

EXPERT SYSTEMS PROVIDE SUPPORT FOR A PROACTIVE MACHINERY MANAGEMENT METHODOLOGY

by

Ronald F. Bosmans

Corporate Manager, Machinery Diagnostic Services

Bently Nevada Corporation

Minden, Nevada



Ronald F. Bosmans is Corporate Manager, Machinery Diagnostic Services for the Bently Nevada Corporation, in Minden, Nevada. In this capacity, Mr. Bosmans is responsible for the development of the Bently Nevada Engineer Assist Expert System. Prior to this, Mr. Bosmans served as Manager of the Machinery Diagnostic Services group from 1976-1989. From 1962-1972, Mr. Bosmans designed and tested centrifugal and axial

compressors for the Allis-Chalmers Corporation in the Compressor Engineering Department. From 1960-1962, Mr. Bosmans was with Waukesha Motors Company in the Experimental Engineering Department, where he participated in the design and testing of internal combustion engines.

Mr. Bosmans has been the author of six ASME papers on rotating machinery, vibration analysis, and expert systems. He received his B.S. (Mechanical Engineering) degree from Marquette University and is a member of ASME.

ABSTRACT

In today's competitive business environment, one is constantly called upon to make decisions that directly influence operations, and, therefore, profitability. In recent years, it has been necessary to evaluate not just "what" needs to be done, but "how" it should be accomplished. Staying competitive in any field of business requires the ability to adapt to an ever changing and dynamic environment. If one's business requires operating and maintaining critical machinery, one needs to be able to make critical decisions and take action. Processes must be kept up and running, while extending machinery life and reducing maintenance costs. It is, therefore, important to have accurate information in a timely manner in order to make effective decisions. The management of critical machinery represents an important aspect of the operations with significant economic burden. Presented herein are many aspects of expert system application in this critical function of business.

WHY EXPERT SYSTEMS?

In industries that have large rotating machinery as a critical part of the plant process, the rotating machinery specialist function is also critical. There never seems to be enough time for the specialist(s) to manage all of the machinery. In the past, when machinery analysis required an extensive set of separate diagnostic instruments, there were not enough instruments (or people) to go around to all the potentially troublesome sites. While it is sometimes necessary to visit a machinery site to perform a complete analysis, now computerized machinery monitoring systems can transfer data from machinery sites to remote locations. However, these systems can produce so much data—trend files, spectra, orbits, startup, and coastdown data, etc.—that the quantity of data to be reviewed can overburden the machinery specialist.

Permanently installed transducers and monitoring instrumentation are typically installed on rotating machinery used in continuous service that is classified as "critical" or "essential" to a particular process. Many of these monitoring systems are supported with a host computer. Computer supported monitoring can acquire, manage, and display data in various plot formats for review by plant personnel. Effective use of these data requires continuous and rigorous review by rotating machinery specialists. To effectively use this database requires conversion of data to information. Once this process has occurred, the information can be extracted and an assessment of the mechanical integrity of a machine can be determined. The assessment of a machine for potential malfunction identification had, in the past, required a machinery specialist, highly trained in diagnostic procedures and malfunction recognition.

In such situations, expert systems can help. Expert systems provide great potential for disseminating knowledge. Much of this knowledge has already led to the development of many computer-based machinery condition monitoring systems. While these systems help to collect valuable data, they themselves do not distribute the knowledge and expertise required to diagnose problems. Expert systems can review machinery data, compare machinery behavior characteristics to a knowledge base, and provide only a summary report to the machinery specialist. Thus, the specialist can more effectively utilize their time focusing only on machines identified as having a serious problem.

Recognition that there are a limited number of machinery specialists has encouraged plant personnel to explore alternatives to performing machinery condition analysis. The evolution of "expert system" technology now provides a vehicle to perform machinery audits in a time effective and comprehensive manner. Two major assumptions or misconceptions regarding the use of an expert system must be avoided. First, the expert system does not replace the machinery specialist. Secondly, an expert system should not be relied upon to detect and define all possible machine problems. It is limited by the information available and the knowledge contained in the system. It will assist the machinery specialist in malfunction recognition and provide recommendations as to possible corrective action requirements. The machinery specialist will review the conclusions and make the final decision regarding corrective action.

THE IDEAL EXPERT SYSTEM

Software development has evolved into a highly refined process. Proper engineering practices require that certain needs be supported by the design and architecture of the integrated expert system. These characteristics contribute to the reliability of information and ease of use, along with the flexibility of such systems. Data used by an expert system should be available automatically in an online capacity. The source of the data can be from many locations, such as a machinery monitoring system, distributed control system, and from reference information and calculated parameters. The benefits and value of online condition monitoring systems are well established. Accurate, detailed

information is available for immediate evaluation, including trend, transient, and current operating conditions.

The online monitoring system, however, merely captures the condition data; the ideal expert system architecture must provide direct access to the data directly from the databases. This method eliminates the possibility of data entry errors, while greatly reducing the time necessary to complete an analysis. Furthermore, the system that extracts its data directly from the machinery database eliminates the necessity for the user to be a vibration expert capable of correctly answering potentially subjective questions.

KEY ELEMENTS OF AN "EXPERT SYSTEM"

- Online data acquisition from an existing database
- Processing (converting) data to an *information* format suitable for use by the expert system
- Machine condition assessment provided through the use of available information, i.e., obtain information directly from an online database
- Malfunction reports, which include the information used to reach a conclusion, and the diagnostic procedure utilized
- Information that describes the nature of the malfunction and the recommended corrective action
- Information for each machine evaluated, including a summary of all malfunction conditions that were tested, malfunctions found, and malfunctions that were eliminated

SYSTEM ARCHITECTURE

- Data acquisition module—This module is part of the computer based monitoring system. It provides data in the form of current values, dynamic wave form data, and trend files.
- Information extraction module:
 - Extraction and processing of vibration data from the data acquisition module
 - Extraction of process information
- Machine parameter module—A description of the machine to be evaluated. Information includes machine type, bearing type and design clearances, rotor geometry (number of blades or gear teeth, etc.), frequency of balance resonances, etc.
- Expert system program module—Performs the assessment of current machine condition by analyzing information from the machine and parameter extraction modules. This is called the machinery audit process.

THE KNOWLEDGE BASE AND MACHINE CLASS RULE SETS

The system executes a logic path by using a knowledge base and rule sets specific to a machine class. A knowledge base contains the information required to detect a potential malfunction condition. A machine class rule set combines and integrates the information assembled by the knowledge base. The rules are structured so that the information is conditionally tested to verify the presence of a malfunction condition. The logic path demands that the required information is contained in the knowledge base and that the rule set uses all available information to yield an accurate assessment of a potential malfunction condition.

The key to creating a successful system capable of detecting malfunction conditions resides in the data available to the knowledge bases. Inadequate or incomplete data restricts the comprehensive development of rule sets. This often gives rise to presenting answers or results with a weighting factor or confidence factor regarding the probability of the answer being correct. User confidence in the system is quickly eroded if the results have a low probability of being accurate.

An expert system requires various forms of data to render a diagnosis. Much of the data are basic and fundamental to a machinery condition monitoring system. As long as the necessary data are available, the process of extracting the pertinent information can remain essentially the same, regardless of the source of the data. This architecture allows the expert system knowledge bases to remain independent of how the data are actually obtained.

Creating knowledge bases and rule sets begins with identifying the machine type (turbine, compressor, gear, etc.) that the logic path will be applied to. There are generic malfunctions found on all types of machines, with specific malfunctions unique to a particular machine type. Mass unbalance is an example of a generic malfunction. Compressor surge is a machine-specific malfunction. Once a machine type has been selected, the associated potential malfunctions are identified. The information required to detect each malfunction condition is also defined. The availability (or lack) of required information determines if a knowledge base and rule set can be created. It is reasonable to expect the system to identify only those problems that can be supported by the available information.

THE SYSTEM ANALYSIS PARAMETERS

For each potential malfunction condition, an expert system should evaluate the following:

- *Magnitude (amplitude) of the vibration*—is used to define the severity of the problem and the urgency of corrective action.
- *Form of the vibration*—is used to determine the shape and direction of the dynamic motion path of the shaft centerline (orbit).
- *Filtered amplitude/phase lag angle*—is used to define the modal distribution of vibration at various lateral locations along the axis of rotation. It is also used to determine the physical source location of the malfunction.
- *Shaft centerline position*—is used to determine the average location of the shaft centerline relative to the geometric centerline (and clearance) of the bearing. From these data, shaft position angle and eccentricity ratio are calculated.
- *Frequency of the vibration*—is used as an aid in classifying the category of the malfunction, e.g., subsynchronous, synchronous, or supersynchronous.
- *Process data*—is used, in conjunction with the vibration data, to cross correlate the observed mechanical behavior to the current operational mode of the machine.
- *Machine geometry data*—is used to correlate malfunction identification with known geometries of the rotor system.
- *Trend file data*—represents the behavior of the machine over a period of time and is used to evaluate changes (gradual, sudden, etc.) and rate of change (linear, nonlinear, etc.) of the data.

BASIC MACHINE AND SYSTEM INFORMATION

Reference information required by the expert system concerning the configuration of the machine train must be obtained during installation and then stored for future access. This reference information is retrieved from files when an analysis is performed. Reference information can be edited in the event of data entry error at installation or if a major overhaul of the machine train does change some particular aspect of the machine train configuration.

A COMPREHENSIVE DIAGNOSTIC METHODOLOGY

Many expert systems currently in use today, rely upon the frequency of vibration as the primary indicator of the type of machine malfunction. Frequency of the vibration is an important piece of information. However, if relied upon as the prime

indicator of a malfunction, it can be misleading. Additional information must be acquired to produce an accurate diagnosis. An example of an erroneous conclusion can be found by examining Figures 1, 2, and 3. A spectrum display of a vibration signal from a compressor is shown in Figure 1.

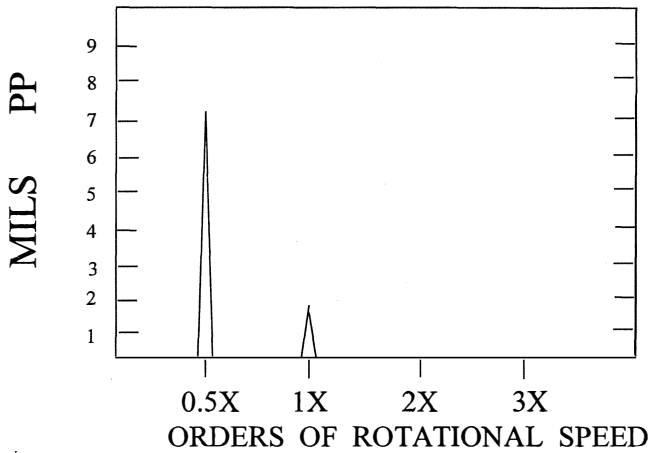
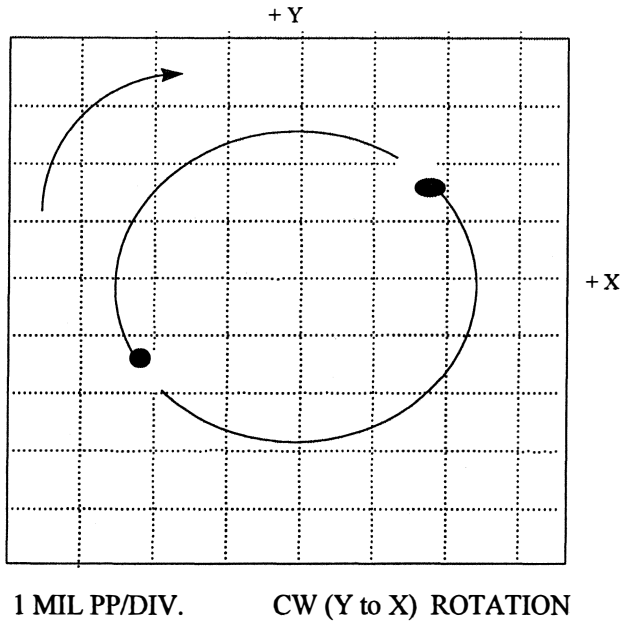


Figure 1. Compressor Inboard Bearing.

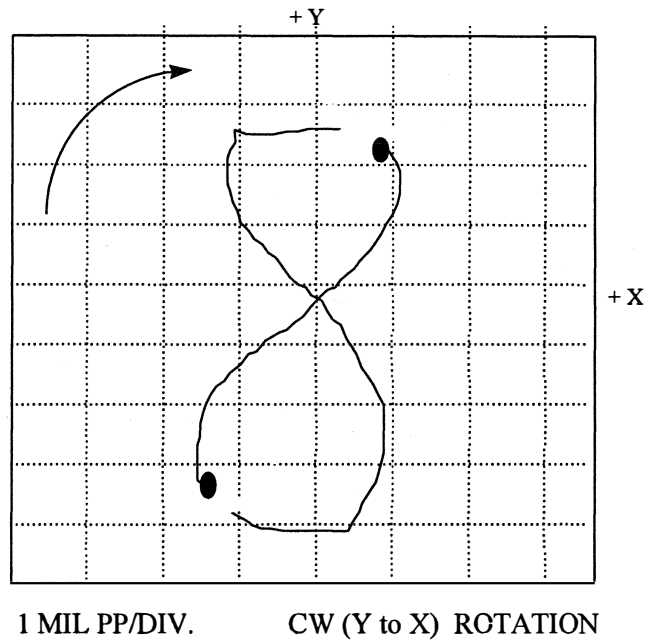
The spectrum display indicates the major frequency component of vibration is occurring at 0.5X. This places the class of the problem as subsynchronous vibration. Fluid-induced instabilities (in general) occur at frequency ratios of 30 percent to 50 percent of rotor speed. If this were the only piece of information used, a malfunction diagnosis of oil whirl or whip may have been determined. However, in order for this to be true, additional information must be evaluated. For a fluid induced-instability to be present, the form of the vibration must indicate a circular orbit (Figure 2), the centerline motion must be in forward precession, and the rotor centerline position must indicate a low eccentricity ratio.



1 MIL PP/DIV. CW (Y to X) ROTATION

Figure 2. Typical Instability Orbit.

The actual form of vibration (for this example) can be seen in Figure 3. The orbit is clearly noncircular, and has both forward and reverse precession components. This additional information eliminates a fluid-induced instability as the malfunction diagnosis.



1 MIL PP/DIV. CW (Y to X) ROTATION

Figure 3. Compressor Inboard Bearing Orbit.

A proper application of frequency domain information requires the use of a *full spectrum*. A full spectrum presents frequency components as forward (+) or reverse (-) components relative to the direction of rotation. An example of this is shown in Figure 4.

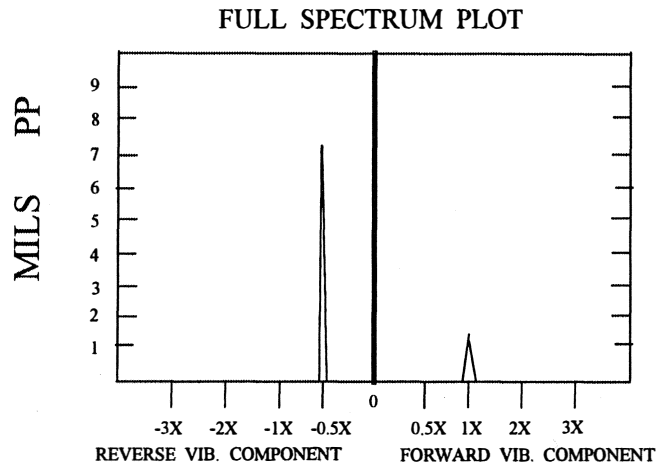


Figure 4. Full Spectrum Plot.

Another example of the proper use of converting data to information can be seen in Figure 5. The DC gap voltages from a pair of proximity probes (X, Y) can be used to determine the position of the centerline of the rotor, relative to the geometric center of a bearing. This measurement permits the calculation of the *eccentricity ratio* and *shaft position angle*. The eccentricity ratio is defined by Equation (1).

$$\text{Eccentricity ratio} = r/C \tag{1}$$

r = Radial displacement of shaft centerline
 C = Radial clearance of the bearing

The shaft position angle, shown in Figure 5, indicates a rotor position that is inconsistent with the direction of rotation and the normal hydrodynamic oil wedge formation. The orbit form is also highly elliptical. The combination of these pieces of information

indicates that an external preload force on the rotor has influenced the current rotor position. The external preload may be due to misalignment.

Shaft Rotation CW (Y to X)

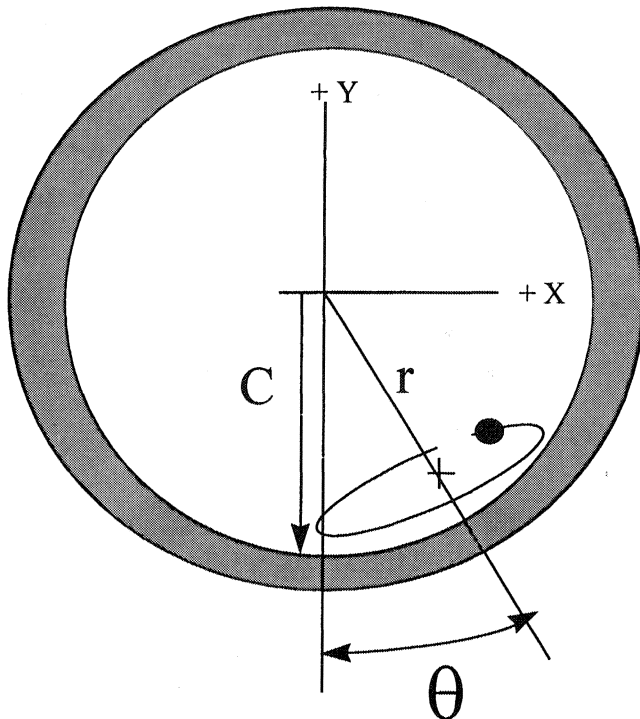


Figure 5. Shaft Position Plot.

There are different formats in which to present pertinent information, depending on the level of detail needed to make decisions. The engineer should have access to more than just amplitudes and frequency content.

The following is an example of the methodology applied to a report from an expert system:

The data was also tested to determine the magnitude of the slowroll vibration vs compensated $1\times$ vibration at operating speed. Slowroll vibration was found to be less than 20 percent of the compensated $1\times$ vibration. The current load on the system is 300 MW. This is 75 percent of normal load. Some turbines are sensitive to thermal variations, or steam inlet/flow variations that may affect the balance state of the unit. If variations reduce as the unit returns to normal power generating operations, balancing may not be required.

An increase in the $1\times$ vibration can be induced by an increase in the synchronous forces, such as mass unbalance. It can also be the result of a degradation of the synchronous dynamic stiffness of the rotor system. This reduction of stiffness may be caused by increased or excessive radial bearing clearances, or rotor centerline position at a very low eccentricity ratio. The current eccentricity ratio is 0.20. Eccentricity ratios less than 0.3 indicate that the effective bearing stiffness has been significantly reduced. This will result in an increase of $1\times$ vibration, with no actual increase in mass unbalance force or change of the balance state of the rotor. The current DC probe gap voltages are -9.32 and -9.51 . Upon shutdown of the unit, the final gap voltages should be measured with the rotor at rest. The difference or change in gap voltages indicates the rotor position change from the online position to the position at rest. This total change is controlled by the available bearing clearance. The design clearance for this bearing is 10 mils. If probe gap information indicates movement greater than design clearances, the bearings should be inspected for wear or damage.

TYPES OF MALFUNCTIONS

An expert system can typically check for the presence of the following machine malfunctions:

- Shaft bow
- High synchronous vibration
- Fluid induced instabilities (whirl and whip)
- Radial preload forces (including misalignment)
- Shaft crack
- Rotor rub
- Loose rotating parts
- Compressor surge
- Electric motor nonuniform air gap
- Gear mesh vibrations
- Pump cavitation

INFORMATION FORMATS, DISPLAYS, AND OUTPUTS

As data are processed, information must be provided advising of malfunctions that were detected and those that were eliminated. The user is then allowed to request additional information regarding the defined malfunction(s) and possible corrective action recommendations. One may also request an explanation of the particular data used and the diagnostic procedure followed that produced the conclusions.

Determining the form of this information is based on what needs to be communicated. Critical information may need to be presented on an operator's display, and detailed engineering data provided in a report format. Reports are structured for individuals who must respond to the malfunction conditions by making decisions and taking corrective action. Because these decisions are made at various levels within a plant organization, different types of reports must be available. Management is typically interested in pertinent operational decisions, where maintenance and engineering may need significant detail and diagnostic information.

An "online" system should be able to actively manage a number of machine trains. If an audit is performed and a malfunction condition is found to exist, information should be posted identifying the problem and possible corrective action. Machinery audits should be initiated based on the needs of both operations and maintenance. These needs will, very likely, be different. Operations may desire machinery audits based on alarm conditions where maintenance would typically need audits to be completed on a scheduled basis. In any case, the ability to manage condition assessment must be flexible enough to accommodate the real world operating practices of industry.

Many expert systems are "session driven" where the user must answer a list of questions about the machine, including its current vibration characteristics. If an error is made answering any of these questions, most systems do not check for the validity of the input data. This could result in the system producing wrong information without any indication. Session driven systems may ask questions that are subjective, requiring conclusions or opinions from the user. Thus, system performance is based, in part, on the user's level of knowledge.

TRAINING AND EDUCATION

Reviewing the process used by the system to determine the presence of a malfunction provides training to the user in diagnostic procedures for vibration analysis. In addition, the information regarding the malfunction should include a description of the nature of the problem and the forcing functions acting on the rotor that produced the observed vibrations. In this

sense, the system becomes a teaching tool. The user becomes acquainted with commonly used terms to describe various malfunctions and the underlying engineering principles. This helps in understanding the nature of the problem. This training tool will provide insight into possible corrective actions, thereby helping to avoid similar malfunctions in future operation of the machine. Experienced machinery specialists can compare methods of diagnostics performed by the system, while new engineers and maintenance technicians can familiarize themselves in rotating machinery diagnostics by using the system as a training tool.

CONCLUSIONS

Plant sites continue to emphasize how valuable knowledge is to their operations. With corporate restructuring and manpower reduction, the knowledge and experience of an organization can be difficult to retain. Expert systems provide users efficient access to the knowledge necessary to make effective decisions.

Computerized monitoring systems have evolved into efficient tools capable of acquiring vast amounts of "data." These data, however, must still be evaluated in some manner before their full value can be realized. The generation of an alarm condition has become, perhaps, less significant than the resulting decision on what to do about it. It has become apparent that changing business needs require a change in operating methodology. Efforts must continue to focus on such requirements. As a tool that helps proactively manage machinery, expert systems are a direct result of such efforts.

It is impractical to expect an expert system to be capable of solving or detecting all potential machinery problems. When implementing expert systems into such operations, it is appropriate to define the malfunctions for which knowledge bases and rule sets have been developed. This precludes any false expectations by the user. Given all required data to the knowledge base, it is then incumbent on the rule set to utilize all information to extensively test for the presence of a malfunction condition. Failing to use all of the available data can result in an inaccurate diagnosis.

Current paradigms within industry position this type of product as an "expert system." Such tools are intended to provide users with the knowledge and methodology necessary to make decisions. As an integral component of the machinery management system, expert systems should be designed to enhance and support the decision making process.

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