CONDITION MONITORING AT ILLOVO WITH SPECIAL EMPHASIS ON THE EXPERT SYSTEM - NSPECTR II

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Abstract

An expert system developed to assist the vibration condition monitoring diagnostician is described. A brief description of types of expert systems and how they work is presented. Four examples are given where the expert system diagnosed problems that would otherwise have been difficult to detect. The advantages and disadvantages as well as initial problems are also discussed.

Introduction

A PC based vibration condition monitoring system has been in use at CG Smith Sugar, Illovo since early 1991. The system utilises CSI Mastertrend software with a 2110 portable analyser. The Nspectr II expert system was purchased in June 1992 to assist with the vibration analysis.

The Need for Additional diagnostic Capabilities

Failure of rotating equipment is a prime factor in causing production delays and high maintenance costs. As both have a direct impact on profitability condition based monitoring was introduced. At Illovo there are 465 machines monitored on a regular basis. This results in 4 891 spectral measurements that have to be analysed on a monthly basis.

The success of an analyst in diagnosing a problem depends upon his ability to pick out features and families of features from the spectral patterns and his ability to correlate these data with stored knowledge to decide finally what the fault is. The number of rules that apply to each peak on the spectrum can overlap considerably, for example at the running speed of the machine, a peak could be: imbalance, load variation, looseness, resonance etc.

As the monitoring programme expands, the analyst needs more time to perform these analyses and too many incorrect or missed diagnoses could result in damage to the credibility of the programme.

Two major developments which help alleviate these data processing problems are (a) increase in sophistication of alarm limits have reduced the number of false alarms, and (b) more recently, the advent of automated expert systems. The latter is the subject of this paper.

Expert Systems

What is an expert system

Expert systems are computer programs which use knowledge and inference procedures developed from human expertise. The knowledge usually takes the form of rules coupled with observed facts. Inference is the logical process which combines rules and facts to produce new facts and conclusions. This tries to emulate human problem solving. These systems cannot compete with humans in the common sense problem areas dealing with social interactions. Fortunately the fields which were considered to reflect high intelligence such as logic and numerical manipulations in the form of equations are relatively easy to emulate. The condition monitoring analyst deals with hard data and relatively narrow problem definitions which can be emulated quite well in an expert system.

Development of expert systems

Building an expert system involves a process often referred to as 'knowledge engineering' This essentially requires the transfer of both human knowledge and algorithmic diagnostic procedures to a computer programme. Thus an expert system is only as good as the knowledge it possesses.

Expert systems have been developed for fault diagnosis, condition monitoring, interpretation, prediction, design, tuition, planning and control. They were initially used in the military, medical, oil and mineral industries but their use in other areas is increasing rapidly. Process control companies are also developing expert system shells that interact with their existing computer based control systems, however these systems can become very complicated as they must react in real time with the process environment and the operator (Watson, 1989).

The 'shell' is obtained by removing the knowledge base and the data from the expert system. Many expert system shells are commercially available for both personal and minicomputers. These contain rule building and editing tools and explanation facilities along with the inference engine.

Types of expert system logic and how they function

The two most widely used logic patterns in expert systems are the 'Forward Chaining' and 'Backward Chaining' patterns. Forward chaining systems accept input data and move through a rule base deducing new facts. For instance, input fact 'a' will be incorporated into the rule 'IF a THEN b' and the new fact 'b' will be deduced and added to a list of other known facts. This logic pattern is useful in those applications where implications of each piece of new data must be evaluated.

Forward chaining systems are commonly called 'production systems' because in each cycle they produce an additional fact. This is a reasonable model of human thinking and is often favoured by researchers.

The 'Backward Chaining' logic pattern, the one used in the Nspectr system, is 'goal oriented'. The logic of this kind of system is based on accumulation of facts which will satisfy certain specific references or 'goals'. This logic is easier to computerise because the goals (inferred facts or conclusions) are already defined and the system is concerned only with facts which will support a logical inference. This technique starts with a goal to be proven and works backwards to resolve it. Backward chaining expert systems direct user sessions by asking very specific questions, such as 'Does the vibration amplitude peak during coast down?' Facts unrelated to a current specific goal are not normally accepted. An exception procedure in Nspectr implements a technique to revise previously entered facts and redirect its 'thinking'. If a narrow focus and lack of generality is accepted, the goal-directed approach can provide systems which operate efficiently, are easy to write and understand, and provide excellent results in their area of expertise.

The key components and interfaces of a typical backward chaining expert system are shown in Figures 1 and 2. Figure 3 shows an example of a rule the objective of which is to gather evidence in support of unbalance in the rotor of a machine.

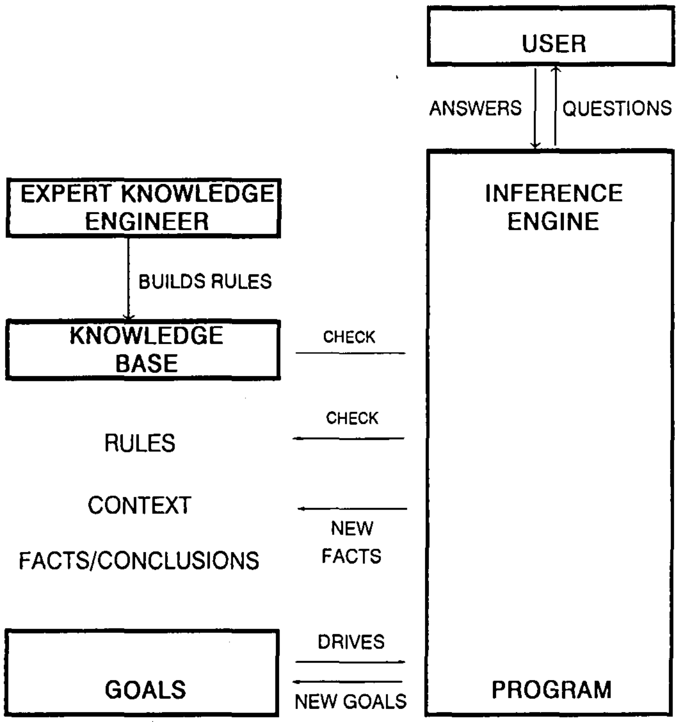


FIGURE 1 Schematic drawing of an expert system (Anon, 1989).

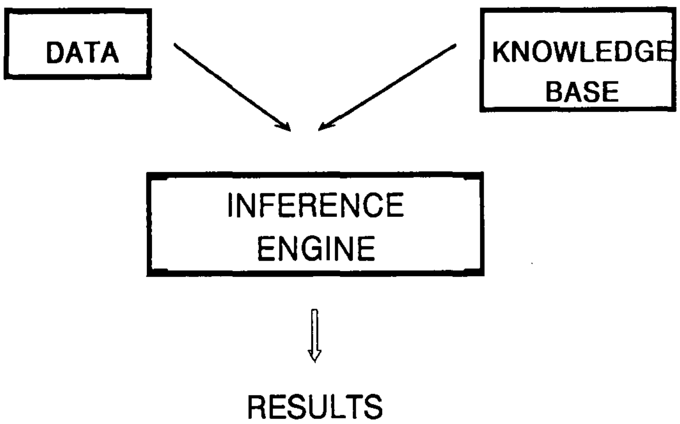


FIGURE 2 Structure of an expert system.

Diagnostic rules for 200201 - A5H - No. 2 turbo-alternator AEG

RULE 217
IF The 1xRPM radial amplitude IS. The 1xRPM radial balance limit* 1.000.
AND The 1xRPM peak is one of the biggest 3 peaks.
AND The ratio between the 1xRPM horizontal and vertical reading IS > .250.
AND The ratio between the 1xRPM horizontal and vertical reading IS < 4.000.
THEN There is evidence to indicate that the problem is unbalanced in the rotor. (060).

Calculated Conclusion Certainty: 60%.

Diagnostic rules for 200201 - A5V

No Rules Fired for this Measured Point!

FIGURE 3 Diagnostic rules for 20021.

The 'IF'-part of a rule are the conditions or expressions the values of which are either true or false. Whenever the conditions become true, the rule 'fires' invoking the action specified in the 'THEN'- part. The entire knowledge base is built up of rules expressed in this format. Once the rule is fired the system then looks for evidence to support the conclusion. As more 'AND' conditions are satisfied the certainty of the conclusion will be greater. The 'AND' conditions are weighted and summed to give the 'Calculated Conclusion Certainty'.

Whenever a problem cannot be resolved using known facts and rules, the user will be consulted to provide additional data. Eventually either the problem is resolved or if there are not enough rules to handle this problem, the conclusion is 'no conclusion can be reached'.

Nspectr II expert system

The Nspectr II expert system has three key components, namely:

(a) Knowledge Base
(b) Inference Engine
(c) Database

The knowledge base

The knowledge base uses both 'rules of thumb' (events that cannot be rigorously proved) and facts (knowledge which is provable). These rules are derived from expert vibration analysts with decades of experience in diagnosing machine faults from vibration data and is refined by making extensive use of case histories. The method of representing the rules is IF (condition) THEN (consequence). If the conditional part is satisfied, then the consequence will follow. The knowledge base contains rules to analyse general faults for many types of equipment and the programme also contains specific rules for the following types of machines: electric motors, pumps, fans, turbines, compressors and gearboxes.

The inference engine

The inference engine provides the ability of the expert system to arrive at a diagnosis. It is basically a program that utilises the knowledge base to operate on the information in the database. It uses linked lists to maintain rules, fact and goals in addition to several other types of data. The strategy used is backward chaining and with the current knowledge base of approximately 250 rules, the time spent resolving goals is typically less than one second.

The database

The database contains, manages and manipulates the conditioned and processed data (i.e. fault specific parameters).

Nspectr uses data from three sources, namely:

- The Machine Configuration File containing the machine design information and measurement point location.
- The Mastertrend PDM Database containing trends and spectral and time waveform data on the points to be analysed.
- Special Test conducted by the user on request of the expert system to increase the certainty of the diagnosis (Anon, 1990).

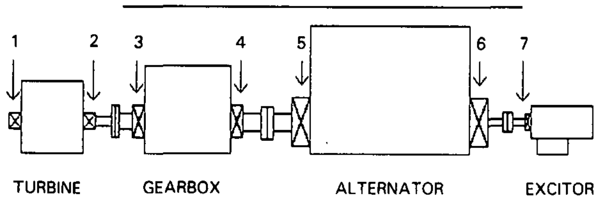
Case Studies

The following case studies have been simplified for the purpose of the paper and only the first and most important diagnosis of the expert system is used.

AEG turbo-alternator

Prior to the 1991/92 offcrop excessive vibration was noted on the AEG turbo-alternator excitor and the rotor was manually diagnosed as being out of balance. It was balanced and on startup the vibration was still there. Due to the 1x and 2x peaks the alignment was suspected and it was laser aligned twice, but the problem was still present. The shaft of the excitor was then suspected of being bent. It was removed and checked and found to be straight. It was noted that a small pre-excitor was positioned after the last bearing and this allowed the shaft to flex around that bearing. The rotor was re-installed.

The whole machine was then re-checked and a drawing was made (Figure 4) with vibration details. From this drawing and the vibration spectrum (Figure 5) it was still difficult to diagnose the problem but the alternator rotor was thought to be out of balance. This could not be proved and to balance the rotor is expensive.



TURBINE HP.	TURB. LP.	G/BOX DE.	G/BOX NDE	ALT. DE.	ALT. NDE.	EXCITOR.
HORIZONTAL		1x OF ALT.				1x = 2.6
1x = m/s	1x = 0.5	= 0.7	1x = 0.96	1x = 2.5	1x = 2.2	1x = 2.5
VERTICAL						
1x = 1	1x = 0.54	1x = 0.42	1x = 0.3	1x = 1.2	1x = 0.8	1x = 2.4
AXIAL						1x = 2.8
1x = 0.7						1x = 1.8

1X IS THE SHAFT ROTATION FREQUENCY
1E ONE TIMES THE RUNNING SPEED

FIGURE 4 AEG turbo-alternator vibrator readings.

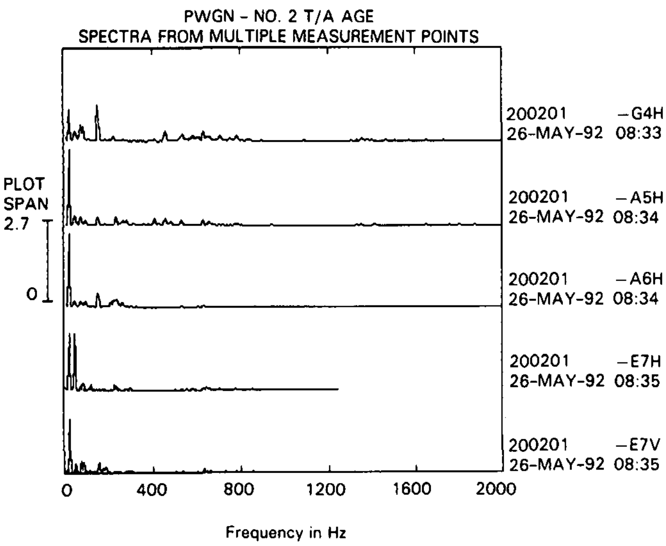


FIGURE 5 Spectral plot for No. 2 turbo-alternator AEG.

The expert system was used and pinpointed the problem to be unbalance in the alternator rotor at 60% possibility (see Figure 6). Even though the possibility was relatively low it served to confirm the manual diagnosis.

Nspectr II Knowledge Base Version: V2.09
Fault Amplitude Basis: STANDARD - NSPECTR2

NUMBER 1) ********** SHAFT PROBLEM **********
200201 -A5H 22-OCT-92 15:41:13
200201 -A6H 22-OCT-92 15:41:40

There is evidence to indicate that the problem is unbalance in the rotor.

Unbalance that develops gradually may result from the build-up of debris on the rotating member. When unbalance occurs suddenly, broken or chipped elements on the rotating member may be the cause. Before attempting to balance the unit, carefully examine and/or clean the unit. This is particularly of concern when the process environment is not carefully controlled on equipment such as fans, pumps, compressors, or turbines.
Possible (60%) Rule 217

FIGURE 6 Diagnostic summary for No. 2 turbo-alternator.

Now that the problem has been identified and after having monitored the machine for two years it is sure that the vibration levels are well tolerated by the bearings. The alternator rotor will be balanced at the next major overhaul.

No. 2 C-strike receiver massecuite pump

During the pre-offcrop survey high vibration was noted on the No. 2 C strike receiver massecuite pump motor. The amplitude at shaft rotation frequency (one time RPM) of the motor was very high, and this would normally indicate an unbalance with low-level second and third harmonics. Misalignment and mechanical looseness were not suspected because there were no large second or greater harmonics (see Figure 7). One of the advantages of the expert system is that an individual machine or the entire database of spectral data can be processed at will.

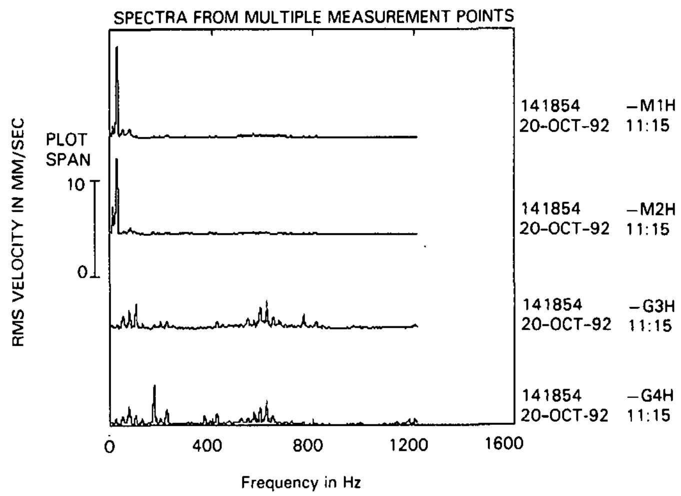


FIGURE 7 Spectral plot for No. 2 C-strike receiver mass pump.

It was when all the machines in the Backend were being processed by Nspectr II that the report shown in Figure 8 was generated. The following were the problems identified by the expert system:

(a) There was a problem with the belt drive between the motor and gearbox.

(b) Bearing problems were identified on the motor drive end bearing. This fault would most certainly have gone undetected in a manual diagnosis, as the scale of the spectral plot dwarfs the bearing fault and only the large 1x peak would have been examined.

(c) Bearing faults were detected on the gearbox drive and non-drive ends. These faults would have been identified manually.

In this case the expert system diagnosed two additional faults. In the first case the analyst would have suspected unbalance in the motor rotor. This would have resulted in a waste of money in balancing the rotor.

NUMBER 1) COUPLING PROBLEM

141854	M1H	20-OCT-92	11:15:20
141854	M2H	20-OCT-92	11:15:31
141854	G3H	20-OCT-92	11:15:47
141854	G4H	20-OCT-92	11:15:58

There is an indication that there is a problem with one or more belts attached to this shaft.

NUMBER 2) POSITION PROBLEM

141854	-G4H	20-OCT-92	11:15:58

The data indicate that the problem is in the outer race of the bearing, and additional bearing fault characteristics were found.

NUMBER 3) POSITION PROBLEM

141854	-M2H	20-OCT-92	11:15:31

The data indicate that the problem may be in the antifriction bearing, most probably in the inner race.

NUMBER 4) POSITION PROBLEM

141854	-G3H	20-OCT-92	11:15:47

The data indicate that the problem may be in the antifriction bearing, most probably in the inner race.

FIGURE 8. Diagnostic summary for No. 2 strike receiver mass pump.

The other advantage of the expert system is that to do effective analysis the details of each machine need to be gathered. This will result in more complete information on each machine. This is a lengthy task but once complete the information is available to all departments.

Spiller table hydraulic pump motor (000807)

The spiller table hydraulic pump is critical to production. Increased vibration was noted on the motor with a reasonably complex spectrum which was difficult to analyse. Initially only the motor was on the regular measurement route, and from the spectrum taken it was diagnosed by the expert system that the fault could have originated from another shaft, not the motor.

The available details of the motor and pump were configured in the expert system. Vibration analysis was then done on the whole machine and the expert system was run. Due to the design of the pump and a lack of information on the bearings and pump internals the system had to work on a lower certainty level.

The Nspectr diagnosed that the most likely problem would be that the coupling was locked up or worn (see Figure 9). The machine was monitored until a suitable stop day so that it could be inspected. It was found that the coupling rubbers had worn and the coupling pins were driving metal to metal.

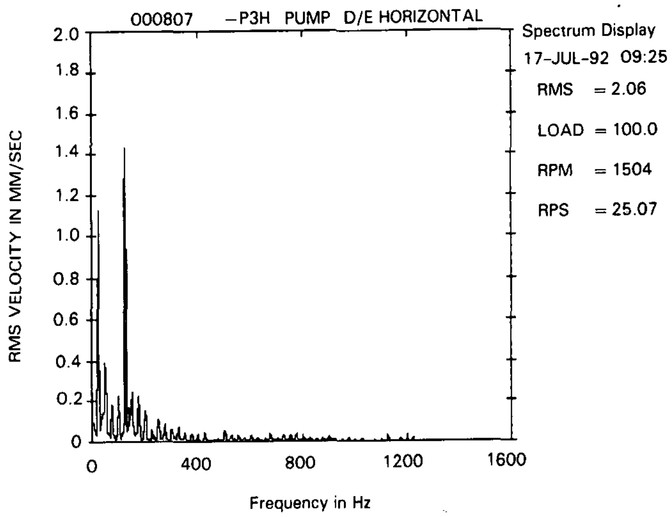


FIGURE 9 Spectral plot for spiller table motor.

New pins and a rubber disc were installed in the coupling. This was one of the first diagnose for the expert system and it helped to create confidence in the system.

No. 2 B-molasses receiving pump (141450)

Unacceptably high vibration levels on the number two B-molasses receiver pump gearbox and motor were noted. The gearbox is flange mounted onto the motor. Bearing faults were evident but could not be pinpointed (see Figure 10). The condition monitoring technician was unsure of the internal design of the gearbox or the bearing positions, but he did know the bearing numbers. He could not diagnose the problem let alone decide which bearing was faulty.

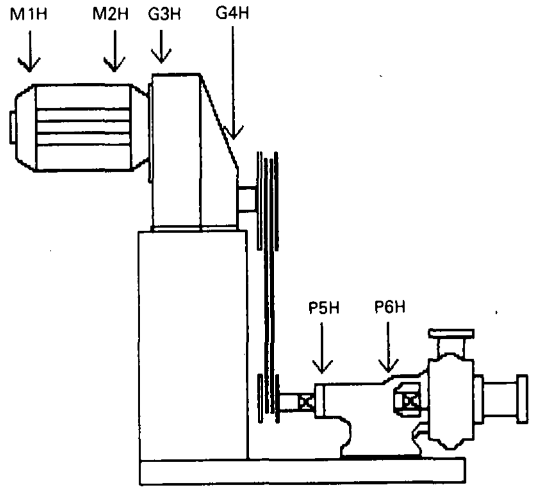


FIGURE 10 No. 2 B-molasses pump.

The bearing numbers were fed into the expert system and the Nspectr II was run. The printout showed that there was a fault on the output shaft bearing of the gearbox (see Figure 11). The system correctly identified the second harmonic on the ball pass frequency on the inner race as having a defect (see Figure 12). This highlighted the accuracy of the Nspectr II as the output bearing on the motor and gearbox were exactly the same.

Fault Amplitude Basis: STANDARD - NspectrII

NUMBER 1) ********** POSITION PROBLEM **********
141450 -G4H 20-OCT-92 10:38:29

The data indicate that the problem is in the inner race of the bearing, and additional bearing fault characteristics were found.

You should inspect the data analysed to verify the existence of a bearing problem and its severity. Then you should inspect the bearing and replace it if necessary.
Likely (72%) Rule 42

FIGURE 11 Expert system report.

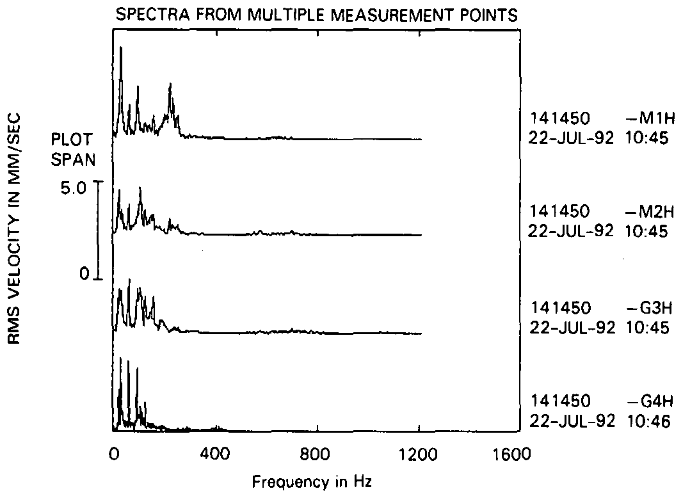


FIGURE 12 Spectral plot for No. 2 molasses receiver pump.

Savings

During the 1991/92 off-crop period a saving of R158 000 was attributed to condition monitoring. A total of 379 machines were analysed and 34 were recommended for maintenance work. An additional 46 machines were maintained at the foreman's initiative. The philosophy of 'If it ain't broken, don't fix it' paid handsome dividends. (This was without the use of the expert system).

During this year's pre-offcrop, analysis reports were generated for 506 pieces of equipment, as shown in Table 1. It can be seen that 39,7% of the machines required maintenance compared to last year's 21% of measured machines. The increase is due mainly to more accurate alarm limits and the use of the expert system. The primary focus of vibration condition monitoring is to reduce stoppages caused by the failure of rotating equipment, but in these economic times the cost of overhauling the machines must be taken into account. It is for this reason that, before overhauling equipment, each artisan must discuss the diagnosis with the condition monitoring technician to determine the most cost effective way of rectifying the problem.

Table 1

The number of machines reported

Back end	Front end	Boilers	Electric motors	Total	
75	52	27	151	305	Satisfactory condition
55	19	27	100	201	Requiring attention

Other savings included: reduced overtime due to less work; increased productivity; reduced maintenance induced problems. During the last crushing season there were no failures on pumps, gearboxes or fan bearings in the Front-end or Boilers.

The expert system has only been in use for a relatively short period of time and has shown its potential to be very effective. The advantage of purchasing a proprietary package with an 'update' contract is important as this allows for the knowledge base to be updated as the system is developed further. The saving attributed to the expert system has not yet been quantified.

Disadvantages and Advantages of Expert Systems

Disadvantages

It is important to realise that the expert system is not a general problem solver. It can be easily fooled or misled. Protecting the novice from inadvertently leading the system to give bad advice is one of the challenges facing those implementing expert systems.

For the system to work effectively the machine design must be described to the database. This includes the number of shafts; how they are driven, connected and supported (i.e. sleeve or roller bearings); the make and number of bearings; teeth on gears; vanes on impellers; prime mover power; load conditions; support structure stiffness; location of measurement points etc. From the above it can be seen that the more information that is available the more accurate will be the result. All this information takes a long time to gather and to feed into the database. Expert systems cannot possess common sense or 'flashes of inspiration' and cannot learn new rules automatically.

Advantages

If all the information is not available it does not stop the expert system functioning but the accuracy will diminish. Expert systems should emphasize the good qualities of human expert advisers and minimise the undesirable ones. They have excellent memories and, once given a set of conditions leading to a diagnosis, will have no difficulty remembering the case next year.

Other advantages are that they are very methodical and they don't panic easily, have bad days, take vacations or retire or move to a competitor taking their expertise with them. They give repeatable diagnosis given the same data. They can encompass knowledge from more than one person and the knowledge base can be easily modified/refined with computer updates as it is not part of the inference engine.

The expert system is a very powerful training aid as the operator can follow the rules that have been used to arrive at the diagnosis as well as look at all the features that it used in its analysis (Hill and Smith, 1990).

Initial Problems with Nspectr II

An initial problem was that if the running speed of the machine varied by more than three percentage points the diagnosis could not be completed. This was a major concern. During a few analyses of suspect machines the running speed of the machine was not described sufficiently accurately for the expert system as these speeds were taken off nameplates and not measured. This resulted in the expert system ignoring a very high one time RPM vibration peak and not finding any fault on the machine. The first update of the expert system in January 1993 solved this problem and to date it has proved reliable.

Conclusions

Expert systems are a fast growing branch of computer science and will soon be common place as a tool to assist in many forms of decision making. Their application to condition monitoring is well suited as they do not require expensive, specialised hardware or software. They also do not require senior technical operators to achieve effective results. A large knowledge base can be used to assist in the diagnosis of complex problems. The expert system is an effective additional 'tool' to have in the vibration condition monitoring 'toolbox' to speed up the processing of information.

Acknowledgements

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