintain good health of the machine and safety of machine.

Keywords: Condition Monitoring and Fault Diagnosis, Vibration Analysis.

I. INTRODUCTION

Maintenance is the management, control, execution and quality of those activities which will ensure that optimum levels of availability and overall performance of plant are achieved, in order to meet business objectives - The British Department of Trade & Industry (DTI) [1].Maintenance strategies can be characterized as a) General purpose,b) Essential and c) Critical

a) General Purpose

- Failure does not affect plant safety
- Not critical to plant production
- Machine has an installed spare or can operate on demand
- These machines require low to moderate expenditure, expertise and time to repair
- Secondary damage does not occur or is minimal.

b) Essential

- Failure can affect plant safety,Machine that are essential for plant operation or part of the process
- They may or may not have an installed spare available
- Start-up is possible but may affect production process

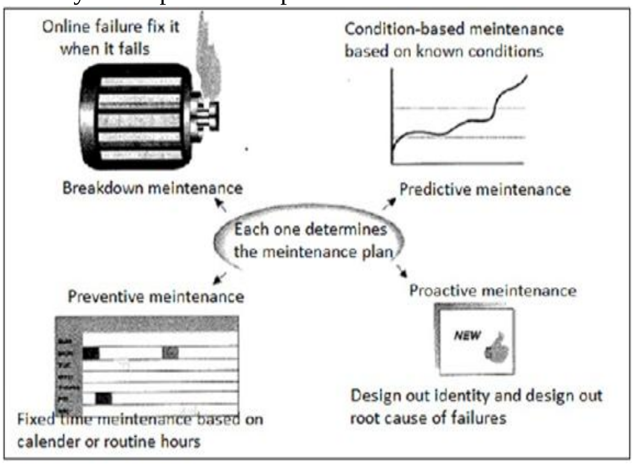

Fig. 1.1 Maintenance Strategies

- High power and speed might not be running continuously
- Some machines that demand time-based maintenance
- These machines require moderate expenditure, expertise and time to repair

c) Critical

- If their failure can affect plant safety
- Machines that are essential for plant operation and where a shut-down will curtail the production process
- Machines which do not have spare parts
- These machines have high capital cost, they are very expensive to repair or take a long time to repair

Condition monitoring pertains to providing information on the condition of plant so that it can be maintained properly. By having such knowledge of machine condition, we can predict incipient failures and stop the plant for maintenance in a planned manner so that the minimum loss of output occurs and the maintenance can be carried out as efficiently as possible .

Our process plants are maintained predominantly by following methods:-

1.1 Run-to-Failure Maintenance

This applies to non essential equipment and machinery where shutdowns do not affect production, materials and replacement are readily available. It allows the machinery to run to failure and only repair or replace damaged components when the machine comes to a complete stop.

1.2 Preventive Maintenance

Preventive or time-based maintenance is to schedule maintenance at predetermined time intervals, based on running hours of machines. In this case replacement of damaged equipment is carried out before problems occur. This allows the machine to run continuously and where the personnel have enough skill, knowledge and time to perform the preventive work.

1.3 Condition-based Maintenance

Condition-based or predictive maintenance periodic monitoring involves periodic monitoring on the health of the machine and scheduling maintenance only when a functional failure is detected. This allows trends of the machine component be constructed and time to failure be estimated. Maintenance can be conveniently planned and allows lead-time for organisation of parts and maintenance personnel and be scheduled. This leads to full utilisation of the machine and possible increase in production capacity.

1.4 Proactive Maintenance

Proactive or prevention maintenance involves tracing all failures to their root cause and to ensure that failures are not repeated. It utilises predictive/preventive maintenance techniques in conjunction with root cause failure analysis (RCFA). RCFA detects and identify the cause of failure and ensures that proper installation and repair techniques are used. It also identifies need for redesign of machine to avoid future occurrence of the same problems and improve the reliability of the machine [3].

Condition monitoring of machinery is the measurement of various parameters related to the mechanical condition of the machinery (such as vibration, bearing temperature, oil pressure, oil debris, and performance), which makes it possible to determine whether the machinery is in good or bad mechanical condition [3]. If the mechanical condition is bad, then condition monitoring makes it possible to determine the cause of the problem. Condition monitoring is used in conjunction with predictive maintenance, i.e., maintenance of machinery based on an indication that a problem is about to occur. In many plants predictive maintenance is replacing run-to-breakdown maintenance and preventive maintenance (in which mechanical parts are replaced periodically at fixed time intervals regardless of the machinery's mechanical condition). Predictive maintenance of machinery:

- Avoids unexpected catastrophic breakdowns with expensive or dangerous consequences.
- Reduces the number of overhauls on machines to a minimum, thereby reducing maintenance costs.
- Eliminates unnecessary interventions with the consequent risk of introducing faults on smoothly operating machines.
- Allows spare parts to be ordered in time and thus eliminates costly inventories.
- Reduces the intervention time, thereby minimizing production loss. Because the fault to be repaired is known in advance, overhauls can be scheduled when most convenient.

Condition monitoring attempts to detect symptoms of eminent failure and approximates time of a functional failure. It utilises a combination of techniques to obtain the actual operating condition of the machines based on collected data such as vibration analysis, oil and wear debris analysis, ultrasound, temperature and performance evaluation [4, 5]. The specific techniques used depend on the type and operation of the machines. Examples of

condition monitoring techniques:

(a) Vibration Analysis – this is the most commonly used and effective technique to detect internal defects in rotating machinery. Vibration measurement is commonly done in gearbox, turbines, bearings and shaft. Using vibration analysis, the presence of a failure, or even an upcoming failure, can be detected because of the increase or modification in vibrations of industrial equipment.

(b) Acoustic Emission Monitoring – this involves detection and location of cracks in bearings, structures, pressure vessels and pipelines. Acoustic emissions (AE) are defined as transient elastic waves generated from a rapid release of strain energy caused by a deformation or damage within or on the surface of a material.

(c) Oil Analysis & Wear Debris Analysis – Oil analysis is a predictive maintenance technique. By analyzing the oil, we can see how the oil is contaminated from debris of surrounding elements. To check the level of contamination in the oil and to analyze the lubricant properties, a sample from the machine is sent to the laboratory to find out the debris contents in the sample. This procedure is made in order to get the exact information about the present state of the health of the oil as well as the machine.

(d) Ultrasonic Monitoring – this is used to measure thickness of corrosion or crack on pipelines, offshore structures, pressure vessels.

(e) Thermography – Thermography is a condition monitoring method that inspects mechanical equipment by obtaining heat distribution from the image. This method is based on the fact that all working components exude heat. By observing the heat pattern of the components a conclusion can be made on which components are damaged. This technique is use for inspecting mechanical and electrical system by taking the picture of heat patterns.

(f) Performance Monitoring – this is used to determine the performance problems in equipment. The efficiency of machines provides a good inside on their internal conditions. For performance and process parameters monitoring, different parameters such as temperature, pressure, flow rate, electrical power and other electrical quantity like dielectric strength, resistance, and impedance are most commonly applied.

II.VIBRATION MONITORING

There are different techniques used for condition monitoring and fault diagnosis of machines. In this section out of these techniques vibration monitoring technique is discussed in details. Whole machine or overall vibration occurring in the 10Hz-10KHz band is considered the best parameter for monitoring structural problems like deterioration or defective bearings, mechanical looseness, worn or broken gears, misalignment and unbalance of rotor etc. and many such problems will cause excessive machine vibration. Vibration generated from a machine contains vital information on the health of the machine and can be used to identify developing problems. Measurements can either be trended to produce an ongoing evaluation of condition or the values obtained compared to the machine's 'normal' value (ISO 2372). The latter is commonly accepted as a one-shot indication of the machine's 'health'.

While internal transmission of vibration is a characteristic of the machine it is important that we monitor at the same point(s) in a consistent way. It is standard practice to mark the measurement point(s) on machines utilising studs or mounts to allow consistent contact of the pick-up transducers. In all cases it is important that –

- Readings are always taken from the same point(s) on the machine.
- Whole machine vibration readings are collected under consistent machine conditions (speed, loading etc.)
- The machine speed (in RPM) is noted.

There is some useful vibration parameters for condition monitoring of machines listed in table 2.1.

Table 2.1 Some useful vibration parameters

Displacement (m)	Velocity (m/s)	Acceleration (m/s^2)
Frequency (Hz)	Bandwidth (Hz)	Spike energy (gSE)
Power spectral density	Peak value	Root mean square (RMS)
Crest factor (CF)	Arithmetic mean (AM)	Geometric mean (GM)
Standard deviation (SD)	Kurtosis (K)	Skewness
Phase (deg)		

Depending upon these parameters the range of techniques available that utilise vibration and associated techniques to determine condition is extensive. The introduction of more and more sophisticated hardware and software continues to see more techniques becoming applicable by and available to maintenance personnel. This will certainly continue and means that techniques that once required trained and experienced vibration specialists are now within the capability of technicians – with the right equipment and a minimum of training. The various techniques fall into this category although specialist help may be needed in initial set up.

Specialised Techniques

As examined the different analysis techniques available in vibration and acoustic analysis, but there are a number of specialised techniques, which normally call in a specialised, that are useful for diagnosis or in specific circumstances. A range of such techniques is listed, in Table 2.2, by 'application' rather than 'analysis technique', as this is the most likely trigger for their use .

Table 2.2 Review of analytical techniques for specific applications

Applications	Analysis technique	What it detects	How it works
Rotating machinery shafts gearboxes etc.	Real Time	Acoustic & vibration signals + shock and transient loads	Signal recorded and played back through real time analyser transformed into frequency – operates through 0-10Hz and 0-20kHz. High resolution and slow
As above + roller & journal bearings, electric motors pumps turbines + diagnostic applications	Real Time Constant Bandwidth	As above + identification of multiple harmonics and sidebands	Vibration detected by accelerometer, signal amplified, filtered and analysed. Bandwidths & frequency can be changed to suit diagnostic needs (Function option with most FFT analysers)
Gear teeth damage pumps roller bearings etc	Time Waveform Analysis	Gear teeth damage, misalignment, pump cavitations, etc	Oscilloscope via vibration meter or real time analyser, measures peak to peak amplitude against time – needs band filters to

An Example of Machinery Fault Detection by Using Vibration Analysis Technique

Consider a typical example of machine system is shown in Fig. 2.1. It consists of a driver, such as electric motor, diesel engines, gas engines, steam turbines and gas turbines. The driven equipment could be pumps, compressors, mixers, agitators, fans, blowers and others. The driven equipment is connected to the prime mover via a gearbox, belt drive, coupling and other connectors. Each of these rotating parts is further comprised of components such as: Stator (volutes, diaphragms, diffuser, stator poles etc.), Rotors (impellers, rotors, lobes, screws, vanes, fan blades etc.), Seals, Bearings, Couplings, Gears, Belts and pulleys etc.

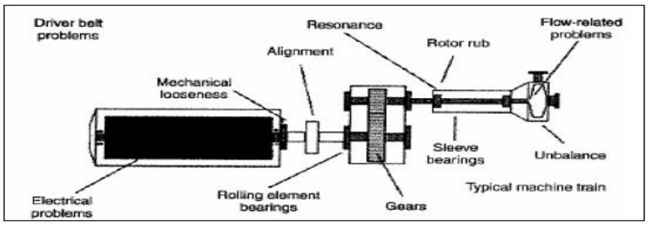

Fig. 2.1 A typical machinery system

All rotating and moving parts are prone to wear and failure after a period of service and when mechanical defects occur, they generate high vibration levels. Some of the common faults are listed in Table2.3.

Table 2.3 Possible faults of machine components

Machine components	Faults
Roller bearings	Cage fault or cage loading, Ball or Roller fault, Race defect, Inadequate lubrication, Installation fault, Bearing loose in housing, Bearing turning on shaft

Journal bearings	Excessive clearance (and looseness), Oil whirl, Oil whip
Coupling	Misalignment
Pump/fan	Hydraulic related pumping problem
Spur gears	Input & output gear looseness, Input & output gear, eccentricity, Misalignment, Bent shaft (input & output) Backlash or oscillating gears, Broken, cracked chipped or pitted teeth (input & output gear), Gear or pinion fault (due to manufacture or mishandling), Preferential wear
Belt	Worn, loose or mismatched belts, Belt/sheave misalignment, Eccentric sheaves, Belt resonance
General	Imbalance, Bent drive shaft, Looseness

III.CASE STUDY ON FATIGUE CRACK STAGES IN ROTATING SHAFT USING VIBRATION ANALYSIS

There is an increasing awareness that maintenance plays an important role in mechanical systems and the choice of the right type of maintenance strategy for right system is a crucial task. An effective maintenance strategy is critical to many operations. It extends the system operating life, improves system availability and retains the system in the proper condition. Maintenance strategies for mechanical machinery which are based on machine condition monitoring can provide significant economic and safety advantages. Rotating shafts that are subject to repeated bending may develop cracks which eventually make the component break. This type of problem is the subject of this case study. There have been many analytical, numerical and experimental studies on cracked rotors. Changes to the shaft frequencies, as well as the harmonic component of the dynamical system response and the evolution of the orbits are the principal effects due to the presence of a crack in a rotating shaft

3.1 Experimental Setup

The test set up comprises a 50HP/37kW three phase electric motor connected to a 3 phase generator by means of a shaft 1450 mm long and 38 mm in diameter. The shaft is connected to the motor and generator using TaperLock couplings as shown in Figure 3.1. These couplings rigidly couple the motor and the generator to the power transmission shaft. A variable resistive load was attached to the generator output. Three piezoelectric accelerometers (DJB type A20-J) were attached using stud mountings, one on top of the bearing housing of the generator nearest the transmission shaft (called Ch1), one on the motor shaft bearing housing nearest the transmission shaft (called Ch2) and the third in the centre of the guard covering the transmission shaft (called Ch3). The measured vibration signals from the accelerometers were fed to charge amplifiers. The voltage signals from the charge amplifiers were connected to an A/D converter comprising a dSPACE DS1102 DSP Controller Board, based on a Texas Instruments TMS320C31 floating-point processor.

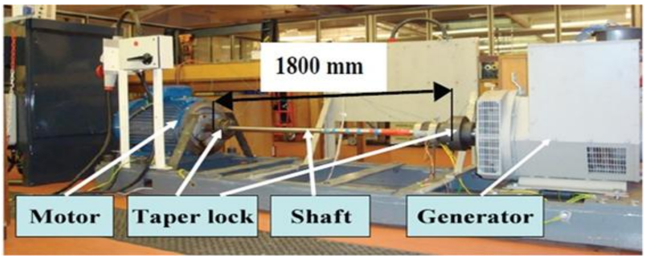

Figure 3.1 Photo of the long shaft rig without shaft cover

The DSP system is supported by Matlab-based software. The sampled time domain signal was converted to the frequency domain using the PSD.

3.2 Experimental Procedures

The aim of the work was to monitor the vibration of the system and identify changes to the vibration caused by the cut depth increasing. The test system was extremely robust and a cut in the shaft was the only way to simulate or initialise a crack in the shaft. The maximum possible loading of the system would not have caused crack initiation in an undamaged shaft. The depth of the cut was increased incrementally to simulate the growth of a crack in the shaft. To identify when the loaded motor system reached equilibrium, a prolonged test was carried out in which the temperature was measured on the motor and generator bearings to ensure the tests being carried out reached a stable state. The results from the temperature test required the test rig to run for more than 4 hours for every defect condition to ensure a stable system. The following test procedure was designed around this requirement.

3.2.1 The Test Consisted of Three Stages

1) Stage one – the reference shaft, which was used to check the system behaviour had not been changed by any other causes, was mounted in the test rig and the frequency responses are measured. The shaft was run at 1550 rpm with a load of 20 KW for 4 hours until a steady state was achieved and then vibration measurements were taken at 30 minutes intervals. This data was used to assess the differences in the system behaviour between runs.

2) The cracked shaft was tested with different crack depths ranging between 0% and 60% of the shaft diameter as shown in Table 4.1. Between each stage of cut depth the reference shaft was mounted again and the vibration response evaluated to check the system behaviour had not been changed by other causes.

3) Step two was repeated three times to confirm the vibration response data was consistent.

3.2.2 Shaft Defects

Spark erosion (SE) was used to provide a method of machining an extremely fine cut (0.1mm wide) to simulate a crack in the shaft at 90° to the shaft axis at the shaft mid length. Any crack produced from stressing the shaft would occur at the highest stress point, which would be at the bottom of the SE cut (Pre-Crack). To improve detection of any crack the surface around the bottom of the pre-crack was polished using very fine emery. The depth of the pre crack was extended as shown in Table 4.1.

Table 3.1 Pre-crack depth increase increments

Cut depth (% of shaft diameter)	Cut depth (mm)
0	0
40	15.2
50	19
60	22.8

IV.SUMMARY

Vibration analysis is the most effective techniques for monitoring the health of machinery. They offer complementary strengths in root cause analysis of machine failure, and are natural allies in diagnosing machine condition.

Crack growth is observed from vibrating results match with stages of crack observed from the fracture surface. It has shown when crack increased the peaks position shift to the left and by changing amplitude of the peaks. The comparison of the vibration results and the beach marks broken shaft is shown very clear, there is significant relation between stages of crack growth and vibration results.

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