Development of the Task-Based Expert System for Machine Fault Diagnosis

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Abstract. The operating mechanism of expert systems widely used in fault diagnosis is to formulate a set of diagnostic rules, according to the mechanism and symptoms of faults, in order to instruct the fault diagnosis or directly give diagnostic results. In practice, due to differences existing in such aspects as production technology, drivers, etc., a certain fault may derive from different causes, which will lead to a lower diagnostic accuracy of expert systems. Besides, a variety of expert systems now available have a dual problem of low generality and low expandability, of which the former can lead to the repeated development of expert systems for different machines, while the latter restricts users from expanding the system. Aimed at these problems, a type of task-based software architecture of expert system is proposed in this paper, which permits a specific optimization based on a set of common rules, and allows users to add or modify rules on a man-machine dialog so as to keep on absorbing and improving the expert knowledge. Finally, the integration of the expert system with the condition monitoring system to implement the automatic and semi-automatic diagnosis is introduced.

1. Introduction
As a branch of artificial intelligence, expert system is a new applied science produced and developed in the early 1960s. As an intelligent program, it can adopt a computer model of human expert reasoning to deal with complex issues needed to be explained in the real world. Since the MYCIN expert system appeared in the field of diagnosis in 1974, people have always been focusing on problems in the research of knowledge-based diagnosis in artificial intelligence [1]. Recently, in the field of fault diagnosis, diagnosis expert system aimed to the different machine has been studied [2-4]. Knowledge reasoning technologies used in these studies mainly include rule-based reasoning,
case-based reasoning [5], reasoning based on artificial neural network [6], reasoning based on rough set theory [7], model-based reasoning and diagnosis [8, 9], reasoning and diagnosis based on statistical methods [10], combining rule-based and case-based reasoning and diagnosis [11, 12]. Objectives of these studies are only some specific machines, or a certain kind of machines.

Compressors are key machines in oil refining, chemical, power and other process industries. Once a fault occurs, it will cause the downtime of system, disruption in production, even catastrophic accidents, which can result in a great economic loss for the producing enterprise. In order to make compressors operate safely, real-time machine condition monitoring systems are deployed on most of them, which can capture abnormal symptoms by the early warning technology, reduce the economic and human losses, and improve the efficiency of machine [13]. Currently, monitoring is generally stronger than diagnosis analysis in most condition monitoring systems, some of them have integrated the function of diagnosis expert system, though not obviously effective and short of generality [14, 15]. Especially, expert systems that are usually for a specific machine or a certain kind of machines cannot be applied in the various other kinds of compressors. For example, when reciprocating compressors, centrifugal compressors, steam turbines, gas turbines and other kinds of machines are monitored by condition monitoring system simultaneously, an expert system will not be obviously satisfiable.

In this paper, a architecture of Task-Based Diagnosis Expert System (TBDES) for machine fault is proposed, it can be flexibly integrated into the machine condition monitoring system, according to the different kinds of machine, and different diagnostic tasks can be chosen for expert diagnosis. In order to escalate the ability of fault diagnosis, object-oriented knowledge representation method is proposed, that is to say, the rules of specific machine can be customized flexibly on the basis of general rules. Multiple interacting modes of knowledge are designed as well to improve the usability of system.

2. Expert System Design

2.1. System Architecture Design

In accordance with the application model of condition monitoring system and characteristics of fault diagnosis, Task-based fault diagnosis expert system adopts the framework of forward reasoning of production rules, in which a fact is defined by a triple structure of object - attribute - value. For example, for the fact ‘dominant frequency’, the property is ‘frequency’, and the value is ‘working frequency’.

Schematic overview of TBDES is shown in Figure 1, and the kernel of TBDES is in the dashed box of Figure 1. The Kernel consists of two modules, including rule reasoning module and interpretation module, and six knowledge bases, including rule base, fault base, fact base, attribute base, maintenance advice base and task base.

The rule reasoning module is the inference engine of the expert system, which adopts the forward reasoning technique. The principle of rule reasoning is to combine facts and rules stored in the working memory to establish a reasoning model, so that new information can be drawn.

The interpretation module is to explain the result of fault diagnosis and thus give maintenance advices accordingly. It adopts fact-based automatic interpretation mechanism. According to the facts with certain causal relations generated in the process of organization and maintenance decision-making, maintenance advices can be generated.
There are two models of TBDES. One is that it is used as a standalone system so that the user can select different tasks to diagnose. In this case, facts are set by means of man-machine dialogue; the other one is that it is integrated into machine condition monitoring system so as to guide the maintenance.

Machines’ Condition data of machine taken from the monitoring system is inputted into the TBDES, and then the health of machine can be assessed automatically. The processing flow is shown in the right box of Figure 1, which is divided into two steps: feature extraction and feature indicator classification. According to the feature index classification inputted, it can diagnose automatically, if there is some fault of machine based on diagnosis, the diagnostic results will be sent back to condition monitoring system.

There are three main differences between TBDES with traditional rule-based expert system.

1. Task-based reasoning technique. On one hand, different tasks can be selected to diagnose according to different kinds of machine; on the other hand, not all rules are involved in the process of reasoning, but only the active rule will participate in reasoning.

2. Object-oriented knowledge representation. Object-oriented technology is an ordinary kind of thinking method used to understand the objective world in the process of software development for the objective world or things of some problem domain to describe objects intuitively and naturally. Its basic characteristics mainly include abstraction, inheritance and polymorphism. Rule-based knowledge representation uses the abstraction and inheritance of object-oriented technology to solve the general rules and particular issues.

3. Diversity of interactive mode of facts. There are three kinds of interactive mode of facts, including: system automatic setting mode, man-machine interaction mode and semi-automatic mode. System automatic setting mode means that facts can be set directly by system without any artificial
interference, when it is called in the condition monitoring system. Semi-automatic mode means it can
be set automatically and interactively in the process of interactive knowledge.

2.2. Design of the Knowledge Base
There are six kinds of knowledge base in TBDES, including: rule base, fault base, fact base, attribute
base, maintenance advice base and task base.

1) Rule base is used to store all the rules in expert system. Attribute of each rule is composed of
rule ID, rule name, prerequisite set of rule, consequence set of rule established, the consequence set of
rules not established, machine type and other elements. Attribute of machine type is a field used for
object-oriented knowledge representation. The consequence set can contain operations of knowledge
for faults, rules, facts and maintenance advices.

2) Fault base is used to store faults in the expert system. Each fault’s attribute is composed of fault
ID, fault name, fault code, machine type, name of fault location, name of fault mode and rule ID of
interpretation and other elements. The rule ID of interpretation is the startup rule ID for the inference
and explanation on how to repair the damage.

3) Fact base is used to store fault symptom values of machine in the expert system, which is fact or
symptom of fact. The attribute of each fact is composed of fact ID, fact name, property ID, machine
type and other elements.

4) Attribute base is used to store a variety of attributes defined in expert system. Attribute refers to
property or type of fact, each attribute is composed of attribute ID, attribute name, description-value
set of attribute and other elements. For example, for an attribute with ID ‘TrendChgType’, its name is
‘change in trend’, and description-value set of attribute includes a sudden change -0, rise higher -1,
down -2, uncertain -3. If a temperature change is needed in the process of diagnosis, a fact which is
temperature change can be defined by use of ‘change in trend’, that is to say, attribute ID of the fact for temperature change is ‘TrendChgType’.

5) Maintenance advice base is used to store fault maintenance advices in expert system. Maintenance advice can be deduced by interpretation module of TBDES based on facts and reasoning,
which can guide the maintenance of machine. Each maintenance advice is composed of maintenance
ID, description of maintenance advice, appliance for maintaining, machine type and other elements.

6) Task base is used to store a variety of tasks in expert system. Each task is an entrance for expert
diagnostic function of the specific machine in expert system, which is initial operation of starting the
diagnostic expert every time. Each task is composed of task ID, task name, and consequence set of
task. The consequence set of task may contain knowledge operation of fault, rule and fact and so on.

3. Development and implementation of the system

3.1. Implementation of task-based interface engine
The characteristic in the process of traditional rule-based reasoning is that the rule matching process is
repeated with each change of the facts, by judging the rules needed to match. Reasoning is the chain
starting a problem and getting the answer, conclusion can be drawn by the facts. Process of rule-based
reasoning is achieved by pattern matching, as shown in Figure 2.
Fault diagnosis is a process of deducing the fault cause based on feature index of the detected status data, by using the fact to screen the cause layer by layer based on the structure of fault tree [16]. In the process of reasoning, in accordance with the structure of fault tree and implementation of rule matching, the rule needed to use is determined at next step.

Rule inference engine of TBDES is presented on the basis of forward reasoning in the traditional technology, and rule task-based reasoning technology is proposed to escalate the speed and efficiency of reasoning, and it can activate different kinds of machines according to the startup rule of a specific machine. Flow of rule reasoning in TBDES is shown in Figure 3.

**Figure 2.** Conventional pattern matching: rules and facts.

**Figure 3.** Reasoning process of TBDES.
It can be seen from Figure 3 that the task is needed to choose for each diagnosis. Task selection is based on machine type and alarm information, and rules and facts are activated according to different tasks. Following steps are taken by the reasoning process:

Step 1: According to the specified task, perform an initialization operation. Initialization means the tasks involved in the relevant rule, fact, fault set, and maintenance advice are loaded in the memory of expert system;

Step 2: Execute consequence set of the specified task;

Step 3: Traverse the active rule in memory. If there are the active rules, package these rules to be as a set of matching rules, or jump to the sixth step;

Step 4: Get the value of all the facts to be the matching rule set. If the fact is not assigned, then assign the value by knowledge interactive interface;

Step 5: Match Patterns by rule set. According to the result of matches, implement operations of consequence set. After that, jump to the third step;

Step 6: Traverse a state of fault occurs in memory, these faults are packaged as a fault set; these faults are the result of diagnosis;

Step 7: Explain all the results of fault diagnosis by interpretation module, produce maintenance advice. Then output the diagnostic results and maintenance advices.

Operating knowledge of rule inference engine of TBDES contains pattern matching of rule and knowledge assignment. The pattern matching of rule is the same as traditional pattern matching of rules in expert system, that is judging whether the prerequisite of rule can be established or not. And according to the matching, different consequence set can be operated. The knowledge assignment contains assignment of faults, facts and rules. The assignment of fault is to set the state of a certain fault, including occurred, non-occurred, deleted and so on. The assignment of fact is to set the value of a fact. The assignment of rule is to set the state of a rule, including activated, prohibited, suspended and so on.

There are two main differences between rule inference engine of TBDES with traditional rule inference engine:

1) Which rules to be used for matching every time is based on the state of rule, rather than change of the fact;

2) In the process of reasoning, after value of each fact is set, the state will not change any more, because the related state data of machine at one moment or before this moment is used to diagnose, when the expert system is used for fault diagnosis every time.

3.2. Object-oriented knowledge representation

All the rules of expert system comprise a logic chain according to a certain logic sequence. Diagnostic process is to operate pattern matching based on the logic sequence of rules. Definition of rules in traditional expert system is related knowledge structure of the known knowledge or other speculated information.

The structure of rule connect one or more prerequisite of IF section to one or more consequences of THEN and ELSE section, that is to say, a rule is composed of a precondition set, THEN consequence set, and ELSE consequence set, a precondition set contains one or more prerequisites, and a
consequence set contains one or more consequences. For example, inference rules of rotor unbalance for rotating machinery are shown in Table 1 [16].

| Name of rules | Rotor unbalance of rotating machinery |
|---------------|--------------------------------------|
| IF (precondition set) | ‘Amplitude of running frequency (1X) is great’ AND ‘Amplitude of twice running frequency (2X) is small’ AND ‘Amplitude increasing with rotating speed increasing or Amplitude decreasing with rotating speed decreasing’ |
| THEN (consequence set) | ‘Rotor unbalance’ |
| ELSE (consequence set) | ‘Rotor misalignment’ |

An object-oriented knowledge representation method refers to the object-oriented programming technology in software development, which uses techniques of overloading and inheritance to improve traditional rule and logic chain of rule-based reasoning. For the rule, it can be redefined some or all in the case that the name of rule is not changed. For logic chain of the rule, a part of logic chain is adjusted on the basis of the whole logic chain.

An object-oriented knowledge representation method is allowed to redefine three parts of rule, that is to say, on the basis of the original rule; it can be customized depending on machine type. For example, the rule of diagnostic expert system of rotating machinery is composed of many rules according to certain rule of logic chain. The rule of rotor unbalance is one of the rules, expert system is appropriate to fault diagnosis for centrifugal compressor, but it is not appropriate to fault diagnosis for gas turbine. In accordance with object-oriented knowledge representation method, diagnosis rule of gas turbine can inherit the diagnosis rule of rotor unbalance of rotating machinery, as shown in Table 2, because the cause of rotor unbalance for gas turbine may be the scale or shedding of blade, and also may be rotor unbalance.

| Name of rules | Rotor unbalance of rotating machinery |
|---------------|--------------------------------------|
| IF (precondition set) | ‘Amplitude of running frequency (1X) is great’ AND ‘Amplitude of twice running frequency (2X) is small’ AND ‘Amplitude increasing with rotating speed increasing or Amplitude decreasing with rotating speed decreasing’ |
| THEN (consequence set) | ‘Rotor unbalance, Scale or shedding of blade’ |
| ELSE (consequence set) | ‘Rotor misalignment’ |

A hierarchy of TBDES diagnostic object is represented in Figure 4. From the point of view of diagnosis, first of all, logical chain of rules from diagnostic knowledge of rotating machinery and reciprocating machine is inputted to expert system, generating general logic diagnostic rule for two kinds of machine, and then depending on the structure differences of specific machines, partial rule and rule chain of general diagnostic rule logic is adjusted, forming expert diagnostic logic rule of
specific machine. So it satisfies both general and specific requirements. On the basis of general logic diagnostic rule, it is customized to meet special needs, and traditionally it needs to rewrite a set of expert diagnosis logic rules.

Rotating machinery in TBDES system contains centrifugal compressor, axial compressor, steam turbine, gas turbine, gas turbine and other types. Reciprocating machinery contains M-type reciprocating compressor, L-type reciprocating compressor, H-type reciprocating compressor and D-type reciprocating compressor and so on.

3.3. Implementation of knowledge interface

Knowledge interactive interface of expert system is to complete knowledge acquisition, that is assignment of fact, and three kinds of knowledge interactions of TBDES are designed, including: automatic, semi-automatic and man-machine interaction.

(1) Automatic

Automatic knowledge interactive mode is an interactive model that TBDES is integrated into the machine condition monitoring system for expert diagnosis. In the process of reasoning, there is no interaction with users. So it can get the value of fact automatically, feature index can be gained by calling and handling the condition data. If there is no fact in the condition monitoring system, on the fully automatic mode, the default value of fact should be used; the flow chart of automatic knowledge interaction is shown in Figure 5.
(2) Semi-automatic

As same as the automatic mode, the semi-automatic interactive mode is also integrated into the machine condition monitoring system, it can automatically get the value of fact that is assigned by machine condition monitoring system, and the fact, which can not be obtained, is assigned by operator by a pop-up dialog box automatically. The diagnostic accuracy of expert system can be increased with the use of semi-automatic mode, relative to automatic mode, because some of the facts can not be obtained only by condition monitoring system, such as: process parameters, vibration noise and oil leakage of machine and other status data of machine. The flow of Semi-automatic mode is shown in Figure 6.
(3) Man-machine interaction

Man-machine interaction mode is that the value of fact is only assigned by users, when TBDES is used as an independent software system, and the man-machine interaction dialog box of TBDES is shown in Figure 7.

Figure 7. Man-machine interaction dialog box.
4. EXAMPLES OF ENGINEERING APPLICATION
TBDES has been integrated into machine condition monitoring system, which can monitor centrifugal compressors, reciprocating compressors, steam turbines and other petrochemical machines. Function of TBDES is integrated into the alarm analysis and diagnosis interface of machine condition monitoring system, and automatic or semi-automatic mode can be selected for expert diagnosis in the software interface. In the interface of alarm analysis, the user can choose alarm log; and click on button for expert diagnosis, and then obtain the diagnostic result. The system has been widely used in turbine compressor and reciprocating compressor of China's oil refining and chemical enterprise. Now the effect of system is introduced below by some instances.

4.1. Application of fault diagnosis for centrifugal compressor
One of the centrifugal compressors in chemical fertilizer plant of a chemical enterprise is driven by high-pressure cylinder and low-pressure cylinder, working speed is about 9300 rpm, which is 155 Hz. At 5:42:43, on July 17th, 2009, vibration value of full-frequency of 2H-channel suddenly increased. The TBDES integrated into condition monitoring system then was used for automatic diagnosis, and the diagnostic results were oil whirl and gas exciting, as shown in Figure 8.

![Figure 8. Diagnostic results of centrifugal compressor.](image)

For the turbine compressor, from the point of view of analyzing mechanism of vibration fault, there are only four reasons resulting in accurate subharmonic vibration, which are support system, rubbing, fluid power and resonance [17]. The frequency of resonance is not only 1/2X (the X indicates the working frequency), but also should be 1/3X and 1/4X, etc. so it was not resonance malfunction. Then from the point of view of phase characteristic, phase of 1X and 1/2X were relatively stable, and there was no anti-precession phenomenon, so it was not rubbing malfunction, according to the process of
primary diagnosis, vibration cause of 2# measuring point should be some problem of support system or fluid power, it was consistent with automatic diagnostic expert system

4.2. Application of fault diagnosis for reciprocating compressor
Structure of reciprocating compressor is 4-cylinder and 4M-type reciprocating compressor, working speed is 300 rpm. At 15:08, on October 30, 2010, the value of piston rod drop changed suddenly, vibration trend and peak value of impact also changed, as shown in Figure 9, auto diagnostic result was support ring fracture, and the diagnostic results were shown in Figure 10.

![Figure 9. Trends and impact peak value of 4# cylinder.](image)

![Figure 10. Diagnostic results of reciprocating compressor.](image)
The value of piston rod drop suddenly increased from -300 um to -550 um, while the peak value of vibration increased from 60 m/s² to 120 m/s², and impact peak value increased from 48.6 m/s² to 134.9 m/s². The temperature of valve was unchanged, so the cause may be malfunction of support ring of piston of 4# cylinder for a preliminary judgment, the maintenance advice was to replace support ring or piston ring.

4.3. Application on automatic diagnosis with semi-automatic diagnosis

An application of automatic diagnosis with semi-automatic diagnosis of machine condition monitoring system in oil refining enterprise of PetroChina is shown in Figure 11 and Figure 12.

As Shown in Figure 11, after choosing the automatic diagnosis mode, the diagnostic results were misalignment, horizontal-vertical unequal of bearing stiffness and shaft crack. In order to improve the accuracy of diagnosis, the semi-automatic mode was set, as shown in Figure 12. After selecting the dialog box to achieve semi-automatic diagnosis, the diagnostic result was confirmed to be misalignment.

Figure 11. Fully automatic diagnosis results of centrifugal compressor.

Figure 12. Semi-automatic diagnosis results of centrifugal compressor.
5. Conclusions

With the maturity of the highly sophisticated production facilities and machine condition monitoring technology, enterprises become increasingly aware of the necessity of promoting machine condition monitoring and diagnosis as well as condition on maintenance. Especially it presents new and higher demands for practicality of fault diagnosis expert system. That is to say, the expert system is needed to be integrated into online machine condition monitoring system so as to diagnose many kinds of machine and guide maintenance effectively. As the task-based expert system for machine fault diagnosis is accordingly proposed in this paper, both the practicality and the usability of diagnostic system are improved. It can not only provide enterprises with fault diagnosis and maintenance guiding, but also improve the efficiency of fault diagnosis, as the fact is shown that the down time is shortened and productive efficiency is improved.

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