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Recent Trends in Condition Based Monitoring with Advanced Signal Processing Techniques

A.A.Darji[1], Dr.P.H.Darji[2], Dr.D.H.Pandya[3]
[1]*Research scholar, C.U.Shah University, Surendranagar*
Email: ankitdarjildrp@gmail.com
[2]*Prof. & Head, Department of Mechanical Engineering, C.U.Shah College of Engg. & Tech.,Surendranagar*
Email: pranav_darji@rediffmail.com
[3]*Prof. & Head, Department of Mechanical Engineering, LDRP-ITR, Gandhinagar*
Email: divyang_me@ldrp.ac.in

ABSTRACT
This paper provides a broad overview of developments and progress in condition monitoring, diagnostics and failure prognosis philosophy & concepts. An assessment is made of current technological capabilities in this critical area. Selected maintenance philosophies, including Condition Based Maintenance, Reliability Centered Maintenance and Profit Centered Maintenance are discussed. Available diagnostic technologies applicable to condition monitoring & prognosis concepts are described. Some recent developments in the rapidly expanding field of high performance turbo machinery are described thru literature survey. This paper is highlighting some observation on technological gaps and problems yet to be solved are presented. Conclusion of 550 references in this interesting field of rotor dynamics is that many difficult problems have been solved over the last three decades. At the same time new breakthroughs continue to advance the signal processing technology with machine learning techniques.
Keywords - Signal processing, Fault Diagnosis, Condition Monitoring

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I. MACHINERY MAINTENANCE PHILOSOPHIES

Condition monitoring of machinery almost always involves more maintenance philosophies applied for the purpose of reducing operating and maintenance costs while at the same time assuring maximum operating time and achieving the highest possible production rate. No matter what philosophy is employed, condition monitoring will involve from one to about twenty detection and diagnostics technologies. In some cases, only one of the available technologies is used. In others, several technologies are applied in an integrated way. This approach is usually referred to as Integrated Diagnostics.

1.1 Condition Based Maintenance (CBM)

At present, a widely accepted and proven approach is called Condition Based Maintenance (CBM). This approach uses the most cost effective methodologies for the performance of equipment maintenance [1, 2]. CBM incorporates a conscious selection process to apply various maintenance philosophies to specific types of equipment, depending on the significance of that equipment to the industry process for which it is used. The key to CBM is being able to perceive or assume a condition as a result of sensing, observation or test. The CBM philosophy includes the following maintenance options: (1) Break-Down Maintenance, (2) Preventive Maintenance (PM), (3) Predictive Maintenance (PDM) and (4) Proactive or Root Cause Based Maintenance.

1.2 Reliability Centered Maintenance (RCM)

This maintenance philosophy is related closely to reliability, another engineering goal for equipment and machinery. Because of the engineering uncertainty associated with the applied stress and the system strength, probability theory is used to describe system reliability. Potential sources of unreliability[3] include the following: failure to recognize the operating environment and the distribution of applied stresses; inadequate design margin (e.g. inadequate strength); human error (in operation and maintenance); low “extreme values” of strength (e.g. bimodal distribution) caused by material defects, design deficiencies or manufacturing induced faults; poor maintenance and inspection practices and abuse. It is obvious from the foregoing list that one of the key elements of a successful reliability program is the establishment of effective maintenance requirements and tasks. Reliability Centered

Maintenance (RCM) is a concept which applies an analytical methodology or logic to set up specific preventive and predictive maintenance tasks for complex systems. Intrinsic to RCM is the identification of critical failure modes and deterioration mechanisms through engineering analysis and field experience to determine the consequences and the most effective apportionment of maintenance activities. Thus, RCM is logically a part of the reliability engineering program used during system design.

1.3 Profit Centered Maintenance (PCM)

The concept of Profit Centered Maintenance (PCM) is suggested by Mitchell [4]. The PCM philosophy is that maintenance is a business issue. The idea is that there are permanent cost reductions, value and profit to be gained through visionary, enlightened change. PCM describes a state of mind characterized by the commitment to creating value. This is contrasted to a cost centered mentality which is focused on operating within budgetary constraints and has no systemic incentive for improvement or optimization. A profit centered mentality is based on the principle that reducing the need for maintenance, exemplified by today's automobiles, is the only way to simultaneously increase reliability and reduce maintenance costs. PCM makes a clear statement of commitment and priority and demands financial measures of performance. Authors describe techniques and methodologies for selecting an optimum blend of maintenance tasks to make a PCM program work [5]. He suggests that selecting the tasks to be employed in a balanced program can be simply compared to a Reliability Centered Maintenance (RCM) process conducted within a strong profitability context. In my view, an effective CBM program with a profitability goal falls in the same category. The problem is that maintenance is not perceived as a profitable endeavour. Quite often, the practice of maintenance is a daily struggle in which maintenance and profitability are diametrically opposed. The PCM concept must be seen as maximum value versus least cost. In this way, it is an inferred profitable investment. Obviously, the PCM concept cannot be fully implemented until the Business Case for machinery maintenance has been clearly established. This has not yet been done.

II. OVERVIEW OF DIAGNOSTICS TECHNOLOGY

Diagnosis is the art or act of identifying a condition from its signs or symptoms. Prognosis is the art or act of predicting a future condition on the basis of present signs and symptoms. Any method used for identifying incipient failures and/or predicting ultimate failure of materials, structures or systems would fall under the scope of diagnostics and prognostics. In the paragraphs that follow, the most commonly used techniques for diagnostics are briefly described. The issue of prognostics is addressed and an attempt is made to place our current capabilities for failure prediction in perspective [6].

2.1 Diagnostic Methods

Vibration signature analysis and oil analysis are two of the most commonly used diagnostic methods. These and other selected NDE (Non Destructive Evaluation) diagnostic tools are briefly discussed below.

2.2 Vibration Signature Analysis

It is not known when vibration signature analysis was first used as a diagnostic tool. It is clear that machinery health monitoring techniques using vibration signatures have been actively used for several decades.

Over the past several years instrumentation and monitoring capability have increased dramatically, but techniques for fault diagnosis have evolved more slowly. The tools are therefore still more advanced than the techniques and there are three technical areas that must be addressed for effective fault diagnosis using vibration; these are condition and fault mechanisms, modification of signal transmission paths and signal analysis [7].

Expert systems using Artificial Intelligence (e.g. neural nets) for machine fault diagnosis are evolving, but developers are limited by knowledge of mechanisms and signal path transmission. Indeed, there is also a need to develop advanced data processing and information identification techniques. As the reasoning and experience associated with current knowledge of machine mechanisms, identification of transmission paths and data processing are finally formalized, expert systems will become more effective.

2.3 Visual Inspection

Visual monitoring can sometimes provide a direct indication of the machine's condition without the need for further analysis. The available techniques can range from using a simple magnifying glass or low-power microscope. Other forms of visual monitoring include the use of dye-penetrants to provide a clear definition of any cracks occurring on the machine surface, and the use of heat-sensitive or thermo graphic paints. The condition of many transmission components can readily be checked visually. For example, the wear on the surfaces of gear teeth gives much information. Problems of overload, fatigue failure, wear and poor lubrication can be differentiated from the appearance of the teeth.

2.4 Oil Analysis

Oil Analysis is a proven diagnostic tool for mechanical failure prevention. One of the more commonly used techniques is called spectrographic oil analysis. It is reasoned that every wearing, oil-wetted component would impart minute quantities of metals to the lubricating oil. Each engine would establish equilibrium quantities of the wear metals in the oil under normal operating conditions. Any increase in the values would indicate abnormal wear conditions that, if undetected, could lead to catastrophic failures. Since the wear metals were in the low parts per million range (100 ppm = 0.01%), the spectrograph was considered the most suitable means of measurement [6]. Advances in both techniques and equipment for oil and wear particle analysis, such as optical oil debris analysis, have been significant in recent years and have been widely reported in the literature.

2.5 Temperature Monitoring

Temperature monitoring consists of measuring of the operational temperature and the temperature of component surfaces. Monitoring operational temperature can be considered as a subset of the operational variables for performance monitoring. The monitoring of component temperature has been found to relate to wear occurring in machine elements, particularly in journal bearings, where lubrication is either inadequate or absent. The techniques for monitoring temperature of machine components can include the use of optical pyrometers, thermocouples, thermograph, and resistance thermometers.

2.6 Acoustic Emission Analysis

Acoustic emission refers to the generation of transient waves during the rapid release of energy from localized sources within a material. The source of these emissions is closely associated with the dislocation accompanying plastic deformation and the initiation or extension of fatigue cracks in material under stress. The other sources of acoustic emission are melting, phase transformations, thermal stress, cool-down cracking, and the failure of bonds and fibers in composite materials. Acoustic emissions are measured by piezoelectric transducers mounted on the surface of the structure under test and loading the structure. Sensors are coupled to the structure by means of a fluid coupling or by adhesive bonds. The output of each piezoelectric sensor is amplified through a low-noise preamplifier, filtered to remove any extraneous noise and furthered processed by suitable electronic equipment.

Traditionally, acoustic emissions as a technique has been restricted to the monitoring of high cost structures due to the expenses of the monitoring equipment. However, as equipment costs steadily fall, the range of viable applications expands rapidly. Olsson et al. present a frame work for fault diagnosis of industrial robots using acoustic signals and case based reasoning [11]. This frame work utilizes the case-based reasoning for fault identification based on sound recording in robot fault diagnosis. Experimental setup for online fault detection and analysis of modern water hydraulic system, and suggested that the incorporation of wavelet transformation into the analysis of acoustic emission opens up the door for future research, which can prove to be very relevant toward condition monitoring[12]. Worked on neural pattern identification of railroad wheel-bearing faults from audible acoustic signals by comparison of FFT, continuous wavelets transform (CWT) and discrete wavelets transform (DWT) features [13].

2.7 Wear Debris Analysis

It is not possible to examine the working parts of a complex machine on load, nor is it convenient to strip down the machine. However, the oil which circulates through the machine carries with it evidence of the condition of parts en-countered. Examination of the oil, any particle it has carried with it, allows monitoring of the machine on load or at shutdown. A number of techniques are applied, some very simple, other involving painstaking tests and expensive equipments. Presently, available lubricant sampling or monitoring techniques like rotary particles depositor (RPD), spectrophotometer oil analysis program (SOAP), Ferro- graphic oil analysis and recent software used techniques are available to distinguish between damage debris and normal wear debris[9]. Every machine ever designed undergoes a process of wear and tear in operation, yet a battery of modern condition monitoring techniques is available to monitor this process and trigger preventive maintenance routines which depend on identifying any problem before it has the chance to develop to the point of final breakdown. Now recently, engineers have been able to extend their knowledge of conditions within operating machinery by studying the particles of metallic debris which can be found in lubricating oil from engines, gearboxes, final drive units and transmissions, or in hydraulic fluid, and recording the number, size, and type of these fragments of debris.

2.8 NDE Techniques

Although vibration and oil analysis are both non-destructive diagnostic techniques, they have been considered separately because they are important, commonly used methods. These and other NDE methods may be used separately or combined in an integrated diagnostics approach. NDE in general is the technology of measurement, analysis and prediction of the state of material systems for safety, reliability and assurance of maximum lifetime performance. It is an old technology (more accurately a set of technologies), yet it is only in recent years that engineers and managers have awakened to the true importance and great potential of NDE. The NDE test technologies that can be effectively applied to diagnostics include acoustics, microscopy, optics, thermography, electromagnetic and radiography. A brief description of some of these methods that are used for fault diagnosis in machinery is provided in the following paragraphs gives more information on these methods [8].

2.9 Motor Current Signature Analysis (MICSA)

MCSA provides a non-intrusive method for detecting mechanical and electrical problems in motor driven rotating equipment. The system is the development of Oak Ridge National Laboratory [10] as part of a study on the effects of aging and service degradation of nuclear power plant components. The basis for MCSA is the recognition that an electric motor driving a mechanical load acts as an efficient, continuously available transducer (the motor can be either AC or DC). The motor senses mechanical load variations and converts them into electric current variations that are transmitted along the motor power cables. These current variations, though very small in relation to the average current drawn by the motor, can be monitored and recorded at a convenient location away from the operating equipment. Analysis of these variations can provide an indication of machine condition, which may be trended over time to provide an early warning of machine deterioration or process alteration.

III. SOME RECENT DEVELOPMENTS

As in this rapidly expanding field, the state-of-the-technology continues to advance. New solutions to troubling problems are emerging. New approaches to turbo machinery condition monitoring are being proposed and implemented. In July 1995, a colleague’s search of the Engineering Index produced 35 particularly relevant references [26]. This paper has not attempted a comprehensive literature search because it would not be appropriate for this paper. Instead, in the paragraphs that follows, will briefly discuss a few selected papers that describe some interesting advancements in this field of high performance turbo machinery.

Transient analysis techniques and describe how an automated on-line system can be used to capture significant turbine start-up or shut-down data. They provide an overview of the use of both performance and mechanical transient analysis as a means to detect imminent gas turbine problems [14]. Also present a methodology for the design of automated diagnostic systems for gas turbines. Their approach involves a multi-stage experimental learning process leading to the selection of the best instruments and measuring positions for the fault cases of interest based upon the diagnostic potential they offer [15]. The procedures are then developed and the necessary background information for the later exploitation of the system is established. The authors demonstrate their methodology using a case history of the design of a blade fault diagnostic system for an industrial gas turbine. Another comprehensive condition monitoring system for hydro- electric plants is also described [16].

A novel optical rotor motion sensor which integrates highly accurate measurement of the angular position and two dimensional center position of a rotating shaft is described [17]. The high resolution measurements are directly related to the condition of the bearings supporting the shaft and should offer a much clearer picture for condition monitoring than measurements made conventionally by sensors on the machine casing. The state of rolling element bearings is an important aspect of condition monitoring of many types of rotating machinery. Randall, R.B. & at Al, proposed some interesting diagnostic techniques based on vibration analysis for planetary bearings used in helicopter transmissions [18].

A theoretical analysis on a model whose spring characteristic represents that of a cracked shaft approximately by a power series. The results show promise and compare favorably with experimental findings [19]. Uses an eigen frequency measurement and sensitivity analysis for crack localization. Expressions of modal crack sensitivity can be found when the analytical expressions of modal shapes are known. For complicated rotors, the finite element method can be used [20].

On ongoing work to investigate the use of higher shaft-orders and non-synchronous vibration to diagnose a particular fault condition, such as a shaft rubbing on an internal seal. Their work is experimental using a specially designed test rig to reproduce rubbing. Rotor rub, a circumstance during which a rotor interacts with various parts, is the source for a variety of different phenomena. [21]. An analysis that he conducted to investigate the jump phenomenon, a situation in which the rotor amplitude can have multi-valued solutions, and the solution has to jump between different solution branches. For the sake of diagnostics, it is useful to determine when this can happen. [22]. IFTOMM, presented a nonlinear analysis of rubbing due to the motion of a vertical rotor touching a bearing. They observed chaotic motion as confirmed by Poincare plots and computed positive Lyapunov exponents [22]. In an exploratory research paper on chaos concepts as diagnostic tools [23]. a total of three different types of problems were investigated: (1) rotor rub-impact, (2) a cylindrical bearing rotor and (3) a tilting-pad bearing rotor. In all three system types, responses rich in sub-harmonic, quasi-periodic and chaotic motion were obtained over a wide range of operating parameters. Furthermore, changes to the chaos structure are sensitive to parameter changes, indicating the potential use of chaos tracking techniques as advanced diagnostic tools.

A diagnostic method of anisotropy and asymmetry in rotor systems utilizing the two-sided directional spectra of the operating responses is presented [24] and tested with a laboratory flexible rotor-bearing system. The experimental results show that the directional spectra can be effectively used for the diagnosis of anisotropy and/or asymmetry in rotor systems by the investigation of 1¥ and +2¥ components in the directional spectrum of unbalance and gravity responses.

Strongly reinforces this idea in presenting five case histories where modeling a rotor has given tremendous insight to problems in the field, diagnostics, balancing and organized corrections of problems. The case histories present work on a 45,000 hp mechanical drive steam turbine driving a Multi-Component-Refrigeration (MCR) centrifugal compressor, a similar rated #9 Barrel Centrifugal Propane Compressor, a four poster air compressor driven by a 20,000 hp 1200 rpm synchronous motor to the bull gear, a 7 curvic coupled nitric acid expander-compressor-starter unit @ 18,400 rpm and a 40 in.-long titanium built dry coupling for an ammonia intermediate barrel compressor. In most cases, the model was compared with actual field data. It is clear that new breakthroughs are being made on turbo machinery diagnostics, almost on a daily basis. It is equally clear that we are still at the stage that engineering judgment and insight play major roles in our successes [25].

APF-KNN approach based on asymmetric proximity function with optimize feature selection shows better classification accuracy. Instead of time domain approach with Hilbert transform here, FFT of IMFs from HHT process are utilized to represent the time frequency domain approach for efficient signal response from rolling element bearing [27]. Further, extracted statistical and acoustic features are used to select proper data mining based fault classifier with or without filter. Experimental evaluation for time frequency approach is presented for five bearing conditions such as healthy bearing, bearing with outer race, inner race, ball and combined defect. Comparison of effectiveness of Artificial Intelligence (AI) techniques in fault diagnosis of rolling element bearings[28]. The effectiveness of three AI techniques viz. ANN, SVM (SMO) and Multinomial Logistic Regression (MLR) were compared for five bearing conditions. Significant of WPT as an effective fault diagnosis tool for ball bearing for its transient signals with experimental validations [29].

IV. CONCLUSION

This paper is intended to be an in-depth treatment of turbo machinery condition monitoring and failure prognosis technology. Paper has discussed the principal machinery maintenance philosophies. A limited overview of diagnostics and prognostics technology has been presented and the limitations with respect to our capability to predict failure were discussed. Some special considerations related to turbo machinery diagnostics were described and selected papers on advancements in the technology were briefly described. Finally, review demonstrated the breadth of interest in this critical and complex technology by describing a few of the many organizations and programs that are a part of the turbo machinery health monitoring community.

Condition monitoring of machinery, particularly predictive maintenance (PDM), is a multibillion dollar industry and is growing each year. Based upon a Thomas Marketing user survey, 58% of the industries surveyed used one or more PDM or related technologies; 36% used three or more. The utilities, petrochemical and paper industries are the major users of PDM. All of these make extensive use of rotating machinery.

A comprehensive technology survey has not been conducted. Such a survey is needed to establish our current capabilities in condition monitoring and failure prognosis. Conducting the survey would quickly become very complicated as one attempt to relate available diagnostic technologies to fault symptoms and failure modes in ‘real’ machinery.

There is a general lack of common agreement on what the Condition monitoring ‘industry’ is. The scope and definition varies according to one’s specialization point of view. New technology applicable to condition monitoring is emerging rapidly. The major problem is not the availability of technology. It is more a problem of introduction and application of the technology.

There are a number of professional societies, associations and institutes concerned in varying degrees with condition monitoring and failure prognosis technology. However, there is not a unified organization or body of knowledge relative to CBM, since this is still an emerging field, cooperation should be encouraged, all interested organizations should faster technology transfer, information exchange, knowledge networking and information base sharing.

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