CONDITION BASED MAINTENANCE: STATUS AND FUTURE DIRECTIONS

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ABSTRACT

Research on condition-based maintenance (CBM) spans disciplines and introduces a wide range of concepts. On the basis 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 goal of the paper is to review the scientific field of CBM in view of the high pace of proliferation of research articles in the domain. The CBM field began in the 1940s with primary efforts due to the railway companies in the western part of US. Today, CBM has developed into a truly worldwide discipline involving such fields as economics, management, insurance, maintenance, and production. This paper also discusses possible advancements and challenges for the future. A number of articles on general surveys, and specific applications in industries are reviewed. It is hoped that this article will contribute to the further advancement of CBM research.

OPSOMMING

Navorsing oor toestandgebaseerde instandhouding (TGI) maak gebruik van uiteenlopende dissiplines en 'n wye reeks van begrippe. 'n Kwantitatiewe ontleding van TGI-publikasies in vooraanstande instandhoudingsjoernale van die jongste tyd plaas die kollig op ontwikkeling van die vakgebied. Derhalwe is die doel van hierdie publikasie 'n ondersoek na die proliferasie en uiteenlopendheid van navorsingsaktiwitete op die TGI-terrein. TGI het in die vorige eeu in die veertigerjare ontstaan in die VSA se spoorvervoerbedryf. Tans is TGI 'n globale verskynsel wat gebruik maak van kennisvelde soos ekonomie, bestuur, versekering, instandhouding en produksie. Hierdie artikel behandel ook toekomstige TGI-ontwikkelings om sodoende vooruitgang te stimuleer.

1. INTRODUCTION

In the past six decades, a large number of books, articles and research projects have been published on the theory, concepts, techniques and applications of Condition Based Maintenance (CBM) [2, 4, 5, 14, 20]. A central thesis of these publications concerns the design, improvement and installation of monitoring tools and their practical applications to the rapidly changing industrial environment [6, 36]. The intriguing question raised is whether it is possible to implement monitoring systems that are efficient and cost effective. Consequently, intensive research on CBM since the last two decades has led a number of top-rated world class manufacturers (WCM) to discover the powerful tools, techniques, and methods embedded in CBM [38]. They have also adopted them to improve company operational performance. Application of CBM saw tremendous improvement in downtime savings, efficient manpower planning, and a healthy work relationship among workers in production and maintenance departments of manufacturing plants. For over ten years, CBM has been successfully applied globally in industry, military and educational institutions, and healthcare systems.

One of the earliest uses of CBM in industry was by railway companies in the western part of the USA. Given the economic climate at that time, equipment replacement could not be taken for granted. As a result, an expectation of keeping aging machines in service emerged. This elevated concerns that poor performance, inadequate safety, and increasingly expensive maintenance may result. To respond to this technological change, railway industries committed their personnel and financial resources to develop the means to predict when mechanical systems would fail and developed diagnostic systems to monitor their condition in real time. Application reports began to appear in the military shortly after the primary efforts of US railways. It showed cases in which outstanding improvements in operational performance of equipment due to properly applied CBM programs were frequently reported.

The US military for instance, anticipated those needs with respect to its military machine (e.g. ships, land vehicles and aircraft) and as a result sponsored significant research through multi-disciplinary research programs of the various universities. Researchers representing a variety of engineering disciplines were assembled to perform studies associated with major integrated diagnostic needs: the need to detect and identify incipient failures, the need to reliably predict occurrences of failures, and the need to monitor the condition of components of systems in real-time. The research efforts of the military have been yielding positive results.

There is a strong conviction that a large part of manufacturing economics is dependent on effective maintenance of productive facilities. Continued advances in the field of CBM are therefore necessary to increase productivity and strengthen the manufacturing economy. Despite this intuition, no compelling information has been available that provides new entrants adequate details for further exploration and developments of the field of CBM.

The present review describes international activities on the development and current state of research in the domain of CBM. Opportunities to further improve the knowledge base in the literature are also outlined. The research leading to this paper and the result following lay a foundation for future theoretical and empirical investigations in the area. Additionally, this work will facilitate efforts to provide information concerning the scope and impact of the well-elucidated studies in CBM research. It should be useful to an audience of individuals, groups of researchers, academia and industrial practitioners.

2. HISTORICAL DEVELOPMENT OF CBM

The purpose of this section is to present a discussion of the important aspects of the English language literature on CBM. A comprehension of the literature is important for managers as a guide towards making useful decisions and a coherent presentation of articles in the field. The tradition has always been documentation of fragmented studies, which portrays a situation where one does not understand what others who are building this structure are talking about. A discussion would be valuable to CBM researchers for a good intellectual climate where some deep structures could be launched. Again, it will be a data source within which one could investigate the adoption of some of its new technology, approaches, and techniques that could enhance performance. Only then can researchers optmise their limited research resources.

The CBM literature has a rich history. At its origin, many articles were written in general terms on the need for CBM practice in industries. These articles avoided quantitative issues and did not assist in understanding how to measure the progress made in a condition monitoring effort. The objective of this section is to present a review of the historical development of this well-documented body of knowledge. This work will also provide a useful departure point for the classroom study of CBM.

Ever since CBM began in the 1940s, the concept has been largely a semantic issue. Numerous authors have focused their attention on CBM but failed to comprehensively investigate its historical evolution. This omission in favour of an exclusively contemporaneous approach has led to confusion among professionals and students alike. In considering the sixty-year history of CBM research, one arrives at a renewed appreciation of the contributions of its practical perspectives to knowledge in the field.

The last two decades have been remarkable for the application of theory, techniques, methods and critiques in the CBM domain. The number of papers in the current decade, hundreds of papers compared with tens of papers in the 1980s also represent how much stronger CBM is today compared with two decades ago. The theoretical knowledge about diagnostic machines as instrumental tools in the scientific field of CBM has increased significantly during the last two decades.

Developments on monitoring techniques have probably taken place mainly during the 1980s, while machinery failure analytical techniques and sensory systems probably developed significantly from the 1990s till date. Today, CBM can be considered a mature field with many papers presenting and solving a wide spectrum of problems, having many different case studies covered by a variety of techniques. After hundreds of papers, it would be prudent to reflect on where the field is today and what has been learnt about the streams of research that have been established in major maintenance-related journals since birth.

Apart from mechanical engineering, the CBM knowledge base has been extended to other areas including civil, electrical and structural engineering, among others. The field has become multidisciplinary and thrives on the interface between academia and industry due to the growing range of industries that necessitated an increased need for high performance condition monitoring solutions.

Mechanical engineering experienced tremendous growth of scientific activities in the area of machine condition assessment and fault diagnosis over the years, new horizons were opened and new exciting applications emerged. Investigations of specific machine fault characteristics and consequential development techniques to detect, diagnose, locate and assess machine deterioration in a reliable manner and the earliest possible instance were carried out. The focus of most research has been on incipient faults in gearboxes, bearings, diesel engines, reciprocating compressors, flexible rotor machines, and induction motors [1]. Studies have also proposed unique solutions in conditions leading to failure of lubrication mechanisms.

Experts with different backgrounds worked together with the need for better mutual understanding to achieve deeper insight into new problems and to jointly discover new frontiers of machine condition monitoring (MCM). The MCM area has well-established research teams with over three decades of active experience. The teams are scattered all over the globe with much concentration in the UK. Prominent groups in the team include the maintenance engineering group of Manchester University School of Engineering, the Cardiff University Engineering group in tribology and gearing, and the Cranfield University Engineering group in Machine Design and Dynamics. Most of these teams have recorded significant experiences and breakthrough research activities in the last two decades.

The usefulness of their research findings has greatly attracted funds from world class organisations, including Rolls Royce, among others. Although fundamental and applied research has been done, and is still going on, there is a wide range of applications and theoretical synthesis that needs to be done. Tailor made research in offshore engineering and marine systems will benefit both the academia and industry. Extensive studies are also sought in the area of highly engineered systems.

Electrical engineering provides a series of exciting results in the area of condition monitoring (CM). Work has been primarily done on intelligent sensors, incorporating the signal processing techniques operating within the distributing processing methodologies. The development of condition monitoring sensors and software, including communicating data and information, the incorporation of intelligence within monitoring devices, and decision making procedures incorporated in automated monitoring systems are the major contributions of electrical engineering to condition monitoring. This unique CM team has provided sound solutions that cover important signal processing and sensory systems. Major applications are in data processing signals with emphasis on spectral estimation, noise minimisation and real time processing. The aspect of dealing with acoustics has also been explored.

In civil engineering, current challenges in the field of parameter estimation with a specific application to condition assessment of structures is one of the focus areas. However, the use of parameter estimation in condition assessment of structures has many problems in implementation. Many of the problems are economic. In addition, many aspects of this technology are still in need of development in order to make the benefits of this technology apparent to the civil engineering community.

This paper gives information on the statistics of some prominent journals in the field of CBM and some partial answers to the later question on what has been learnt during the last six years. The rich stream of papers, several hundreds, give, of course, the full answers. However, if one were to express in a few words what has been learnt, then one would probably stress the following points: (1) New techniques can be developed on the basis of wide experience, while two decades ago we often had to develop them in a knowledge vacuum. (2) If well founded theories could be proposed, then we have a wide spectrum of modelling approaches. It then means that there is more research to be carried out in the use of models as a tool in CBM research. (3) There are many shortcomings in current research and a rich pool of opportunities for knowledge expansion. (4) We are very close-or at least much closer than two decades ago to a CBM theory, or rather a pattern of CBM theories. It means that we understand much better the properties of the system to be theorized, which of course will inevitably lead to better theories and techniques which reflect the pertinent properties of CBM. (5) Much more comprehensive knowledge of the proper behaviour of parameters and techniques in the field is at hand. It would be impossible to present in a few pages the development of CBM during the last two decades. The paper shall therefore turn to another question: where is the field today?

3. THE CBM FIELD TODAY

The above question can be best answered by giving the word to a range of selected documentation that has been distilled out of the literature. These are front-line studies on different aspects of CBM. The literature on machine condition monitoring (MCM) has tended to generate studies that focus exclusively on diverse aspects of MCM, such as modelling, monitoring systems, electronic systems and acoustics. As such a review along these lines will be provided. We wish to point out that the work will be limited to the review of literature along the modeling dimensions of vibration and signal based studies. It is obvious that a more serious critical review could only be achieved if more areas are covered including techniques, surveys and systems of the CBM aspects of interest. The limitation is basically due to time and resource constraints. Hence we proceed to review models in the CBM literature.

3.1 Modelling CBM Activities

A review of the general field of condition monitoring has led to several crucial observations about previous work of reknown experts in the field, particularly on modelling. Since modelling is the backbone of research, perhaps, the high rate of proliferation of studies in the modelling area is encouraged by the mathematical inclination of experts in the field. As such it will be difficult for researchers with low mathematical affinity to make much progress in such an area as diverse as modelling in condition monitoring.

An important observation is that top rated studies have been established in diverse areas of modelling in vibration, sensors, signal, noise control, thermodynamic performance monitoring, lubricant oil, corrosion monitoring, NDT, inspection techniques such as MPI, ACPD, ultrasonic, eddy current, radiography, acoustic emission. Studies have focused on important components of machinery mainly bearing and gearing systems as well as the investigation of cracks. Most research has extensively covered rolling components. The application of condition monitoring models can also be found in diverse areas such as water pumps, agricultural machineries, helicopter systems, pavement systems and rolling mills. The following is a brief description of the important work done by the University of Manchester CBM research group.

In a chain of studies Shi and other colleagues [25-29] demonstrated expertise in their diagnostics modelling. This opened up areas for investigation that will keep researchers busy for the next several decades. An important research carried out is that of a neural network model which involves the use of a wavelet filter. The principal thrust of the work is the use of sensitivity of a wavelet filter to capture the abrupt changes that occur in hydrodynamic systems and to use the high frequency of a neural network to isolate the fault class. This group of experts developed a model to improve the Kalman filter and model output can be used for fault classification by means of the neural network.

An important extension of the research carried out by Shi and other colleagues lie in the application of fuzzy logic to improve the Kalman filter concept. In isolating the fault class the analytical process may identify different groups in fuzzy logistic variables. Thus, the various classes could be described in natural language. The fuzzy approaches to a problem solving offers a suitable framework for fault classification in its various aspects. Thus, one employs fuzzy-logic modeling by transforming the human expertise into IF-THEN rules. This approach has the advantage of revealing semantic uncertainty with the associated non-specifying measure. Further development on these sets of studies could result into integrating the concepts of fuzzy logic with that of artificial neural network to form neurofuzzy. This emerging concept in the soft-computing literature could be adopted to profit studies on fault classification in manufacturing and other maintainable systems.

In a companion paper by Shi et al. [25] a comparison of methods applied for fault diagnosis of electro-hydraulic systems was made. The paper aims to provide a basis for method selection in fault diagnosis of electro-hydraulic (EH) control systems. A comparison is made between model-based approach and the neural network method because they are the most popularly used in this field. The theoretical backgrounds of the model-based approach and the neural network method are summarized in easy steps to follow for application. The pros and cons of these methods are also analyzed based on capability comparisons. It is concluded that the model-based approach is in an advantage position in fault sensitivity, whilst the neural network method is superior in the case that no convenient model is available.

It is also found that these two methods are complementary. The combination of the model-based approach and the neural network method will give benefits mutual. While this study appears beneficial to the CBM community, there are a number of extensions that could be made to the work reported here. A possible consideration of extensive data tests of the two models may be helpful. In doing this, there is need to approach it scientifically through the design of experiments. Experimental design is a valid procedure used by scientists across the globe in order to ensure that representative data are tested with the model and that the conclusions drawn are scientific and justifiable. The comparison of methods and their subsequent modification for small and medium enterprises (SMEs) may also be considered. This would be useful for developing countries where efforts are invested in encouraging small business investments that are the bedrock of economic development.

In another study, Shi [26] presents the failure analysis and fault simulation of the electro-hydraulic servo (EHS) valve. The aim is to provide solutions to some difficulties that exist on the fault diagnosis of the EHS valve such as failure modes and fault symptoms. The failure analysis will give the fault modes of the valve by means of failure investigation. The fault symptoms are obtained by means of fault simulation. According to the principle of the valve, a mathematical model has been derived in the paper. After combining the math-model with the failure modes, the fault model is developed for use with the EHS valve. A new approach, digital fault simulation (DFS), is then developed to implement the simulation.

In the approach, some faults can be investigated, including faults in operating principle failure and faults that cannot be implemented in the test rig. As a result, many useful symptoms can be obtained from the simulation. This will provide a signature basis for the maintenance and fault diagnosis of EHS valve. The paper could be extended if a focus on sensitivity analysis of the mathematical model developed could be made. Based on this, one could determine the degree of responsiveness to changes by increasing the parameters by some accounts.

The analysis of the problem described here may not be limited to failure modes but could be extended to effect analysis. With the simulation package developed it will be beneficial to link the various effects of failure to modes in monetary terms. With this, the professional manager who manages systems would be able to decide on what to do based on the cost analysis presented.

In another work, the wavelet analysis applied for fault detection of an electro-hydraulic servo system was studied [27]. The paper presents the development of a wavelet model-based diagnostic methodology to perform fault detection in an electro-hydraulic servo system. The objective is to introduce the wavelet analysis into the fault detection of control systems and from this study, a range of research could emerge and it may be beneficial if some soft-computing tools could be integrated into the existing analysis. One of such tools is fuzzy logic with application to wavelet analysis. Here, one considers the results of the analysis in natural language, hence subject to fuzzy logic treatment. Artificial neural network could also be applied to wavelet analysis. From this may be the integration of wavelet analysis with the fusion of fuzzy logic and artificial neural network (i.e. neurofuzzy concept). It is important to test the sensitivity of the emerging models.

Another interesting study by Shi and associate [28] is on non-destructive fault induction in an electro-hydraulic servo system. The paper aims to solve the problem of high research expense on the fault implementation of electro-hydraulic servo (EHS) systems. Due to high integration and high sensitivity of the system, any failure induced in it may cause the whole system to crash. This makes the fault implementation high risk. In order to make the research on fault diagnosis easier a non-destructive approach is developed in the paper. On a test rig, several kinds of faults are implemented by adding additional circuits in the system. The first one is implementation of circuit failures in the torque motor coils of the EHS valve. It is carried out by means of a switch circuit. The second kind of fault is leakage of the actuator, which is carried out with a parallel loop to the main supply loop of the actuator.

All these faults or failures repeatable without any destroying in the system itself. The test results have been given at the end of this paper. The results show that this is an economical way and provides researchers in this field a convenient approach in fault analysis of EHS systems to give an effective approach to detect faults in an electro-hydraulic servo system. After comparing the continuous wavelet transform (CWT) and the discrete wavelet transform

(DWT), this paper gives the selection. A discrete wavelet transform is chosen to analyze the pressure response signal from a test rig with electro-hydraulic position control system. Signals from healthy condition, incipient fault condition to failure condition recollected from a test rig with electro-hydraulic position control system. The results show that some problems exist on the wavelet analysis when directly applied for control systems.

As a solution, the paper develops a wavelet model-based approach (WMBA). In this approach, a model in DWT form is built for the electro-hydraulic servo system in its healthy condition. This model is used to generate a residual signal by comparing the healthy signal and the signal and in the running system. By processing the residual signal, faults from incipient fault to serious fault can be detected effectively. As the conclusion, wavelet analysis can be a powerful tool in the fault diagnosis of control systems.

The non-destructive approach has a number of merits but could be extended by future researchers. An incorporation of the artificial intelligence principles into the model would give the model a heightened value. Also there is a need to state how the system could be installed in various environments of manual, semi-automatic and automatic systems.

Another study of prime importance to the the CMB community is carried out by Elshanti and associates [10] on dispelling the rumours about model-based diagnostics. The paper aims to dispel the rumours about model-based diagnostics by providing an illustration using a common control system problem. After discussing the principle of the model-based diagnostic approach, the paper answers the most frequent questions in the application of this method. A classical multi-tank system is developed to show the diagnostic scheme from system modeling, through data collection and residual generation to fault detection. Finally, the paper concludes by stating the pros and cons of model based methods.

In another study, an implementation of a model-based approach for an electro-hydraulic servo system was investigated by Elshanti et al. [11]. The first part of the paper reviews the development of the model-based approach. A model of a selected electro-hydraulic position servo system is built in simu-link in the second part of the paper. A few types of faults such as the amplifier offset, backlash and fatigue of the servo valve are induced into the system. Finally, some fault detection has been carried out by means of a model-based approach. In extending the study the implementation process could be made in different environments of varying level of automation. For example, the study could be carried out in small-scale enterprises (SMEs) with the results compared with that of a complex system.

It is worth noting that this compendium of studies are initiated and is still further developed at the University of Manchester Maintenance Engineering group.

A similar research centre of high repute is that of the CBM group at the University of Toronto. Jardine [14, 15] being the lead researcher has directed a number of resulted-oriented researches particularly in modelling CBM activities. Three main groups of model are developed. These are: Weibull modelling function, the proportional hazards model (PHM) and the financial model [2, 3, 5, 14-17, 30, 34-38].

The Weibull model uses condition data to diagnose equipment problems. The PHM model relates the risk of a component failing with condition information. It uses a Markov chain model to describe the behaviour of components over time. This is used together with the PHM to form a statistical model with is used with cost information to calculate the optimum component replacement strategy. Clearly, replacement decisions are made with individual components taking into account their age and the most current condition information available. The third group of models has a financial flavour, which uses clients estimate of relative maintenance cost. It uses sensitivity analysis opportunity, which can indicate how much changes to the ratio will affect the result. The research carried out by this CBM group has yielded positive results with the development of a prototype software package to the market place. This practical tool, called EXAKT, the CBM optimiser, is perhaps one of the most effective CBM packages available.

The paper by Jardine et al. [15] reports the development of an optimal maintenance program based on vibration monitoring of critical bearings on machinery in the food processing industry. Statistical analysis of vibration data is undertaken using the software package EXAKT to establish the key vibration signals that are necessary for risk estimation. Once the risk curve is identified using a proportional hazard model, cost data are then blended with risk to identify the optimal maintenance program. The structure of the decision-making software EXAKT is also presented. The paper concludes that perhaps the most important benefit of the study was the realization by maintenance management that it is possible to identify key measurements for examination at the time of vibration monitoring – thus possibly saving on inspection costs.

In considering the above paper, a focus on vibration monitoring is helpful for condition-based maintenance. However, vibration is only one of the important elements for condition-based maintenance. Therefore, the package could be extended from the existing vibration based to incorporate noise and acoustic elements. Noise level could be measured in decibels. Therefore, the software could be designed such that when the limit of the noise level is attained, signals could be sent to the system controller for machinery breakdown precautionary measures or preventive maintenance activities.

In another study, Marseguerra et al. [19] consider a continuously monitored multi-component system and use a Genetic Algorithm (GA) for determining the optimal degradation level beyond which preventive maintenance has to be performed. The problem is framed as a multi-objective search aiming at simultaneously optimizing two typical objectives of interest, profit and availability. For a closer adherence to reality, the predictive model describing the evolution of the degrading system is based on the use of Monte Carlo (MC) simulation. More precisely, the flexibility that is offered by the simulation scheme is exploited to model the dynamics of a stress-dependent degradation process in load-sharing components and to account for limitations in the number of maintenance technicians available.

The coupled (GA and MC) approach is rendered particularly efficient by the use of the ‘drop-by-drop’ technique, previously introduced by some of the authors, which allows to effectively drive the combinatorial search towards the most promising solutions. An extension of this work could consider the application of fuzzy logic or neurofuzzy for determining the optimal degradation level beyond which preventive maintenance should be performed. This then means that the process will be viewed in natural language such as “very good”, “good”, “bad” and “very bad”. This gives opportunities for measuring systems where the state is not precise [37].

In a study on data fusion applications in intelligent condition monitoring, Starr [30] investigated the changes of process parameters in maintenance actions. The author noted that the identification, monitoring and fusion of data from key parameters could provide greater confidence in decisions. The paper reviews architectures or frameworks, and draws examples from manufacturing and plant applications. The chief application shown establishes the key vibration monitoring parameters for equipment within a paper mill and aids the maintenance optimization process. Since data fusion is a relatively new term to the condition monitoring community, its application to other areas of condition based maintenance would be beneficial to professionals and researchers.

A great number of areas in acoustics and sensors need to be explored. For instance, consider the self-learning ASPS (automated sensor and signal processing selection) paradigm. Data fusion could be integrated into self-learning methodology for the classification of the system's normal and faulty states and the selection of the most appropriate sensors and signal processing methods for detecting machining faults in end milling. This will enable the condition monitoring designer to use previous system faults or incidents to design an on-line monitoring system, reducing the system's development time and cost.

In another study the concept of an adaptive model of rotating machinery subject to random deterioration was investigated by Zhan et al. [38]. They noted that due to the non-stationarity of vibration signals resulting from either varying operating conditions or natural deterioration of machinery, both the frequency components and their magnitudes vary with time. However, little research has been done on the parameter estimation of time-varying multivariate vibration signals for the on-line estimation of the state of rotating machines using a modified extended Kalman filtering algorithm and spectral analysis in the time-frequency domain.

Using artificial vibration signals with abrupt changes and time-varying spectral content has tested adaptability and high spectral resolution capability of the model. The implementation of this model to detect machinery deterioration under varying operating conditions for condition-based maintenance purposes has been conducted by using real gearbox vibration monitoring signals. Experimental results demonstrate that the proposed model is able to quickly detect the actual state of the rotating machinery even under highly non-stationary conditions with abrupt changes and yield accurate spectral information for an early warning of incipient fault in rotating machinery diagnosis. This is achieved through combination with a change detection statistic in bi-spectral domain.

It is interesting to note that condition based maintenance, which has much foundation in the UK Universities and research centres has spread its tentacles to other parts of Europe. Vaxjo University is a prominent institution that has trained CBM experts in Sweden. Presently led by Al-Najjar [1, 24], the Terotechnology group has made extensive studies in using vibration analysis in problem solving in condition based maintenance with application in a paper mill and manufacturing companies in general. Vibration modelling allows prediction of the response of simple structures. A group of studies has been carried out to identify the vibration frequencies for damage in rolling element bearing at paper mills and to determine their significant amplitudes.

Extensive effort is also made to develop a model for monitoring and controlling the economic importance of investments in vibration-based maintenance (VBM) since the benefit of improvement in VBM can be found in many disciplines such as production, quality and logistics. Currently modelling efforts are carried out on how to control product quality and saw mill profitability through controlling machines and process's condition.

A review of previous work and current status of the vibration modeling literature may be incomplete if no attempt is made to mention the contributions of the centre for Vibration Engineering at the Imperial College of Science and Technology, UK. The efforts of lead researcher David Ewins in the mathematical modeling of structural vibrations via experimental measurements is extensive. This is completed by studies in other areas by other team members. Areas such as vibration of complex structures and fluid field vessels, computer controlled vibration measurements, FFT spectrum analysis software development, vibration problems in gas turbines and rotor dynamics are some that much documentation has emerged.

Modelling and experimentation in vibration also form the basis of many other researchers who currently have a compendium of research articles. The efforts of Vandiver and his team [9, 31-33] at MIT represent an important contribution to the CBM literature in general. This team focused on the dynamics of offshore structures and flow induced vibration.

The machine dynamics laboratory group of Tampere University of Technology, Finland is also carrying out modelling efforts. Studies have focused on modelling the acoustic emission (AE) of condition monitoring with a high frequency vibration from the surface of the object concerned. The results of an investigation of an influence of typical running parameters on the acoustic emission from grease-lubricated roll bearings are given.

As discussed earlier, the field of CBM has a wide range of areas. One of the most extensive areas is that of signal processing [21]. It could be said that studies have proliferated in this area at such a rate that it becomes difficult to track the extent of explorations in various research centers. However, records indicate breakthrough efforts in countries such as Australia, Japan, Poland, China, USA and Hong Kong. The University of New South Wales in Australia has some worthwhile records in the area of FFT – based methods of separating signals. Randall and Antoni [21] are notable team members of the signal research in this area.

3.2 Application studies on CBM

In a study by Prickett and Eavery [20], the case of a company engaged in the manufacture of a range of sheet metal products, for which a flexible manufacturing facility has been installed, are examined. The introduction of this system has caused the company to examine its maintenance procedures, which are based on a traditional breakdown and repair approach, and has prompted an investigation into the possibility of implementing a condition-based approach to maintenance. The investigation presented by the authors, together with a review of currently available options, and an outline of the planned move towards condition-based maintenance is shown. While this is a case study of practical importance, it has many areas of improvements. An important area is the application of robotics in the improvement of condition monitoring process.

The metal production system considered may consist of operations or tasks that are dangerous for human beings to monitor. It may also be in unusual places where human beings could not survive. For example, if the system consists of a machine that produces substances like sulphuric acid and a jet of liquid, human beings stand a great risk in monitoring that task. Therefore, robots will be suited for the condition monitoring of that equipment. Another extension of the work is the application of artificial intelligence in monitoring a task. Trends in computer science show that various aspects of Artificial Intelligence (AI) are emerging, and other trends show that these advances are being applied to create intelligent information systems. The application of AI to the case study may offer great success in prompting machine uptime, and consequently company profitability.

4. THE RESULTS

Tables 1(i) and 1(ii) show the number of papers versus the year of publication. It contains information on (1) the number of CBM papers published in scholarly peer-reviewed journals over a period of 6 years (1997 – 2002), (2) The cumulative figures of the number of CBM papers over the 6 years period. As can be seen, the number of papers is decided on the basis of the number of good papers. It also reflects the development of the field of CBM. It is probably realistic to say that activity in the CBM field is more than 8 times higher than it was 6 years ago. For example, the number of published papers on CBM in all the journals in 1997 was 12 while it rose to 98 in year 2002.

Journal	JPME	JME	EJME	JQME	MARCON	IFRIM	COMADEM	
Year								Total
1997	8(8)	3(3)	-(-)	1(1)	-(-)	-(-)	-(-)	12(12)
1998	7(15)	3(6)	-(-)	1(2)	-(-)	-(-)	-(-)	11(23)
1999	7(22)	6(12)	-(-)	3(5)	-(-)	-(-)	66(66)	16(39)
2000	6(28)	4(16)	-(-)	4(9)	34(34)	-(-)	16(82)	14(53)
2001	2(30)	7(23)	1(1)	4(13)	-(34)	-(-)	122(204)	14(67)
2002	3(33)	2(25)	2(3)	1(14)	-(34)	6(6)	-(204)	14(81)
Total	33	25	3	14	34	6	204	81

Table 1(i): Number (cumulative number) of condition based maintenance papers

Journal	ICCIE	IERC	JORS	IESA	JSP	RESS	RAMS	CMVA	ICQR	EJOR	JOAP	INFOR	
Year													Total
1997	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	12(12)
1998	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	11(23)
1999	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	1(1)	-(-)	-(-)	17(40)
2000	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	1(1)	1(1)	16(55)
2001	-(-)	1(1)	-(-)	-(-)	-(-)	2(2)	-(-)	-(-)	-(-)	-(-)	-(1)	1(2)	17(72)
2002	1(1)	1(2)	1(1)	1(1)	1(1)	1(3)	1(1)	1(1)	1(1)	1(2)	-(1)	-(2)	24(98)
Total	1	2	1	1	1	3	1	1	1	2	1	2	98

Table 1(ii): Number (cumulative number) of condition based maintenance papers

What can be read into these statistical results? What trends can be observed in the type of papers published in the field of CBM? An attempt to answer these questions on the basis of the results of the statistical analysis of the papers published in maintenance-related journals wil be made.

An experiment with the number of pages published over the years to evaluate in-depth understanding of each paper on CBM was carried out. It is thought that the more the number of pages of a CBM paper, the higher the likelihood of much understanding of the author in CBM thought. If a paper contains very few pages, it possibly reflects a low understanding of the contributing author(s) in the field.

5. CONCLUDING REMARKS AND FUTURE RESEARCH

We began this paper with the realization that we are in a wonderful age of discovery about issues in CBM research and that there is need to have a documentation on what researchers are doing all over the world. This may serve as useful reference material for new entrants into the field of condition based maintenance. For example, undergraduates and postgraduate students of universities may need to understand some of the previous research on CBM in order to launch into CBM research. On the other hand, experienced researchers and academia may need to refresh their memory of the past in order to have a fresh look at present and future issues. One of our findings is that there are many researchers in CBM across the world and each group or team has its own focus that is strongly influenced by the needs of the local industry that need to be researched.

Another issue that influences the research thrust of CBM groups or teams is the sophistication of the facilities in the environments that the research group is located. This largely depends on the level of development of the economy of the environment being considered i.e. developed or developing countries. For instance, highly sophisticated equipment and facilities are common in a developed country like the USA where equipment is remote-controlled and complex to operate. As such, the condition based maintenance techniques developed for this equipment and facilities may require a high level of sophistication.

On the other hand, in developing countries where many of the equipment and facilities used for production are obsolete, less complex condition monitoring techniques are required. A lower investment in cost of maintenance is also required, when compared with a high investment requirement in complex system maintenance of developed countries. The reason solely hinges on the low level of company profitability that exists in developing countries. It could be stressed that the techniques used all over the world for CBM may not necessarily be the same since development of models and techniques are an innovative process. Innovation itself may not be a neat and linear process where things are necessarily done in an orderly fashion and manner.

In this article, we have set out to create a common understanding of CBM research based on the work of key scholars. The goal of the article is to advance and sharpen our understanding of CBM research. As much as it is our goal to be clear about our purpose in writing this paper, it is also important for us to be clear about what is not our purpose. We are not attempting to provide an all-encompassing framework on the literature on CBM research. Rather, we are attempting to provide a starting point for integrating knowledge across research in this domain and suggest avenues of future research.

We explored studies in various novel-engineering disciplines: mechanical, electrical, highway, transportation and industrial. We have also discussed work on computing and mathematics. Further research will need to go beyond these disciplines to include much of operations research and statistics. In addition, we have started by identifying key categories. Future researchers may find new categories and techniques as the set of disciplines considered expands, and the field progresses. For example, monitoring techniques is expected to explore the newly discovered chaos tracking techniques in diagnostic systems for assessing machinery conditions. Currently, the work on the development of a toolbox for monitoring and diagnosing the chaotic behaviour of rotating machinery is in progress by a number of experts in the field. This is expected to run in parallel and be integrated to the traditional techniques, and extended to any mechanical system.

In this work, a predictive model for the expected number of CMB papers is suggested. While this serves as a framework for other research investigations, it has a number of inherent weaknesses. Scholars should refine our arguments and model and should evolve an analytical model that intelligently combines the multiple attributes of the situation under which the forecast is made. We have omitted books published on CBM in our research. This could be incorporated into future studies to give a more precise outlook of our model since books are useful instruments in disseminating CBM knowledge.

Clearly, a number of them are available in the literature. Using multiple sources of information we advocate the incorporation of some salient elements into the modeling to give it an alternative outlook. We need to consider the following: the number of researches currently engaged in CBM research and their respective years of experience, the number of research centers or departments of the university actively riding the CBM vehicle, their years of establishment and their rates of research proliferation, the available funding and frequency of its release. If all these are incorporated into the model, the result that may evolve will be a novel model worthy of emulation and with a high potential of applicability and reliability.

A large effort should be devoted to develop techniques to associate the diagnostic parameters (chaos quantifiers) to the amount of damage. Clearly, the framework presented is meant to provide a starting point to begin a dialogue that spans the existing work and sets a new research agenda in the field of CBM.

From the findings of this study, it is recommended that many areas warrant investigations. A top priority research is the development of CBM software that should be comprehensive, automated and useful as a management tool. Although some software has been developed, it is the thinking of many scholars that extensions of such software should be made to make them more relevant, more applicable and tailormade to meet industrial needs. The CBM software should centre on the CBM model structure. The development of the CBM computer software from both producers and consumers perspectives is essential. The relevant dimensions from producers' perspective are accuracy, capability, features, completeness, conformance, serviceability, stability and structuredness. From a consumer perspective, relevant dimensions include capability, communication, completeness, conformance, features, flexibility, simplicity and stability. However, by utilizing the CBM software, the maintenance department has permanent records in a database that can be manipulated to provide specific product cost and reliability information.

Reports can be electronically transmitted to a CBM database. An interesting dimension in the CBM software development could be the ability for system users to access data entry screen, reports, and data submission modules through an Internet browser. CBM CD-ROM software could be put in place, functionality ported over to a server, enhanced and made available at a website (i.e. www.CBM.model.com). It could be developed such that no special software is required and the operator can access the system from anywhere on the Internet.

While we do not expect this paper to spark a sudden proliferation of an already established field, we believe that this research can be an important intellectual tool for both refocusing our work and creating new intellectual opportunities. This paper presents valuable ideas and perspectives for doing research on CBM.

As stated earlier, research related to CBM has proliferated in recent years. We do not pretend to be inclusive to deceive ourselves that any of these ideas represent the thinking of all, or even most scholars. From a search of relevant literature, these were the themes that emerged and surfaced, not only in maintenance engineering but also across a range of scientific journals. We anticipate the transformation of the discipline in the future age. This will be a journey that one has to go – one that may experience change in its course as new generations of scholars contribute to the dialogue and to the action.

As noted earlier, this work presents a review, hence, it lays a foundation for future inquiry. It has not only offered a basis for future comparisons, but has prompted a number of new questions for investigations as well. While topics that might be considered as a result of this work are numerous, some are of particularly broad interest or impact.

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