SELF-DIAGNOSIS OF HYDRAULIC CIRCUITS USING EXPERT SYSTEMS

Q. Guo, R.T. Burton
G.J. Schoenau, C.M. Sargent

Dept. of Mechanical Engineering
University of Saskatchewan
Saskatoon, Saskatchewan, Canada

ABSTRACT

The rapid advances in computer, microcomputer and microprocessor technology has opened many new application possibilities for the fluid power industry. Smart controllers integral to the hydraulic component are now commercially available using concepts which as much as five years ago were considered strictly academic.

Associated with this growth has been the development of computer software for purposes of control, data collection and manipulation, circuit simulation and design. The combination of the microcomputer with relevant software can produce a very powerful design and control tool specifically oriented towards fluid power applications. One such approach uses a microcomputer and the reasoning capabilities of an artificial intelligence based high-level language programming technique known as "expert systems".

An expert system allows the programmer to develop both mathematical and symbolic logic in terms of defined words and phrases called rules. These rules can tell the computer to monitor a certain device, to switch on or off a specified valve, or to do a complex mathematical evaluation if a certain set of conditions are satisfied. Use, then, of an expert system in control and condition monitoring is greatly facilitated using this approach. If these rules are coded to reflect verbal statements rather than analytic information, then the expert system can be applied as an example to the process of design.

This paper will consider the application of an expert system to the control, monitoring, and self-diagnosis of a hydraulic circuit. The philosophy behind the expert system approach will be briefly examined and its application to diagnosis and control of a hydraulic circuit presented through very basic examples.

KEYWORDS

Expert system, self-diagnosis, condition monitoring.

INTRODUCTION

Very high costs can result from an unscheduled shutdown of an important piece of equipment due to component failure. Consequently, a great deal of interest has been developed in techniques which can monitor the health of a hydraulic system and predict its performance over time. If a fault can be diagnosed in the early development stage, then corrective action can be taken at the next scheduled maintenance shutdown. If the fault has the potential for catastrophic action, the system can be stopped at an appropriate time as determined by the controller or operator.

The process of monitoring a system has been labelled "condition monitoring" and includes many types of actions. The most common methods for condition monitoring implementation can be simply classified as noise measurements, steady state and transient performance analysis. These techniques can utilize very sophisticated analytical prediction algorithms to determine system parameters or, indeed, something as simple as the experience of a veteran operator.

Noise, both airborne and fluid borne, has been used to determine and predict the performance of hydraulic pumps and loads (1,2). Sound and mechanical vibrations can be used to determine cavitation, or deterioration in bearing (2,3). The use of prediction techniques such as Kurtosis on vibration information can be used to predict the existence of small fractures in bearing well before they can be detected by normal operator observations (4).

Steady state techniques have been used to assess the health of a fluid, a component or a complete system. For example, regular sampling of the system

fluid combined with ferrographic analysis and fluid property measurements can be used to determine excessive wear internal to the hydraulic system (5,6). This is perhaps the most common form of condition monitoring and has a proven track record for reliability in determining the state of the system.

Other techniques which combine the aforementioned approaches or use transient or frequency response information have also been used (7). Advanced mathematical algorithms such as signature analysis of noise can be applied to measured data in order to establish the presence of abnormal signals due to small faults.

Once sufficient data has been accumulated and the appropriate analysis completed, a decision as to the course of action must be taken. This decision can be made on empirical evidence based on years of experience or from theoretical considerations stemming from prediction techniques. The decision can also be based on human operator experience or on advice solicited from an expert in the area.

As a result of the decision, some action must be implemented. This could be of the form:

1. Complete system shutdown (catastrophic failure),
2. A continuation of the operation until the next scheduled shutdown or shift change,
3. A continuation of the operation but at a reduced level until the next shutdown,
4. A switch-in of redundant components to maintain the existing level of operation until scheduled shutdown.

The process, then, consists of detecting a condition, diagnosing the fault, and a decision on a future course of action. These latter two processes are usually conducted 'off-line' and require the knowledge and experience of an 'expert' either locally or as a consultant. The recently introduced technology of 'expert systems' developed by the artificial intelligence research community allows the transfer of the 'expertise' in decision-making process of an expert to a computer program. This technology is ideal for addressing the problem of fault diagnosis and subsequent advice as to actions to be taken. If this type of human expertise can be transferred in this form to a computer program, then it should be possible to incorporate this into the hydraulic system so that the system is continually monitoring its own health and predicting future behaviour. This is called 'self-diagnosis' and ideally the 'expert system monitor' can make decisions regarding shutdown--can advise the operation of possible component failure to allow sufficient time for ordering a new component, etc.

The purpose of this paper is to introduce the concepts of an expert system as applied to the self-diagnosis of hydraulic circuits. The expert system has the capacity to accommodate both qualitative and quantitative information and hence is ideally suited for this application. Perhaps of greater importance, an expert system can capture human knowledge and expertise to monitor

and diagnose its own condition. This paper will consider only a very simple application, but it must be emphasized that the complexity associated with many of the aforementioned monitoring techniques can be integrated just as well.

EXPERT SYSTEMS

Before introducing the use of an expert system (sometimes called a knowledge-based system) in hydraulic system self-diagnosis, it is desirable to give a brief presentation on what an expert system is and to examine the reasoning process behind it. An understanding of the mechanics of expert systems is really not necessary for using the approach as far as an "end user" is concerned. However, some background information can help in understanding the examples to be considered and clarify some of the "jargon" that is commonly found in discussion of expert systems.

Expert systems are computer programs in which the special problem solving skills of an expert in a particular area have been transferred to a computer and thus are available to a user on a consultation or indeed, control basis (8). When the computer performs as competently as the expert, then the program may be considered as a true "expert system" (9). There are many ways in which the experience of an expert can be codified. This paper will consider only one technique which makes use of "IF-THEN" RULES (also called production rules).

Production rules are a method of expressing knowledge by a set of conditional statements. For example, consider the statements used to determine the placement of a flow control valve in a hydraulic circuit (10):

```
IF    Flow control is required
AND   The load is resistive
THEN  A flow control valve should
      appear before the actuator.
```

This rule would be one of a large number of rules which together comprise the "knowledge base".

IF-THEN rules are composed of two parts: IF's (antecedents) and THEN's (consequents). In this rule, if it is known that "flow control is required" and "the load is resistive", then it is deduced that the statement "a flow control valve should appear before the actuator" is true and from now on, this statement is known to be true if it is ever referenced again in the program.

Appendix A contains a brief description of how the expert system deduces whether statements are true or false. The reader who has no experience with expert systems may well be advised to follow through the example in Appendix A to aid in understanding the examples which are discussed.

In its most general form, the production rules in the IF-THEN format can reflect a statement, condition or action (procedure) as illustrated below:

IF Statement A
AND Statement B or IF Condition A
THEN Statement C THEN Condition B
or IF Condition A IF Statement A
AND Condition B or AND Condition B
THEN Action C THEN Action C

In the original example, statements were used to represent some information in the IF-THEN rules. However, the antecedents could very well be a condition of some device or the results of some action (procedure). For example, the antecedents could be subroutines which monitor several transducers and check to see if their measured values fall within acceptable limits. If all transducers do, then the subroutines would return a true condition to the IF and AND statements. Since the two antecedents are true, then the expert program deduces that the consequent (THEN statement) is also true. The consequent could be some action such as the adjustment of a valve (if a false is returned to one of the antecedents). This particular form of the IF-THEN rules facilitate interfacing the expert program with external devices.

It should be noted that a combination of statements, conditions and actions is possible with both antecedents and consequents; hence, the use of the rules is very flexible in combining statements with information from external devices and other computer programs.

The advantage of the aforementioned technique lies in the fact that it now becomes possible to interface the expert program with mathematically based algorithms and external devices for measurement and control. When combined with knowledge based on human expertise, the system becomes a powerful monitor and controller capable of self diagnosis.

APPLICATION TO CONDITION MONITORING AND CONTROL

In order to demonstrate the application of expert systems, several examples as applied to a very simple hydraulic circuit configuration, will be considered. This circuit is illustrated in Figure 1. In the first instance, suppose it is of interest only to determine if a component has leakage. With reference to Figure 1, a measurement of flow at A and B combined with knowledge of the position of the directional control valve would provide sufficient

Figure 1. Basic circuit layout.

information to determine if leakage at the directional control valve exist. If there is leakage, the only action would be to provide the operator with the information that leakage does occur. A rule to implement this process could be as follows:

IF Transducer A has been monitored
AND Transducer B has been monitored
AND Transducer A is not equal to Transducer B
AND Control valve is not in the center position
THEN Leakage is occurring at the control valve
ANDTHEN Operation is informed.

In this example, each statement is based on another set of rules which establish their truth or falsehood. For example, "Transducer A has been monitored" would be based on another set of rules which would temporarily cause the program to exit the expert program, and execute an external program. The function of this program would be to activate an A/D convertor, read the flow value, store the value in some buffer, and return a true value to the expert system (specifically, to the statement "Transducer A has been monitored"), and control is returned to the expert system. Because execution of the condition or action rules is software and machine specific, the actual mechanism to execute the rules is not of prime importance and not discussed here. The reader is referred to the references cited.

In this first example, the leakage condition of all critical components can be determined by monitoring more flow transducers and pump/motor tachometers. A series of logical statements similar to that listed above but in greater detail could then be written for the complete system.

This above example illustrates a very fundamental but simple application of condition monitoring. System parameters are measured and compared to each other. A level of increased complexity and indeed intelligence can be added to the program. For most components, empirical data is readily available on specific properties over a range of operating conditions. As an example, the volumetric efficiency as a function of system pressure for a pump can be defined for a specified model. This is illustrated in Figure 2. This characteristic can be encoded into a suitable form in the computer by means of a look-up table. Since the system is capable of measuring both pump flow and shaft speed, the volumetric efficiency can be calculated. In addition, load pressure is also available. By adding to the rule base, it is possible to compare the calculated volumetric efficiency at a specific pressure to the values stored in the look-up table. If outside the limits, an error message can be issued. Possible rules to be added to this rule base are:

IF Pump efficiency is calculated
AND Efficiency value is compared to look-up table
AND Efficiency falls outside acceptable limits
THEN Inform operator.

Figure 2. Typical Volumetric Efficiency Characteristics.

The power of the monitoring system can be expanded by allowing the system to check the status of the transducers first to establish if they have gone out of calibration or experienced drift. This is readily accomplished by adding the rules

IF Transducer A is OK
AND Transducer B is OK etc.

to the original rule base. This physically can be accomplished by comparing measured values to some standard (in this case, the equivalent flow reading obtained from the tachometers). However, this check on transducer status may require the temporary interruption of the circuit operation. With reference to Figure 3, a check on the calibration of the pump flow meter would require a comparison of the tachometer and flow transducer at unloaded conditions. As such, an unloading valve could be switched in and the status check initiated. Rules to be added to the base could be:

IF It is time for calibration of flow transducer A
THEN Initiate unloading sequence
ANDTHEN Do calibration check.

This example illustrates how the expert system can be used to activate an external device based on some preprogrammed criteria.

Figure 3. Test-arrangement for flow transducer calibration.

The aforementioned examples utilize only a limited amount of the capabilities of an expert system. The rule base can be made more intelligent by incorporating sophisticated prediction techniques into the program. For example, since volumetric efficiencies of components are known, then a history of their values as a function of pressure and any other parameter can be kept over time. A calculation on the rate of change of the volumetric efficiency could be used to determine how long a system can operate before severe damage occurs to the complete system or indeed, the operation becomes too inefficient. In essence, both empirical information and prediction algorithms can be accessed by the rule base.

One of the most appealing aspects of an expert system is to incorporate human knowledge and experience into the rule base. To demonstrate this, suppose the circuit illustrated in Figure 1 is part of a large hydraulic network. An operator has found that if a pump's volumetric efficiency falls off, additional flow can be supplemented from another circuit by connecting two circuits and "stealing flow" when load conditions permit (Figure 4). The key to success of this maneuver is determining when suitable load conditions exist. Obviously, the operator bases his decision on some criteria. Codifying this experience incorporates a new dimension to the operation of the system. An example of the rule base might be:

IF Volumetric efficiency drops off to level A
AND The load of secondary circuit 1 is in a clamping mode
AND The load of primary circuit 1 is higher than B
AND The boss is not around
THEN Direct flow from circuit 2 to circuit 1.

An expert system can also be used to keep track of service records of a system and to warn the operator or, indeed, take action if certain procedures have not been followed upon. As an example, for the circuit in Figure 1, provision has been made for the taking of fluid samples. Rules can be written such that specific information

Figure 4. Example of flow sharing in hydraulic fluids.

must be periodically provided to the system for health monitoring. Such information may consist of a table relating the percentage of different metal particles in a sample or the value of fluid density and viscosity. Rules can be written to monitor the amount of time that has expired since the last fluid sample was taken. If a sample is due, then the expert system informs the operator that it is time to do so. If after a predetermined time, the information is not forthcoming, the system can be frozen until it is satisfied.

Once the fluid sample information is obtained, then it is possible to use the expertise of an "expert" to determine the state of the fluid or the condition of the system. A great deal of expertise is required in interpreting the information and providing the best action to be taken, but once this knowledge is encoded, the system has the advantage that expert advice is always at hand.

As a last example, a situation which requires monitoring, decision and action to determine a fault location is considered. Again, consider the circuit of Figure 1. In this situation, a sound measurement is included. By using filtering or transform techniques, the noise level or frequency spectrum can be extracted. The expert system can direct the necessary measurements to be made and to initiate relevant algorithms. Using the fact that a frequency component of audible noise exceeds a preset level combined with volumetric efficiency calculations at the pump, it is possible to determine the location of a fault or a set of undesirable operating conditions (in this case, cavitation of the fluid or failure of a bearing). In the simplest case, if a loud audible noise is detected in a certain frequency range and the volumetric efficiency of the pump drops, then it may be concluded that the pump is cavitating and corrective action specified. If the efficiency does not change but the noise persists, then a bearing fault is the probable cause. If this information is correlated to pressure ripple at various locations, then the location of the bearing fault could be pin-pointed.

Interfacing the expert system to a hydraulic circuit similar to the configuration of Figure 1 has been completed by the authors (11). A very simple rule base was developed in which the measurement of component leakage at various locations was to be ascertained. The rule base and subsequent implementation was successful given the simplicity of the situation. The test system is now being expanded to include some of the monitoring and control ideas previously mentioned. Of particular interest is the development of algorithms to reduce the number of transducers required in the monitoring process.

DISCUSSION AND CONCLUSIONS

The preceding section has considered several possible scenarios for monitoring and controlling simple hydraulic circuit using an expert system as the central "administrator". The algorithms and control schemes were very basic and, in most cases, very limited in application. The monitoring of a system to provide maximum information

about the health of the system and the most efficient action to be is a very complex subject. Indeed, each single facet of condition monitoring and prediction techniques can be and, in many cases, is a subject of intense research. Correlating various concepts to provide more information can increase the complexity of the situation even more.

A point that must be emphasized is that the expert system deals with rules and not with algorithms. In making decisions, the expert system requires only true and false inputs. The determination of those inputs can be a very complex procedure as the preceding discussion indicated. To demonstrate this, consider the antecedent:

IF A bearing fault in the pump has been isolated.

This statement can be added at any time to the expert system rule base EVEN THOUGH THE TECHNOLOGY TO ASCERTAIN THE TRUTH OF THE STATEMENT HAS NOT BEEN FULLY DEVELOPED OR REFINED. The method to determine the location of the fault could be very simple but very restrictive (as would be the case in the example cited earlier). As the technology to improve the reliability of the identification process improves and as the complexity of the analysis increases, the basic algorithms can be upgraded--in many cases, completely independent from the expert system.

In conclusion, the expert system is a very powerful concept and has shown tremendous potential for condition monitoring, control purposes and self-diagnosis. Research is needed to improve the monitoring and control aspects, but the basic foundation to bring it all together exists--the expert system.

REFERENCES

1. Hunt, T.M., "An Assessment of Condition Monitoring Techniques on High Pressure Water Pumps for NCB use Underground," High Pressure Water Pump Seminar, I. Mech. E., London, May, 1986.
2. Eda, K.A., and de Freitas, F.J.T., "A Study of Pressure Fluctuations in the Suction Lines of Positive Displacement Pumps," Proceedings of the Institute of Mechanical Engineers, Vol. 199, No. B4, pp. 211-217.
3. Bagnoli, S., Capitani, R., and Citte, P., "Comparison of Accelerometer and Acoustic Emission Signals as Diagnostic Tools in Assessing Bearing Damage," Proceedings of the 2nd International Conference on Condition Monitoring, London, England, May, 1988.
4. Volker, E.A., "Kurtosis in the Prediction of Bearing Faults," Ph.D. Thesis, University of Waterloo, 1984.
5. Ukrainetz, P.R., Nikiforuk, P.N., and Bitner, D.V., "Wear of an Axial Piston Pump under High Temperature and High Pressure Conditions," NCFP Journal, 1988, Volume 1, pp. 13-16.
6. Fey, C., "Identifying Component wear

Through Metallurgical Analysis," NCFP Journal, 1988, Volume 1, p. 187.

7. Butches, D.W., "On-Line Monitoring of Continuous Process Plants," Ellis Harwood Ltd., 1983.

8. Dixon, J.R., and Simmons, M.K., "Computers that Design: Expert Systems for Mechanical Engineers," Computers in Mechanical Engineering, November, 1983, pp. 10-18.

9. Brown, D.C., and Chandrasekaran, B., "An Approach to Expert Systems for Mechanical Design," Proceedings, Trends and Applications, 1983, National Bureau of Standards, Gaithersburg, Md., May, 1983, pp. 173-180.

10. Sargent, C.M., Burton, R.T., and Westman, R.W., "Expert Systems and Fluid Power," Proceedings of the 8th International Fluid Power Symposium, BHRA, Liverpool, England, April, 1988, pp. .

11. McCullough, D., Peoples, J., and Light, B., "Expert System for Monitoring a Hydraulic Circuit," Design Report, Mech. Eng. Dept., University of Saskatchewan, Saskatoon, Saskatchewan, Canada, January, 1987.

APPENDIX A (Reprinted from Reference 10)

To give a simplistic illustration of how an expert system can draw conclusions which can configure a circuit or exact some control, consider the following example:

	FORMAL FORM	SIMPLE FORM
IF	Flow control is required in the forward direction	IF A
AND	The load is resistive in the forward direction	AND B
THEN	Flow control should appear before the actuator in the forward direction	THEN Z

Note: In the simple form, A represents the statement "Flow control is required in the forward direction" exactly as it is written. If this statement appears in the exact form elsewhere, we can replace that statement by the letter A. In essence, this is what the computer does.

In order to prove that Z is true, it is necessary to establish that A and B are also consequence of other statements such as:

	FORMAL FORM	SIMPLE FORM
IF	Direction of motion is forward	IF F
AND	Actuator velocity must be controlled	AND C
THEN	Flow control is required in the forward direction	THEN A
IF	Direction of motion is forward	IF F

AND Resistive forces are greater than inertial or runaway forces AND E

THEN The load is resistive in the forward direction THEN B

It is noticeable that the statement "Direction of motion is forward" is common to both rules and hence appears as F in both rules. To summarize, the rules can be rewritten as follows in the simple form:

IF	A	IF	F	IF	F
AND	B	AND	C	AND	E
THEN	Z	THEN	B	THEN	A

The approach used by various types of expert programs to establish the goal Z are many. But the one used in these studies follows a backward-chaining system (inference engine). The program searches the rule base for an initial goal. The first one it comes across, it tries to prove true or false. Once completed, it continues to the next goal and tries to prove it and so on. If any goal cannot be established as either true or false, it quits and tells the user that it cannot prove anything.

In this example, only one goal is presented. In reality, it may be one of many, as dictated by the application. The computer first finds the goal Z. To be true, then both A and B must also be true. If either A or B are found to be false, then Z is deduced to be false. The order used in this program to find out something about A and B is as follows:

a) The program looks at the first statement in the IF-THEN rule; in this case, A. Let us assume that the state (true or false) of A and B is not yet known by the computer. The computer then looks through all THEN statements to see if A can be deduced through another series of IF-THEN statements. In this case, it can through the rule:

IF	F
AND	C
THEN	A

b) In order to establish A, the computer must establish first F and then C. It looks for F. If not in a THEN statement elsewhere and it has never been considered before, it has no information to base a decision on. It has no choice but it ask the user about F. Therefore, on the user's screen a question would be asked similar to the following format:

IS F TRUE? YES (Y) or NO (N)

If the user responds Y, then F has been established true and from now on in all IF-THEN rules in which F appears, F will be known to be true.

c) The computer then looks for C. Let us assume that C has already been established as true. Then since C is true and F is false, then the computer deduces that A is indeed true. If A ever appears in any subsequent rule, it shall forthwith be known as true.

d)	IF	A
	AND	B
	THEN	Z

Now that A has been established, the computer must now look for B. Since nothing about B is known, the computer starts looking through all IF-THEN rules until it sees B in a THEN statement. In this case, B does appear in a THEN statement:

```
IF    F
AND   E
THEN  B
```

e) To establish B, the computer examines the first IF statement F. From above, it is already known that F is true. It moves on to E. Assume that E is also true (from a previous enquiry). Then B is deduced to be true and finally, the goal Z is also deduced to be true.

The above example illustrates how the expert program uses IF-THEN rules to establish known true facts. By outputting all facts which are known or deduced to be true, then the user has obtained the best answer for his application based on rules created by an expert.