Turbomachinery Condition Monitoring and Failure Prognosis

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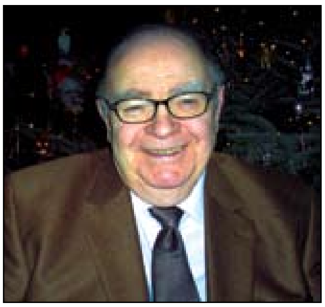

Henry C. Pusey received a B.S. degree in Physics from Randolph-Macon College in 1952. He was employed by the U.S. Army from 1952 to 1958 in shock and vibration research and development. In 1958 he joined the Shock and Vibration Information Center (SVIC) and was the Director from 1973 to 1983 when he retired from federal service. SVIC is now called SAVIAC (Shock and Vibration Information Analysis Center). Over his career he organized, managed and conducted more than 40 technical symposia, along with numerous seminars, workshops and short courses. Mr. Pusey is currently an independent consultant and the immediate past Executive Director of the Society for Machinery Failure Prevention Technology (MFPT), a division of the Vibration Institute.

This article provides a broad overview of developments and progress in condition monitoring, diagnostics and failure prognosis technology applicable to high performance turbomachines. 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 of turbomachinery are described. Some observations on technological gaps and problems yet to be solved are presented; available information resources and organizations with active related programs are identified. In a 1969 monograph, Loewy[1] stated that the first published work on the dynamics of rotating shafts was by Rankine[2] in 1869. Loewy also said that Gunter[3] pointed out that Rankine's neglect of Coriolis acceleration led to erroneous conclusions which confused engineers for half a century. Loewy suggested in 1969 that confusion still existed, in otherwise knowledgeable circles, about many aspects of rotor dynamics. In his book, he identified more than 550 references on this topic in the open literature; today there are undoubtedly thousands of technical publications relating to the dynamics of rotating machinery. In my view, this is evidence that many difficult problems have been solved over the last three decades. At the same time new breakthroughs continue to advance the technology.

High Performance turbomachines are now extremely important elements of worldwide industry. The electric power, petrochemical, mining, marine and aircraft industries are prime examples for which turbomachinery is crucial to business success. Failure and resulting downtime can be very costly to the industry involved. Rieger et al[4] published a definitive paper on this topic.

In this article, I will discuss selected aspects of the present state-of-the-technology of condition monitoring and failure prognosis for turbomachinery. I will examine the process of monitoring operating machinery for the purpose of detecting potential causes of failure in time to avoid costly damage or downtime. I will discuss several machinery maintenance philosophies in terms of their potential roles in condition monitoring and diagnostics.

I will provide an overview of our current capabilities in diagnostics and prognostics. Some special considerations related to turbomachinery diagnostics will be discussed for the purpose of showing that somewhat different techniques are often required for rotating machinery than for other equipment such as internal combustion engines. I will identify selected recent advances in turbomachinery condition monitoring and diagnostics and highlight a few critical problems that are yet to be solved. Some key organizations and programs, either in place or planned, that are concerned with machinery monitoring, diagnostics, prognostics and failure prevention will be identified with the hope of motivating more effective interchange of information on advances in turbomachinery maintenance technology and improving communication links among the key players.

Machinery Maintenance Philosophies

Condition monitoring of machinery almost always involves one or 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; at least ten of these may apply to turbomachinery. 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. In the paragraphs that follow, several maintenance philosophies are discussed.

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Condition Based Maintenance. At present, a widely accepted and proven approach is called Condition Based Maintenance (CBM). According to DuBois,[5] this approach uses the most cost effective methodologies for the performance of equipment maintenance. 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. DuBois[5] gives detailed definitions of each of these options.

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[6] 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.

Profit Centered Maintenance (PCM). The concept of Profit Centered Maintenance (PCM) is suggested by Mitchell.[7] 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. Bond[8] describes techniques and methodologies for selecting an optimum blend of maintenance tasks to make a PCM program work. 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 endeavor. 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.

Overview of Diagnostics And Prognostics 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. More details on the material that follows is in a paper by Pusey.[9]

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.

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.

According to Eshleman,[10] 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. Eshleman provides a detailed discussion of these areas in his paper.

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.

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. Pusey[9] discusses the process. 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.

NDE Techniques. Although vibration and oil analysis are both nondestructive 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, electromagnetics and radiography. A brief description of some of these methods that are used for fault diagnosis in machinery is provided in the following paragraphs. Reference 9 gives more information on these methods.

Motor Current Signature Analysis (MCSA). 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,[11] 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.

Prognostics

Most prediction methods involve mathematical models for fatigue life estimation, stochastic models for cumulative damage or trending algorithms of one sort or another. These methods have not yet been effectively applied by the predictive maintenance community for on-line prognostics. Eshleman[10] provided an assessment of prognostic capabilities that is largely still valid.

Procedures for prognosis of failures (life estimation) have been established most commonly for turbine blades. Even those procedures have serious limitations. There have also been successes in the prediction of disk life for HP/LP high temperature applications and in predicting the rate of crack growth from known flaws in rotor bores. Life estimation has usually been based on limited experience with failures of specific machine components. The remaining life of a machine or component must be based upon wear, the environment, and the history of stress cycles in the machine. These factors must also be considered when establishing a baseline or current condition. Only after the present condition of a machine is known, can meaningful life estimates be made. Information about current condition can also be used to evaluate the effects of changes in components and wear in order to assess whether or not machine life can be extended. The techniques of prognosis involve diagnosis, condition models and failure models.

Failure models that predict time or cycles to failure have been available for materials and simple structures for years. But no failure models have been developed for factors other than stress and strength. Theoretically, structural failure models that are broken down into small elements can be applied to complex components and machines for the purpose of life prediction. Good results are now being obtained with computer models that have been experimentally verified and calibrated. However, the development of failure models and the data to implement them is still a challenge for engineers.

Special Diagnostics Considerations

I have already discussed diagnostics and prognostics as parts of the condition monitoring process. The use of special sensors and data collectors are also essential to the monitoring process. I identified over twenty sensors[9] used to gather data for diagnosing machinery performance using available diagnostic techniques. A vast knowledge base of sensor technology applicable to diagnostics exists and is growing. The role of sensor technology committees, such as the MFPT Society Committee, is to bridge the interface between the mechanical and diagnostic systems in machinery condition monitoring.

The principal technologies with applications to turbomachinery include: vibration monitoring; lubricant, fuel and wear particle analysis; bearing analysis (temperature, acoustic emission, ultrasonics); performance monitoring; infrared thermography; proximity or position monitoring; and visual inspection. Under certain circumstances, motor current signature analysis may be useful. It is important to note that more than one technology is usually employed for effective turbomachinery condition monitoring. Guy[12] points out that, for turbine generators, modern data collectors are capable of acquiring the necessary information to monitor and trend the equipment health. The data must be both dynamic, such as vibration, and static, e.g. temperatures, pressures and flow. Effective comparison of these data provides the insight to make maintenance decisions that keep a turbine generator in reliable condition while increasing its availability.

In general, continuous condition monitoring is required for turbomachinery; this is not necessarily required for other equipment. However, according to Guy[12] the presence of continuous monitoring does not eliminate the need for establishing baseline data for trending purposes, nor for periodic monitoring. The continuous monitoring system warns the operator about immediate problems. Periodic monitoring, along with the collection of external data, provides a means for analysis and projection of potential long term problems both with respect to maintenance and operation.

Roemer[13] prepared some informal comments on turbomachinery diagnostics at the author's request. An edited version of those comments is presented below. In my view his suggestions highlight some important considerations related to condition monitoring of this class of equipment.

1. There are two principal aspects of turbomachinery condition monitoring, aero-thermal performance monitoring (not important for smaller machines) and mechanical component vibration diagnostic monitoring.
2. Turbomachinery usually involves more critical operational aspects than smaller rotating machines. Therefore, diagnostic systems should employ some type of sensor validation method to identify failed sensor hardware. Sensor recovery techniques are also necessary for measured data used in automatic control systems.
3. An integrated diagnostic technique using trending analysis, performance analysis, vibration analysis, oil analysis and borescope inspections is necessary for accurate turbomachinery diagnostics.
4. The transient aspects of condition monitoring of turbomachines are very important for larger machines. For example, start-up and shut-down load changes are important to diagnose rotor train faults like bearings, etc. Furthermore, trending and comparison analyses during start-up and shut-down can help diagnose fouling, bearing problems, gear box problems, fuel lines, etc.
5. Information about rotor dynamics can be very helpful for fault diagnosis of turbomachinery. Consider that a critical speed analysis is useful to examine closeness to criticals, effect of speed changes and amplification factors. The analysis results may be used to diagnose the level of unbalance response, a bent shaft and bearing clearances. In addition, information on stability can help diagnose oil whirl/whip, seal coupling effects and aerodynamic excitation. Mode shapes can be used to diagnose rubbing between rotors and seals/casings. Finally, if unbalance can be located on a large rotor train, it can indicate maximum displacement.
6. Performance deterioration monitoring indicators may include: (a) fouling detection, (b) erosion, (c) increased clearances in seals, valves or blades, (d) foreign or domestic object damage (gas turbines), and (e) exhaust gas temperature spreads (gas turbines).
7. Turbomachinery monitoring tends to want to emphasize fatigue life of specific components. Examples include monitoring LCF/HCF cycles, thermomechanical fatigue, life to crack initiation or crack propagation. These are obviously not the concerns when monitoring a pump or a motor.
8. All turbomachines behave differently, even similar ones. Therefore extensive knowledge must be obtained from expert resources, through interviews with maintenance personnel and from testing and modeling. Such knowledge is essential and must be used to diagnose a particular machine effectively.
9. Off the shelf expert systems are usually difficult to apply to turbomachinery. For example, a condition such as misalignment does not show up with clear phase changes across couplings, and large 2× vibrations are often associated with generator eccentricity problems caused by either electrical or mechanical root fault conditions.
10. Important turbomachinery 'health' indices include: compressor swallowing capacity and efficiency; combustion pressure loss and efficiency; and HP/LP mass flow capacity and efficiency.

In the excellent text by Mitchell[14] two chapters are devoted respectively to general and specific machinery characteristics that are involved in determining machine condition. A careful reading of these chapters makes it clear which of these characteristics are applicable to all machines and which are related only to rotating machinery. Mitchell distinguishes between continuous and periodic monitoring, describes the types of equipment to which each applies and provides considerable detail on recommended methods of monitoring specific equipment. In his book Mitchell states that a great deal of the information presented is opinion; however, much of machinery analysis is opinion. He also wrote The information and guidelines outlined in this chapter and book can not make anyone an expert. Like riding a bicycle, expertise and the confidence necessary for success can only be gained by doing. He is right on both counts. To be really useful, a book on this topic needs to be presented with full understanding of the complex and ever changing nature of the technology. Mitchell's book is easy to read and understand, contains no advanced theory and is highly recommended to anyone interested in or concerned with condition monitoring.

Some Recent Developments

Early in this article, we noted that, in this rapidly expanding field, the state-of-the-technology continues to advance. New solutions to troubling problems are emerging. New approaches to turbomachinery condition monitoring are being proposed and implemented. In July 1995, a colleague's search of the Engineering Index produced 35 particularly relevant references. I have not attempted a comprehensive literature search because it would not be appropriate for this article. Instead, in the paragraphs that follow, I will briefly discuss a few selected papers that describe some interesting advancements in this field.

Roemer[13] has emphasized the importance of transient aspects. The need for transient analysis was emphasized in a 1994 paper.[15] The authors discuss 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. Loukis et al[16] 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. 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 hydroelectric plants is described by Mechefske et al.[17]

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.[18] 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[19] proposed some interesting diagnostic techniques based on vibration analysis for planetary bearings used in helicopter transmissions.

Roemer[13] stated that there have been some recent advances in cracked rotor detection. Two papers related to this problem are cited in references 20 and 21. In the first, Ishida et al[20] conducted 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. The second paper[21] uses an eigenfrequency 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.

Porada et al[22] reported 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. Isaksson[23] reported on 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. Picolli et al[24] 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. In an exploratory research paper on chaos concepts as diagnostic tools,[25] 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.

In a paper by Lee and Joh,[26] a diagnostic method of anisotropy and asymmetry in rotor systems utilizing the two-sided directional spectra of the operating responses is presented 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.

Roemer[13] also suggested that knowledge about rotor dynamics can be very helpful in fault diagnostics. Jackson[27] 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 turbomachinery 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.

Key Organizations and Programs

Condition monitoring is important to some societies because rotating machinery is an integral part of their vehicles or equipment. The Society of Automotive Engineers (SAE) and the American Helicopter Society (AHS) are in this category. Other societies such as the American Society for Mechanical Engineers (ASME) and the Society for Experimental Mechanics (SEM) are interested because their engineering discipline is applicable. Institutes like the Electric Power Research Institute (EPRI) and the American Petroleum Institute (API) represent industries which must use turbomachinery.

A comprehensive technology survey is needed to establish our current capabilities in condition monitoring and failure prognosis.

Some professional societies have machinery monitoring and diagnostics as a major part of their mission. The Vibration Institute and its National Division, The Society for Machinery Failure Prevention Technology (MFPT), are valuable resources for information about turbomachinery condition monitoring. On the world scene, the International Symposia on Rotating Machinery (ISROMAC) began in 1985. The International Federation for the Theory of Mechanisms and Machines (IFToMM) held its Seventh International Conference on Rotor Dynamics in Vienna, Austria in September 2006. The 20th International Congress on Condition Monitoring and Diagnostic Engineering Management (COMADEM) is to be held in Faro, Portugal in 2007. The COMADEM conferences are well-received, especially in Europe. As Executive Director of the MFPT Society, I had the privilege of organizing and conducting the 13th COMADEM Congress in December, 2000 in Houston, TX. The MFPT Society hosted the conference; it was very successful.

Another past source was *P/PM Technology* magazine and its well attended annual conferences in the 1990s. *Sound and Vibration* (this publication) and *Maintenance Technology* are two technical magazines important to this field. There are several others. There are a number of alliances, collaboratives and centers of excellence. Some are associated with Universities, such as the Maintenance and Reliability Center at the University of Tennessee, and some independent organizations. The success of any such efforts depends on an aggressive vision for maintenance technology and cooperation. To insure success, however, all the key players, including those in the public sector, must be aware of each other and all must get involved. Jointly sponsored activities are not only highly desirable, but essential. Cooperation, not competition, provides the greatest opportunity for solving difficult problems. Such cooperation may take the form of jointly sponsored conferences, special seminars and workshops or agreements to organize reciprocal special sessions. To this end the MFPT Society is already engaged in cooperative efforts with several professional societies including SEM, STLE and ASME. It is generally recognized that professional societies serve their members by helping them grow professionally. I believe that they should also provide a 'real' technical information resource for the technical communities that they serve. For example, the MFPT Society routinely responds to technical queries at no charge.

Closure

This article is not, nor was it intended to be an in-depth treatment of turbomachinery condition monitoring and failure prognosis technology. Instead, I have attempted to place the state-of-the-technology in perspective. I have 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 turbomachinery diagnostics were described and selected papers on advancements in the technology were briefly described. Finally, I 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 turbomachinery health monitoring community. It is appropriate to close the article with a few observations and conclusions.

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 attempts 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 specialized 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. Even though we have made significant progress since the first version of this article was published in 1999, development of effective prognostics for turbomachinery is still needed.

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 foster technology transfer, information exchange, knowledge networking and information base sharing.

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