Classification of maintenance techniques and diagnosing failures methods

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Abstract. Equipment components essentially the parts responsible for power transmission and bearings will expose to multiple types of stresses, including external stresses coming from the nature of the working and internal stresses resulting from movement between the moving parts or thermal industrial processes. These stresses lead to damage or defect, which adversely affect the current or future performance of these systems. To ensure the reliability of the machine or structure has to establish a continuous condition monitoring system that can detect the abnormal condition state early. This paper will cover the monitoring techniques used to observe the mechanical conditioning of the vital components (such as bearings, shafts, gearboxes, etc.) in an ultra-low frequency rotating machinery in industrial applications including hydroelectric generator, steel mills, paper mills, water sewage plants, cement kilns, and wind turbines.

1. Introduction

Slewing bearings of heavy-load are utilized broadly in huge low-speed mechanical equipment. The rotational speed of such equipment commonly ranges from 0.1 rpm to 5 rpm and the bearings of high capacity are working in complex conditions and difficult.

All strategic structures and huge machines have a very big economical cost during construction and at the same time are designed for a long period of work and service, such as large production and industrial institutions such as cement factories and hydroelectric power plants, cooling towers for nuclear reactors, tunnel boring machines, Port hoists and coal mining machinery, which are called low-frequency machinery, as well as, Highway, Bridges, dams, Astronomical observatories. In the context, appropriate check and observation programs and equipment are required with continuous maintenance became more important than ever. So that modern Structural Health Monitoring (SHM) with a Nondestructive Testing (NDT) manner has been developed In order to meet these requirements. Another importance of Structural Health Monitoring is to guarantee the reliability of existing infrastructure projects.

The processes of achieving defect-recognition for a civil and mechanical engineering infrastructure are known as structural health monitoring whereas for machines condition monitoring. These processes ensure continuous good operation, and safety of infrastructure projects to execute its essential assignment within the desired life span with proper maintenance expenses.
There are certain specifications and conditions for any equipment or construction that set by the
designer to enable them to execute the required performance and to work without any problems,
smoothly and with regular manner. These conditions describe the status of the equipment or
construction and them assembly components, and the extent they are affected by factors of extinction,
that should not be surpassed during the ongoing operational work.

During the service life and work period of all equipment or any structure will expose to multiple
types of stresses from several sources, including external stresses coming from the nature of the
working task to be accomplished or from the surrounding environmental conditions and factors of
weather conditions during the seasons over the year or internal stresses resulting from power transfers
and movement between the moving parts or components or thermal stresses as a result of friction or
thermal industrial processes. the effect of these stresses either leads to a change in the shape and
dimensions of some parts or erosion of surfaces or expose them to internal cracks and offer them to
fatigue in the structure, all of these are called damage or defect, which adversely affect the current or
future performance of these systems.

To be able to detect and monitor these changes in the material characteristics and to respond in an
appropriate manner before serious and dangerous damage is caused, the establishment of a damage
recognition system is essential. The continuous monitoring of structural status can detect abnormal
state early, Which facilitates the implementation of effective and more efficient maintenance programs
to avoid and repair damage in advance, which is useful in reducing costs and increasing the life of the
machine or structure.

According to the effect of erosion agents and depreciation and obsolescence, Appear the
importance of maintenance programs for the sustainability of the work of devices within the scope of
the required specifications and conditions. It is necessary to keep the equipment running continuously
without any Breakdown during its service life, and for this reason, the managers of the institutions and
the operators should Emphasis that the best maintenance programs are followed.

2. Maintenance

Maintenance is defined as the combination of all technical, administrative and managerial actions
during the life cycle of an object intended to retain it in or restore it to, a state in which it can perform
the required role with satisfying performance (or a combination of roles of an object which are
considered necessary to provide a given service) and keep the machines and equipment, work at an
expected level of reliability and dependability [1].

| Table 1. Maintenance techniques |
|--------------------------------|
| **Corrective Maintenance** | **Preventive Maintenance** | **Predictive Maintenance** |
| Operation status of machine | out of service | out of service | working or out of service |
| Reason of interference | Fault | planned inspection | planned control or continuous measurement |
| Tasks to be carry out on the machine | replace of components | to take machine down to inspect and replace components | |
| Purpose of interference | return to work | to guarantee the working for a period | to predict and detect faults |
Maintenance and repair instructions that are strictly followed reduce the probability of sudden faults and thus unnecessary losses of money, time, and production. In other critical cases, faults in equipment may cause dangerous damages, even causing danger to labor staff lives. Generally, there are three maintenance techniques: corrective (or reactive) maintenance, preventive maintenance, and predictive maintenance (Table 1) [2].

In the past, much more of these maintenance programs were less than demand, and the alternatives were very little. In numerous applications, just visual observation has been adopted to assess the condition of the equipment. Often, the decision was to run the equipment until it occurred failure instead of executing preventive maintenance. This is known as the corrective maintenance technique leads to unscheduled downtime, higher labor costs, and faster assets obsolescence. To avoid these costly catastrophic events, many institutions resorted to adopting preventive maintenance. In this approach, will appear a large challenge is that it is time-based, a hat means the inspections and addressing of equipment executed at harmonic intervals regardless of actual assessment of the need to do so. Therefore, failure may occur during an unexpected time or through the misuse of excessive, In sometimes, numerous equipment replaced without any true assessing its remaining Usability or present performance. All these problems, in addition to the technical development in the field of computers, high-precision, and inexpensive sensors pushed the development towards predictive maintenance (or condition-based maintenance).

It has become very clear that the basis for predictive maintenance is high-precision sensors that reflect the true description of the equipment condition in addition to wire and wireless signal technology and the development of analytical algorithms and computer programs.

2.1. Reactive maintenance
The reactive maintenance approach can be compared to that of the civil defense and emergency personnel because the work begins after the emergence of a problem or disaster. In fact, the equipment (or a building structure) remains in service and works until the defect appears and breaks down or completely destroys as a result of a failure in the structure, part of the power transmission, or one of the bearings. The replacement or repairs operations will be done when equipment has already broken down, in order to renovate the equipment to its typical operating condition. A Reactive Maintenance approach is one that basically operates on the run-to-failure manner. This approach while it keeps costs low periodic maintenance, but it is can be costly in the long-running time.

At first glance, an interactive maintenance approach reduces maintenance expenditure for keeping equipment and reduces the number of laborers working in the maintenance field, this is all the advantages of this approach. However, these two features disappear immediately if a failure or disaster occurs, and additional expenses appear in several aspects. When any machine or device stops due to a malfunction without warning, it leads to a great loss in the time of production and materials. This also leads to an increase in labor costs and expenses to restart the equipment, and therefore the worker must work overtime. eventually, this is an incompetent use of labor, materials, and time management [3].

2.2 Preventive Maintenance (PM)
Preventive maintenance is a time-based statistical approach that aims to predict and stop equipment failures before they occur. inspection operation on equipment is executing at a regular time schedule regardless of the actual necessity of its doing so. Thus a sudden unexpected failure may occur out of time-schedule a result manufacturing error in any spare parts or improper excessive use of equipment. sometimes, equipment is replaced without the real need or estimate of its remaining working life and its present performance.
This approach includes periodically frequent maintenance operations that include inspection, checking, cleaning, greasing, lubrication, adjustments, and calibration.

Ultimately, preventive maintenance aims to achieve the absence of any breakdown or failure and ensures that the system or equipment will not stop, thus increasing the service life of the equipment and maintaining the safety of laborers.

Despite all the advantages of preventive maintenance, it suffers from dangerous and very expensive aspects and major obstacles, for example, need to develop complicated scheduling methods and very restricted times. Also, the issue of unexpected failure out of the time schedule, meaning either the machine or equipment to be out of service until the date Subsequent maintenance or carrying out emergency maintenance, which is very expensive and on the other hand, At the same time, such accidents are dangerous to workers and great loss may occur as a result of replacing parts that can work more time and do not need to be replaced.

All these challenges and difficulties have directed toward predictive maintenance [4-8].

2.3 Predictive maintenance

Predictive maintenance (Condition- Based Maintenance ) is based on using several non-destructive tests to specify the condition of the machine and determine the time for maintenance and when it is needed.

Predictive maintenance leans on continuous or cyclic condition monitoring sensors to discover the signs of failure or defect.

In this approach, the maintenance decision is taken according to the evidence-of-fault that foretoken of the emergence of the beginning of the defect in any part of the machine in order to be replaced, corrected or repaired.

The information describing the conditions of the equipment must be accurate so that the decision-makers can determine when and how maintenance, repair, replacement, or alteration procedures are made, thereby reducing costs and increasing reliability to the maximum extent [9-11].

As above It is obvious that, the importance of using high-precision sensors and accurate by the method of nondestructive inspections.

There are many advantages to using a predictive maintenance program:
1- achieve the minimum machine downtime leads to increased revenue
2- Improved machine's reliability, thus increasing working hours.
3- Reducing unjustified or unplanned maintenance, thereby saving an extra cost that was lost.
4- Providing more spare parts.
5- Maintaining more safety and life for laborers.

Disadvantages:
1- Increased cost in diagnostic equipment and software.
2- It requires more staff training.
3- Increasing the complexity of systems.

3. Condition Monitoring Techniques

Condition monitoring is the all activities that are carried out periodically and continuously to measure one or more than one of the parameters to specify the machine reliability and to observe the existence or arising of the failure in machines. According to the advanced improvement of the huge equipment technology as a result of the industries 'need, any unexpected defect is a major catastrophe that affects the safety of workers and the machine significantly.
Condition monitoring techniques are essentially utilized on rotating equipment. Condition monitoring techniques vary according to the type of equipment, the workplace, and the surrounding environment. Below, the most important techniques are extremely used in many applications: [12,13].

1. Vibration analysis.
2. Temperature analysis.
3. Motor current signature analysis.
4. Infrared Thermography analysis.
5. Ultrasound analysis.
6. Lubricant (or oil) analysis.
7. Acoustic analysis.

Condition monitoring warning period is useful and technically feasible just when described related with respect to the time, this relation defined as p-f curve (Figure 1), where ‘p’ define a measurable potential failure i.e. machines still working normally with failure existence but less efficiency, and ‘f’ is a functional failure, i.e., machines cannot perform its demand function before breakdown. A failure development time or p-f curve is very useful and important in predictive maintenance programs [14].

![Figure 1. P-F curve of condition monitoring](image)

### 3.1 Vibration Monitoring

Vibration is the periodic movement of a particle around a certain point that is considered the point of stability or repetition of a specific machine condition during its operation, and given that most of the machines and equipment are by their nature rotating, therefore the vibration characteristic is inherent to them.

The monitoring of machine vibration conditioning has gained wide attention because it provides great potential in assisting industrial maintenance programs. Vibration signal analysis is a quick technique for diagnosing equipment malfunctions, especially for rotating machines. The dynamic response alters directly with the change of the system condition and thus changes the shape of the vibration signal of the machine. Therefore, vibration signal analysis holds large information about the condition of the equipment.
By the mean of vibrations analysis technique, it is possible to identify all the expected faults that may occur in the equipment, below the most common faults can be identified by analyzing the vibrations, imbalance, bearing failures, belt and chains looseness, misalignment, resonance, and natural frequencies. Electrical faults in motors, bent shaft, gearbox failures, cavitation in pumps, and critical speeds [15-17].

According to [18] and [14], P-F curve vibration analysis is the most important and widespread technique used for condition monitoring, effect detection, and structure’s health monitoring analysis because it is easy to collect data and easy to identify system's defects, all these make vibration analysis the most famous monitoring technique, as well as it allows continuous monitoring due to its non-destructive nature.

3.2 Temperature Monitoring
The temperature monitoring and thermal analysis of the equipment is an inherent indicator with the appearance of corrosion thus increases friction in the rotating parts, especially mechanical bearings. The rise in temperature contributes to the acceleration of equipment aging and machinery by changing the properties of grease and lubricating fluids on the one hand and increasing thermal stresses on the other hand [19,20].

The importance of monitoring temperature in multiple systems increases, depending on the nature of the system, for example, in nuclear and chemical reactors and oil refineries. These systems are generally effective in relation to temperature. As for electrical power plants, it is necessary to monitor the temperature of the steam and thermal boiler cycle on one aspect and the electricity generation files on the other aspect [21].

Moreover, temperature monitoring is absolutely necessary to know and track the efficiency of cooling system performance.

3.3 Motor Current Signature Analysis
Motor current signature analysis (MCSA) is an extremely significant technique in the predictive maintenance approach. Although this technology is rarely utilized, however, it is relatively young, but it is rapidly winning approbation in the industry nowadays. The concept of such technique arose and was first suggested from the early 1970s or use in nuclear power plants for motors placed in a dangerous zone and motors that cannot be accessed [22]. This technique can diagnose electrical faults represented by stator faults and shorting of a stator phase windings, bad connection of windings, air-gap irregularities, fractures and cracks in the rotor bar, and moreover, mechanical faults related to belts, couplers, alignment, shaft bend, and ball bearings defects [23,24].

3.4 Infrared Thermography Analysis
Infrared Thermography is one of the non-destructive techniques and it is a very important tool of predictive maintenance and condition monitoring that used vastly in energy conservation in electrical, petrochemical, iron, and other thermal process industries (Figure 2).
Infrared thermography is the science of collect and analysis of thermal radiation by using non-contact thermal imaging cameras or sensors. Thermal cameras can catch infrared radiation emitted from any object to detect its heat pattern or thermal abnormality. Planck’s Law and Stefan-Boltzmann’s Laws are the main principles of infrared thermography. All bodies have a temperature above 0 K radiate electromagnetic radiation in the infrared range of the light spectrum and the intensity of the radiation is related to the temperature of the body.

The thermography system is used to discover bad insulation or locate areas where the insulation is ineligible, and to estimate how quite recent insulation works have been accomplished. However, Infrared Thermography is an ingenious technique because it is noncontact, and can be applied to a wide range of systems working with high-temperature heat exchangers, bearings, insulation equipment, electrical circuit breakers, and steam pipelines in power plants [26, 27].

3.5 Ultrasound monitoring technique

Ultrasound technique is based on the sound pressure wave with a recurrence frequency higher than 20,000 Hz. The frequencies most appropriate for structure health monitoring and reliability of equipment are between 30,000 and 40,000 Hz. Ultrasound detectors are utilized to test the quality of objects by measure the heterodyning of a very high-frequency sound.

The original signal will maintain the quality and characteristics when a very high-frequency sound wave is converted to an audible sound wave, so that, Ultrasonic technique helps maintenance labors the ability to hear ultrasound.

The main causes of the ultrasound waves are friction, impacts, and turbulence, that is means by filtering the sound signal can estimate the equipment’s reliability.

Ultrasound technique gives a solution for many problems so as to distinguish it in several aspects, including, it is very directional; therefore, problems may readily be located, it is not expensive, according to the P-F diagram, it provides an early alert sign of close and Imminent mechanical failure.

The heterodyne circuit is an essential part of the ultrasound detectors device. It picks up the ultrasound signal exposed by the transducer and modifies it into an audible signal (< 20 kHz). To be heard This heterodyned signal can be boosted by an audio amplifier using standard headphones, or can be use converter to process it to obtain an equivalent output in decibels (dB) [28].
3.6 Lubricant (Oil) Analysis Monitoring

In predictive maintenance programs Oil Condition Monitoring operates a very important role, it helps in avoidance of costly defects and failures in machinery, power-plants, and slew bearings by the pursuit of the quality changes in machinery lubricant and. It provides an early-warning of disastrous problems that may occur close, and it also supports smooth and reliable machinery working. The Operational defects and problems in components (especially rotating components) of machines, engines, and others often appear in the condition of the lubricant used. Continuous lubricant condition monitoring can recognize big mechanical problems before they influence on the efficiency of machinery working. Lubricants have to be efficient even it works with difficult conditions, as it exposed to high pressures and continuously, high temperatures, and other hurtful conditions, like water contamination, abrasion, and oxidation.

For a long period of time, scientists and experts with extensive experience were able to develop devices and sensors in order to monitor one or several parameters of the condition of oil efficiency.

Oil monitoring sensors can be classified into four types: 1) Measurement sensors of Electrical or Magnetic properties [29]. 2) Measurement sensors of mechanical properties (Viscosity), 3) Measurement sensors of Chemical properties (Acidic), 4) Optical sensors [30]. Oil can also cool the moving parts and, it also carries the metallic debris particles created by mechanical contact, which reflects the health condition of the equipment and its moving components [31].

According to modern scientific researches, capacitance or permittivity variation can be utilized to monitor the oxidation, water contamination, and wear particle concentration. The capacitive sensors have been quite applied for numerous reasons such as very well stable for a wide range of temperatures, simple design, robust adaptability, good dynamic characteristics, and noncontact measure. Although the capacitance measuring method has some disadvantages, such as it is sensitive to lubricant quality, total acid number, water quantity, and viscosity, but they are still practically and effectively the most method in many industrial applications [32-34].

3.7 Acoustic Analysis Monitoring

Acoustic Emission technique (AE) is a condition monitoring approach that can be applied to analyze emitted sound signal waves created by defects or cracks. The small deformations, corrosion, and cracking that have occurred before structural-functional failure cause a fast release of strain energy, which induces acoustic emissions (AE) temporary elastic waves. There are other sources of Acoustic Emission that comprise impacting, cyclic fatigue, friction, turbulence, material loss, cavitation, leakage. The acoustic emissions are spreading and expanding on the surface of the material like Rayleigh waves [35]. Piezoelectric crystal Acoustic Emission sensors which are made from a ceramic such as lead zirconate titanate (PZT) measure the displacement of these waves [36].

Collect and monitor data all information by each of the sensors. If there are any defects in some locations, the signal characteristics from the sensor linked near the discontinuity are represented in a various manner, then implementation the process of analyzing the discontinuity has to be achieved, so that it is possible to define the defect location and suspicious zone of the equipment. In general, the information analysis can be done by two manners. The first approach depends on the analysis of basic signal parameters such as the rate, energy, and amplitudes, etc [37].

In this approach, in order to execute faster analysis and reduce the amount of data stored, the signal itself is not recorded, but only a few of the parameters of the Acoustic Emission signal are recorded. However, occasionally these parameters lose immense information which makes the distinguishing of defects very hard [38].
While the second approach depends on the complete wave form analysis technique rather than just its parameters. The second approach provides better noise recognition than the first approach [39], and also better offers data interpretation capability by allowing the employ of signal processing methods and wavelet techniques [40].

It is important noting that this technique works with signals of high-frequency bandwidth and has been widely applied for condition monitoring of rotating machinery and structures health monitoring. In order to distinguish the Acoustic Emission (AE) technique than the ultrasonic technique is the frequency range of signal and parameters for condition valuation. the Acoustic Emission (AE) technique operating ranges from the 100 kHz to 1 MHz but the ultrasonic technique works within the frequency range of 20 kHz to 100 kHz. the abnormality examines utilizing Acoustic Emission (AE) technique implements through several testing parameters such as ring down counts, events, rising time, duration, and peak amplitude, whereas listening to the characteristics of sound or RMS indicator on the panel the abnormality is the detection manner [28].

4. Conclusion

Condition monitoring has become a very important technology in all industrial maintenance of equipment and structures, it has gained increasing attention in all countries of the world. By using condition monitoring technology, many benefits can be achieved for industrial enterprises and companies including, keep labor's lives, ensuring production quality, lengthening equipment’s life, achieving maximum work efficiency, optimal energy use, and reducing the risk of accidents and severity of devastation. In this paper, a brief summary of the different techniques utilized the condition monitoring of machines and equipment was written. After a general review of all the techniques, it can be concluded that the choice of the best approach or method of the equipment condition monitoring depends on several variables and factors that must be considered, including the type and source of stress on the equipment, the type of work performed by the equipment, the type of defects to be monitored and the surrounding environmental conditions and the Workplace nature, etc. It was also observed that monitoring using the method of vibrations analysis is significantly the best method, due to its ease and directly related to any change in the dynamics of the equipment resulting from the occurrence of defects and cracks in the structure or bearings.

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