An overview of diagnostics and prognostics of rotating machines for timely maintenance intervention

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Abstract. Failure of mechanical system can primarily be attributed to failure of timely intervention by the maintenance crew. Mechanical failure of mechanical system is mostly attributed to damage to mechanical systems due to wearing of mechanical components due to improper lubrication. Various instruments and systems are generally installed to monitor the condition of mechanical systems like steam turbines especially where reliability of system is critical like nuclear plants. This is commonly termed as ‘Condition Monitoring’. It involves continuous monitoring of health of rotating machines say steam turbine system. Instruments installed to monitor the health of machines are designed to provide an alarm through Distributed Control Systems, which are followed by a series of machine tripping systems thus keeping the operator free from the task of manually tripping the systems. The unexpected anomalies of instruments along its abnormal behaviour of equipment, decreases the availability of the machine. Condition based Monitoring (CBM) is critical to nuclear industry and it is done to gather data about the health of a machine and then analysing that data by taking proper maintenance action on components under abnormal behaviour. The information from the plant operations and maintenance i.e. real time data is key to monitoring the health of said rotating machine. Thus, CBM techniques increase the reliability of the machine by accurately estimating the condition of critical components in real-time especially in case of rotating machines in a nuclear plant. This paper discusses the diagnostics and prognostics of rotating machines using analysis of lubricants and bearings as these components are inevitable to any rotating machine.

Keywords: Maintenance; Diagnostics; Prognostics; Lubricating Oils; Bearings

1. Introduction

Today, life seems to be impossible without machines and the need for more work and more power generated with the help of these machines is increasing every day. The maintenance of these machines determines a reliable development for any organization. Besides this, maintenance is always a better option than buying a new one because we can imagine the difference between the cost of establishing a new machine and the cost of its maintenance [1]. Maintenance of any mechanical component preserves the value of that component and this value can be reflected as the proper working of the equipment for
a longer time and also in the sense of safety of the plant and its operators. Preserving the condition of an individual machine component also results in reliable functioning of entire machine. Thus, the health management and maintenance of any machine component are the most important concerns for the owners of the machines and hence a robust maintenance program for the optimization of operational cost and for maximizing the availability of the equipment need to be developed [2][3]. Maintenance techniques can be brought under three categories namely, corrective, preventive and predictive maintenance [5][6]. Concept of maintenance is not new and with time these maintenance techniques have changed a lot. For example, in the past, the idea of reactive maintenance was followed where the machines were continued to be used until they broke down. To avoid the unavailability of these machines and loss in economy associated with it, the idea of proactive maintenance techniques was introduced. The preventive maintenance techniques which were based on the bath curve model were still found to be unnecessary for components which do not follow any such curves like in the maintenance of aircrafts, this concept was found unnecessary [7].

To counter this, reliability cantered maintenance (RCM) was introduced to optimize the maintenance program of a company. A detailed exploration of maintenance models in a very condensed way is given by Fraser et al. [8]. The idea of Condition based maintenance (CBM) is being adapted as the state-of-art method of maintenance as it can detect faults by comparing a healthy system with a faulty one besides measuring the magnitude of fault and suggesting a suitable maintenance task and finally predicting the failure [4][9]. Thus, a CBM technique has a unified fault diagnosis and prognosis approach which helps in detecting any abnormalities, assessing the degradations, diagnosing the faults and predicting the remaining useful life of any machine [10]. Therefore, this paper discusses the different diagnostics and prognostics techniques that can be used for condition monitoring of any rotating machine by analysing its lubricant and bearings.

2. Diagnostic and Prognostic Techniques
We need diagnostic and prognostic techniques for the development of a well-designed maintenance program which can help in decision making by understanding the degradation process of any machine component by collecting and analysing data to understand its condition [4].

2.1. Diagnostics
The condition monitoring system delivers the data relating the functioning of a machine. The information gained from these data can be used to determine the status of machine health and its deterioration. This process of determining the health is referred as diagnostics. It is basically a pattern recognition from the measurement of the faults in the system [9]. It is an important part of predictive maintenance programs for checking the machine health [11].
2.2. Prognostics
Prognostics is an emerging discipline to scientifically detect and identify a failure mode within a system. It deals with predicting the development of defects of any machine component [12].

The first crucial part of a successful prognostic system involves an early diagnostic of a defect with a sufficient lead time for enabling monitoring and actions [13]. An overview for exploring failure prognosis has been done by [14] and [9].

3. Condition Monitoring of Lubricating Oil

3.1. Defining lubrication oil and problem statements
A lubrication oil provides a continuous film of oil between contacting surfaces, the sole purpose of which is to reduce friction and avoid wear of the rubbing surfaces thus preventing seizure of the contacting surfaces. Failure of a lubricant at the rolling element leads to rapid heating and wearing at the contacting surface and as a result the bearing fails [15].

3.2. Factors responsible for lubrication failures
Lubricant failure is the most responsible factor which causes failure of any industrial equipment [16]. Lubricants fail due to low standard practices followed in the plant that strain them.

The factors responsible for lubrication failure are:
(a) temperature
(b) moisture
(c) foreign material
(d) viscosity
(e) contamination

By understanding the ways in which these factors create lubrication failure, root cause analysis (RCA) professionals can enact their RCA plans to predict, prevent and eliminate these failures completely. Machinery lubrication professionals employ this powerful technique to find out and remove the underlying reasons for technical problem or human error behind the failures [17].

![RCA technique](image)

Figure 2. RCA technique followed by the lubrication professionals [17]

3.3. Prognostics and Diagnostics for Lubricating Oil
An early warning for machine failures can be provided by the oil degradation process. The degradation in the protective properties of any lubricant is caused due to the variation in its chemical, electrical, optical and physical properties [18]. Lubricant condition monitoring strategies can help in determining
the health of the entire machine components and help in mitigating the possible machine component failure by analysing the degrading conditions of the lubricant. These degradation processes are monitored by various sensing techniques and this forms the base for the principle of lubrication oil monitoring. This also compliments the predictive and proactive maintenance plans to avert any potential catastrophic equipment failure [19]. Thus, under CBM, lubrication system monitoring can be great help in machine warning system and its diagnostics and prognostics [20]. These real-time monitoring techniques can not only increase the operational duration of lubrication oil in order to increase machine availability but also prevent unnecessary cost of maintenance [21].

For a correct assessment of the health of any machine component, we require well defined data obtained by some reliable sensing techniques. These techniques are used to see the degradation features like oil oxidation, water contamination, particle contamination, oil dilution etc. In case of lubrication, sensors are meant to access the performance of the oil properties. The commercially available sensors which are used in the industry to measure the oil properties are:

(a) humidity sensors [22]
(b) particle-concentration sensors [23-25]
(c) particle-counter sensors
(d) dielectric constant sensors [26-29]
(e) viscosity sensors [30-32]
(f) sensors to measure the air content in the oil.

Junda Zhu et al [18] in their survey have described many such sensors in details of their electrical (magnetic), physical, chemical, and optical principles. Coronado and Kupferschmidt [20] studied the performance of oil properties sensors under extreme ambient temperature and vibration levels. To monitor the machines, oil samples are tapped from the system by some specialists and are sent to labs for analysis. This is called off-line monitoring technique. This process neglects the actual oil condition because of delay in oil sampling process and its analysis [18]. Some of these sampling and data collection methods have been reviewed by James M.W. et al. [19]. As actual condition of the oil can be best determined when a machine is running, there is a need for online data acquisition system for condition monitoring of lubrication oil.
Figure 3. The relationship among the basic degradation features, performance parameters, and available oil condition sensors [18]

[19] in their review on lubrication condition monitoring techniques have classified the approaches for prognostics and diagnostics into three main areas as given in the figure as 1. Statistical 2. Model based 3. Artificial intelligence 4. Hybrid approach

4. Condition Monitoring for Bearings

4.1. Defining bearings and problem statements
Bearings are the inevitable parts of any machine component as they come into picture whenever there is a relative movement between links. They are used to enable rotational or linear movement, while reducing frictional and handling stress and thus enhancing efficiency of any machine. Bearing failures are one of the foremost causes of breakdown in any rotating machinery. Once they fail, they induce failure in the adjacent machine components leading to machine trips [33]. Fundamentals of the bearings and their classification can be summarized in the articles [34-35].

4.2. Factors responsible for bearing failures
Due to their continuous operation they are subjected to a lot of stresses and they fail due to many factors like failure of lubrication, contamination, improper mounting, misalignment, fatigue, overheating, tight and loose fits and improper handling. Some of the notable defects caused due to these factors are: formation of flakes on the surface, pitting, spalling [13][36], depression damage, abrasion, wear[37] and corrosion. These defects can cause the bearings to get heated which causes bearing cages and seals to deform and could lead to bearing lock-up. and when the hot lubricant in their contact break down, they can cause scoring and even etching of the bearing surfaces just like what water does to the roads. Different modes of failure of bearings were reviewed by Nihil et al [38]. Scot [39] presented various bearing failure investigation techniques which could enable us to take a satisfactory remedial measure for a greater reliability of the machines. A simple bearing failure can lead to a complete shut-down of any production unit and can lead to a great loss in economy until the fault is set.

4.3. Prognostics and Diagnostics of Bearings
A Predictive Health Monitoring tool is a must for the successful operation of any industry. It can predict failures and avail a great amount of lead-time for maintenance. It can help in extracting the features about faults in rolling element bearings and help in the fault detection followed by its diagnostics and prognostics and hence determine their remaining useful life [40]. A lot of research has been done in the field of signal processing for vibration and acoustic emission analysis to detect the faults in the bearing. Any imperfection in the rotating component produces periodic pulse. The magnitude of these pulses depends on the load characteristics of the system. Signal processing methods attempt to emphasize these defect signals over background noise. Shiroishi,J. et al.(1997)[33] were among the first researchers to realize that diagnostics capabilities could lead to possible prognostics. Williams et al [38] worked on early detection of crack propagation and natural crack growth during the damage. Unlike other researchers who had used artificially induced cracks, they claimed to be the first to have studied real cracks propagation. Numerous prognostic approaches for bearing health indication which have been proposed for condition monitoring of bearings can be classified as either model-based or data-driven [14].

(a) Model based approach: They work on assuming a suitable mathematical model [41-44]
(b) Data driven approach: They work on data obtained from sensors or by manual measurements. These are again subdivided into: statistical [45,46], knowledge based/artificial intelligence [47-49] and Hybrid approaches.

Dong Wang et al. [50] in their review on the prognostics and diagnostics on the basis of vibrations, classified bearing health condition into categories based on mechanical signal processing and machine learning. Xiaodong Z. et al. [10] proposed a unified fault diagnostic and prognostic architecture that consisted of three diagnostics and prognostics tools including principal component analysis, hidden Markov models and adaptive prognostic model.

5. Conclusions
The lubrication and the bearing condition monitoring are a subject of interest because of the criticality of operations and cost involved with the running machines for instance in thermal power plants, process industries, etc. The aim of the current study was to review the possible diagnostics and prognostics techniques used for their condition monitoring. The study classified and reviewed the different lubrication and bearing defects, factors affecting their health and condition monitoring techniques that can be achieved by analysing their degradation processes. For a successful condition monitoring there is a requirement of good data collection and sampling methodologies. There is a need of online methods to prevent distortions in data of actual conditions of the systems. Emergence of artificial intelligence has allowed us to predict the advent of any anomaly in the system and days are not away when machines will not require any human interventions for their maintenance. As a result of implication of these techniques, organizations can adopt these condition monitoring programs and the technologies to harness the benefits of maintenance.

6. References
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