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〈Orignal Paper〉

A Study on the Diagnostic System for Reactor Coolant Pump

원자로 냉각재 펌프 진단 시스템에 관한 연구

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ABSTRACT

The Reactor Coolant Pump(RCP) that is currently being used in nuclear power plant is a large, single-stage, vertical pump that circulates the coolant from the steam generator to the reactor core in the primary system. During normal operation, the RCP may experience unexpected vibration, thermal stress, and wear. Because these conditions can possibly lead to plant-reliability problems, issues regarding the monitoring of the RCP have increased. Most monitoring systems currently being used by U.S. nuclear power plants can indirectly detect RCP problems by monitoring for abnormally high vibrations, but few of these systems can diagnose the root causes of the problems. This paper reviews the major RCP problems and their root causes, and construct a knowledge base that relates the vibration characteristics to root cause for diagnosing RCP problems. Finally, it provides a diagnostic algorithm to help with developing diagnostic systems for RCP

요 약

원자력 발전소에서 운전되고 있는 원자로 냉각재 펌프는 대형 수직 펌프로서 증기 발생기로부터 원자로에 냉각재를 순환시키는 중요한 역할을 담당하고 있다. 원자로 냉각재 펌프는 운전 조건 및 각종 결함에 따라 진동, 열적 변형, 마모 등의 비정상 상태에서 운전될 수 있으며, 이로 인한 발전소 신뢰성 저하의 원인이 된다. 따라서 이 펌프의 감시 및 진단에 대한 연구가 계속되어 왔으며 각종 시스템이 설치 운용되고 있다. 그러나 미국내의 거의 모든 냉각재 펌프 감시 시스템은 펌프의 고진동 여부만을·나타내며 진동의 원인을 진단하기 어렵다.

본 연구에서는 최근까지 주로 발생되었던 미국내 원자로 냉각재 펌프의 문제점을 분석하고 이들의 원인별 진동 특성을 지식베이스화 하였으며, 진단시스템 개발을 위한 알고리즘을 제안하였다.

1. Introduction

The reactor coolant pump plays an impor-

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tant role in transferring coolant from the steam generator to the reactor core in the primary system. In spite of its importance, the RCP has experienced numerous problems during the last two decades, including problems with seals, motor stator, shaft crack, and vibrations. Fixing these problems often results in significant outages for nuclear power plants as shown in Table 1.[1]

A reliable monitoring and diagnostic system for detecting RCP problems can ensure that the pump is operating effectively. It is possible to avoid costly repairs, unnecessary outages, and serious accidents resulting from secondary failures. Early problem detection also helps plant personnel to plan their work, for example, to schedule maintenance, determine manpower requirement, and order needed components for repairing equipment.

Today monitoring systems have become more widely used, understood, and refined. Most of these systems detect RCP problems by monitoring the RCP amplitudes, but few of these systems can diagnose the root causes of problems. S. Kastrui presented the result of survey on the diagnostic methods and their applications that are currently being used by U.S nuclear power plants at the EPRI NMAC 8th conference on Dec., 1996.[2] Among these methods, the vibration analysis is currently the most effective method for RCP monitoring and diagnostics because it takes most of the physical factors that are affected by vibration into account.[3~6] These factors include temperature, pressure, flow, and rotating speed, etc.. Most RCP problems can be correlated with vibration data for these factors, so a knowledge base that relates the vibration characteristics to the corresponding factors would be very helpful in determining the causes of problems. Consequently, the trend in RCP research is to concrete on developing a diagnostic system that uses different vibration signatures to diagnose the causes of RCP problems.

Many companies have developed and/or implemented monitoring and diagnostic systems for RCPs.[6~8] Most of these systems use a knowledge base that is based on the relationship between the symptoms of a problem and

Table 1 Economic importance ranking of PWR plant's system/component(1993~95)

Rank	System/Component	Outage length (hr)	Contribution to total forced outage length (%)	Total number of failures
1	Steam extraction piping	5623.5	9.98	1
2	Reactor coolant pump	4798.5	8.51	18
3	Transformer	3543.4	6.29	17
4	Steam generator	3221.9	5.72	11
5	Safety injection valve	3216.2	5.71	2
6	Main feed water pump	2518.1	4.47	27
7	Generator bus duct	2129.6	3.78	3
8	Breaker	2101.4	3.73	3
9	Auxiliary feed water pump	2048.6	3.63	1
10	Electro hydraulic control system	1566.2	2.78	15
11	Circulating water system	1548.5	2.75	5
12	Generator support system	1524.1	2.70	15
13	Reactor coolant system	1426.2	2.53	8
14	Main steam isolation valve	1402.5	2.49	10
15	Service water system	1132.7	2.01	2
16	Control rod drive system	1115.7	1.98	9
17	Emergency diesel generator	1093.3	1.93	3

the cause of the problem. The relationship enable the system to deduce the cause of a problem by identifying the symptoms of the problems. Sometimes it used a matrix to match the characteristics of abnormal rotor vibrations with the causes of problems and also used three weighting factors (small, middle and large) to improve the reliability of diagnosis.[7] But the effect of this limited number of factors on the reliability needs to be closely studied. At any rate, knowledge of the relationship between the characteristics of different types of vibrations and the causes of these vibrations is crucial for solving RCP problem and for developing an RCP diagnostic system.

The purpose of this paper is to identify the major RCP vibration problems and their causes, and to use this information to create a knowledge base for diagnosing these problems. Also, this paper will provide a diagnostic algorithm to help with developing future monitoring and diagnostic systems for RCP.

2. RCP Description

Figure 1 shows the Westinghouse 93A model

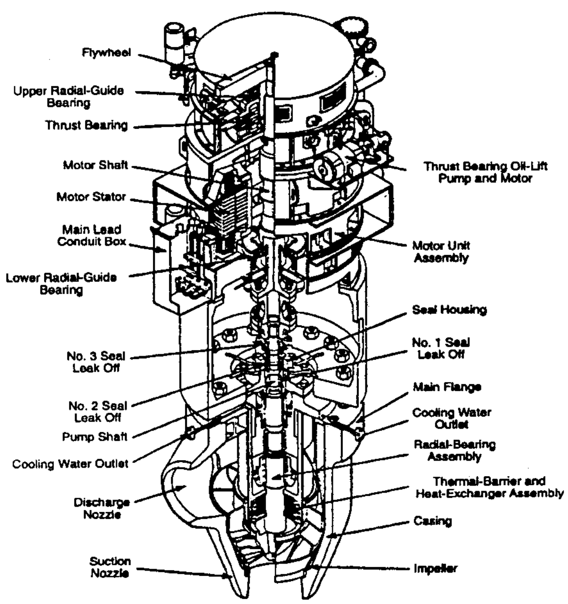

Fig. 1 Reactor coolant pump(W.H 93A model)

of the RCP, which is installed at "Kr" nuclear power plant, Korea. This pump is one of the most important pieces of equipment in PWR nuclear power plant because its reliability has a direct influence on the safety and availability of power plant as a whole. The reactor coolant system can be divided into three major parts : the pump, the motor, and the seal assemblies. Both the pump and the motor are supported by a water-driven hydraulic bearing and by upper and lower oil-filled hydrodynamic bearings. The three seal assemblies and their housings prevent the reactor coolant from leaking into the reactor vessel through the pump shaft.

In the monitoring system, two proves(X and Y) are positioned near the coupling hub, one at the pump discharge and one at a right angle to the discharge as shown in Figure 2. The keyphasor is installed between the two proves, and standard phase of the spike signal is set to a predefined position for every rotation. The two proves monitor the displacement vibrations of the pump and motor shaft.

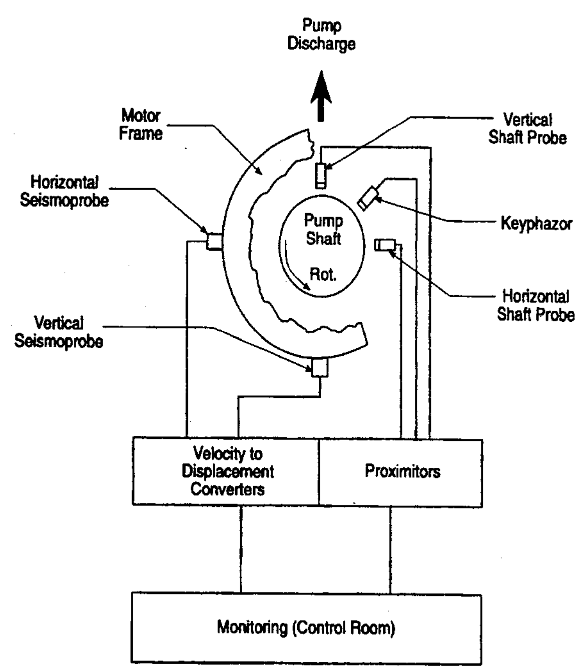

Fig. 2 Probe system for monitoring RCP vibrations

Date : 95. 1. 1 Unit : Arkansas nuclear #1 Model : Type AN
Failure Narratives
While the unit was at power, an 'RCP VIBRATION HI' alarm was received in the control room. .... The pump motor bearing temperatures were also reading off-scale high. Reactor power was manually reduced to 60%........ Investigation of the motor revealed both the upper and lower motor bearings had lost babbit material. CR-1-95-001 addresses the investigation. ....

Date : 96. 4. 4 Unit : Palo Verde #1 Model : R01
Failure Narratives
Unit 1 was in operation. Vibration technicians identified an increasing trend on RCP 2B which was indicative of shaft cracking. ..... When vibration level approached 10 mils, the unit was shut down and the RCP was removed from service to allow an inspection of the RCP. Inspections confirmed the shaft was cracked at approximately 46 inches from the top of the shaft in the impeller fit region.......

Fig. 3 Example of NPRDS search

and the keyphasor monitors the relative phase between vibration sensors. Seismoprobes are also used on the RCP and motor to monitor frame vibrations. The transmitted voltage is proportional to the velocity vibration, and the voltage is changed to displacement vibration by the velocity-displacement converter.

3. RCP Key Problems and Root Causes

Operating under high temperature, pressure, and radiation, the reactor coolant pump performs the critical function of circulating water to cool the reactor core. Therefore, the RCP has a major impact on the economics, safety, and availability of nuclear power plants. Also, a substantial amount of time is required to repair an RCP compared to the amount of time required to repair other components. In addition, RCP problems can possibly lead to the loss of a small amount of coolant during normal operation.

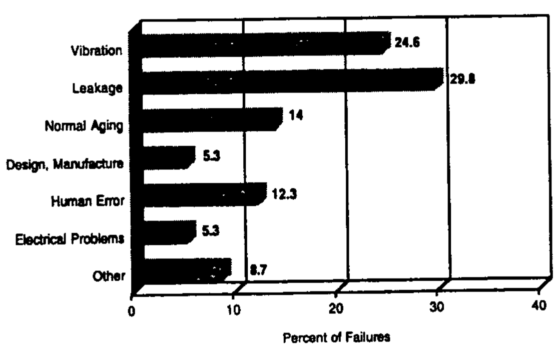

Fig. 4 Causes of RCP failures

The first step in this research is creating a knowledge base to learn as much as we could about RCP problems and their symptoms and root causes. To do this, we searched the Nuclear Plant Reliability Data System (NPRDS) database for problems that had occurred from 1993 to 1996. This search yielded 57 problems that resulted in a plant trip, a shut down, or a power reduction. An example of NPRDS search is shown in Fig. 3.

As shown in Fig. 4, the major causes of RCP problems are leakage and vibrations. Aging equipment and human errors also contribute to these problems. In our research, we found that 24.6 % of the problems were directly caused by vibrations, and another 5.2 % were indirectly caused by vibrations. We also found that small vibrations can indirectly cause seal problems. Like leakage problems, some stator-winding problems can also be contributed indirectly to vibrations. Sometimes, mechanical and thermal stress coupled with vibration can cause the rotor bar to crack, resulting in damage to the stator windings. These windings can also be damaged by the rotor and the stator rubbing together as a result of bearing wear and misalignment. Although vibrations do not directly cause RCP problems, such as trips or shutdown, they indirectly cause these problems by adversely affecting seals and stator windings. In fact, most nuclear power plants usually do not want to trip a pump manually because the resulting vibrations could cause major problems, either directly or indirectly. These problems may not affect safety, but they could decrease the availability of the plant and impact it economically. Consequently, the RCP must be closely monitored to ensure that the plant is available as much as possible. Because vibrations significantly affect the RCP, we also searched the NPRDS database for information on the possible causes of vibrations. This search yielded 29 problems that occurred from 1990 to 1996. As shown in Fig. 5 and Table 2, the three major causes of vibrations are

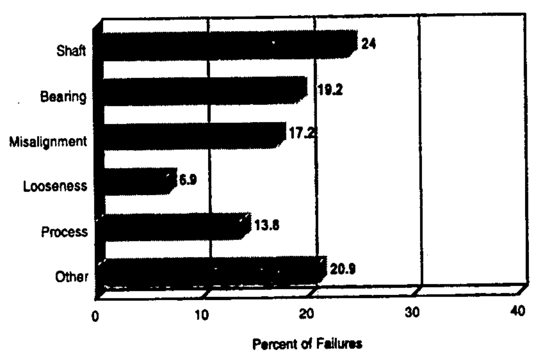

Fig. 5 Root causes of RCP vibrations

Table 2 Major causes of RCP vibration problems

Causes		Percentage
Shaft	Crack	10.3
	Shear	3.4
	Bent	3.4
	Unbalance	6.9
Bearing	Damage	6.9
	Rubbing	10.3
Misalignment		17.2
Looseness		6.9
Process		13.8
Unknown mechanical vibrations		20.9
Total		100

misalignment(17.2 %), cracked shafts(10.3 %), and rubbing(10.3 %). Other causes include unbalance and looseness.

4. Construction of Knowledge Base

Many monitoring systems are currently used to monitor RCPs in nuclear power plants. When these monitoring systems detect any deviations from normal conditions, the root causes of the deviations or problems should be determined. Knowing the relationship between symptoms and causes may be the key to diagnose problems. An automated diagnostic system for RCPs can be developed by modeling the vibration symptoms associated with each problem in knowledge base. This, however, may be hard to do because several problems have similar vibration symptoms. Moreover, the interpretation of the vibration symptoms can be affected by factors such as vendors, experts, case histories, RCP models, operating conditions, and sensor types and locations.

To begin with, we focused on the major causes of vibrations in the RCP such as cracked shaft, rubbing, misalignment and unbalance which were identified from NPRDS.

For this project, Information was gathered from the following sources[9~12]:

- **Survey.**
  A survey on RCP condition monitoring and diagnostic techniques was sent to all EPRI NMAC members of U.S and international plants.
- **Database.**
  The Nuclear Plant Reliability Data System(NPRDS) database was searched for information covered the years 1990 to 1996.
- **Experts and case histories.**
  Numerous RCP experts were consulted and several RCP case histories were reviewed to obtain information based on RCP experience.
- **Literature survey.**
  RCP papers including eight proceedings of

Table 3 Symptoms of abnormal vibration

Vibration causes	Symptoms
Crack	· The 1x rpm vibration amplitude becomes the dominant frequency · The magnitude of the 1x rpm vibration will tend to increase slowly · If a crack develops in an area where the shaft is held in place by a bearing, a sleeve, or some other restriction device, severe damage will occur within a short time : :
Misalignment	· 2x rpm vibration will be dominant. If the bearings in Westinghouse RCPs are misaligned, no significant 2x rpm vibrations will occur in the RCPs due to misalignment. · Initially, the 1x rpm vibration change rate is low; then the change rate returnes to close to zero · The shape of the orbit will be elliptical with an inward indentation : :
Rubbing	· When a seal rubs against another component, the 1/2x rpm vibration amplitude will increase, and the 1x rpm vibration amplitude will increase slightly · Several different integer subharmonics, such as 1/2x, 1/3x, and 1/4x, can be emitted simultaneously (not found in Westinghouse RCPs) · The wave form of time-based signals will be slightly truncated : :
Unbalance	· The dominant frequency of the vibrations is the synchronous speed of the rotor · When thermal unbalance occurs, the magnitude of the vibrations will change slowly-the RCP can experience a significant thermal unbalance due to seal injection during startup, resulting in excessive vibration : :
:	: :

Table 4 Cause-symptom table for RCP abnormal vibrations

Cause	Freq. of vibration	Change of magnitude	Change of phase	Shape of orbit	Slow roll vector	Bearing oil temp.	Dir. of Vib.	....
Cracked shaft	· 1x rpm · 2x rpm (high)	· Sudden change after tiny change (2x slowly growing) · Variable during transient	· Not necessary · 1x phase change often occurs	· Inner loop ($k\Phi$ is not rotating)	Change	No change	Forward	...
Misalignment	· 1x rpm · 2x rpm (medium) · 3x rpm	· Almost constant (esp. 2x trend) after a change	· Change - 1x stable - 2x change	· Triangular · Elliptical with an inward indentation · External loop	Change (much)	Change	...	...
...	...	...	...	...	...	...	...	...

EPRI conferences were reviewed to obtain the information of RCP abnormal vibration characteristics.

The symptoms of abnormal vibrations are shown in Table 3.

5. Diagnostic Algorithm and Results

We constructed a cause-symptom table that relates the vibration characteristics to the major causes of RCP problems.[10] Some contents of cause-symptom table is described in Table 4. We also provided a knowledge base containing detailed information on the vibration characteristics associated with each cause. Using this knowledge base, system analysts can diagnose the root cause of a problem more effectively.

Any automated diagnostic system can be developed for RCPs by following the diagnostic procedures that are generally used by system analysts. If system analysts process a large amount of data from each sensor, they may be able to reduce the number of human errors resulting from the lack of relative knowledge.

Figure 6. shows a suggested diagnostic system. Sensors on the pump and motor are used to monitor vibrations, bearing-oil temperature, pressure, flow, and so forth. Signals from these sensors are analysed and converted to data that can be compared with the normal operating data for each unique RCP. Each RCP has its own unique vibration characteristics, which are determined by factors, such as the RCP model and its respective rotational speed, maintenance history, and operating conditions; therefore, the normal operating data, thresholds, and design criteria for each RCP can be determined on an individual basis by the plant analysts. To allow for the uncertainty of knowledge expressions, an expert system must have a way to calculate its degree of confidence in the accuracy of a conclusion based on the weight of the evidence. We used the fuzzy set method, which was first suggested by professor Zadeh in 1965. After defining the membership functions to be used to evaluate each fact in the knowledge base, we quantitatively calculated the weighting factor of each type of vibration data, using several evaluation functions for each fact as shown in Fig. 7. For example, if the cause of vibration is misalignment, one of the symptoms will be an increase in the temperature of bearing. Using existing probability theory, it is impossible to determine the seriousness of the increase in temperature. A fact-evaluation function with a value between 0 and 1 can be used to evaluate and characterize the data in terms such as High, Change, Large, or Fast. Figure 8 shows one of the fact-evaluation functions that were defined for previous example. A fact evaluation function

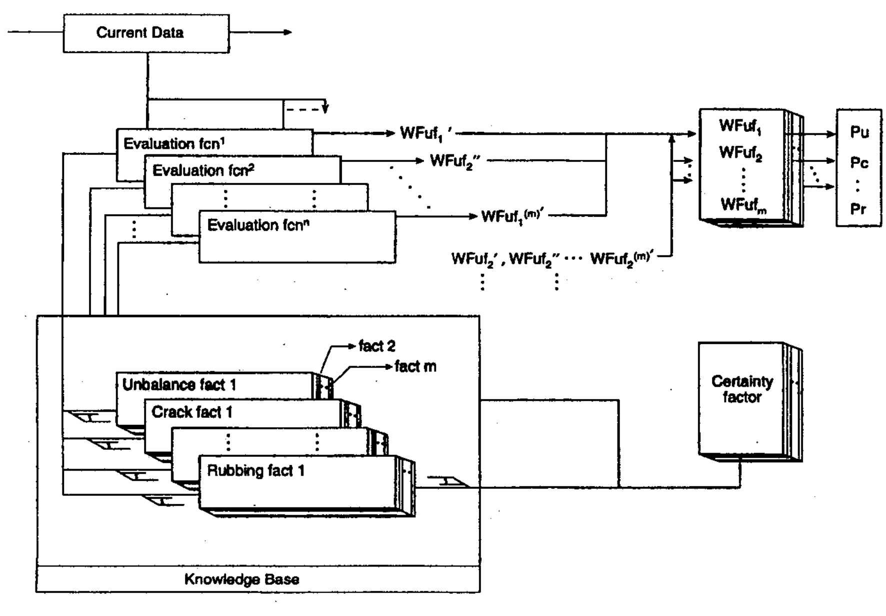

Fig. 6 Block diagram of a diagnostic system

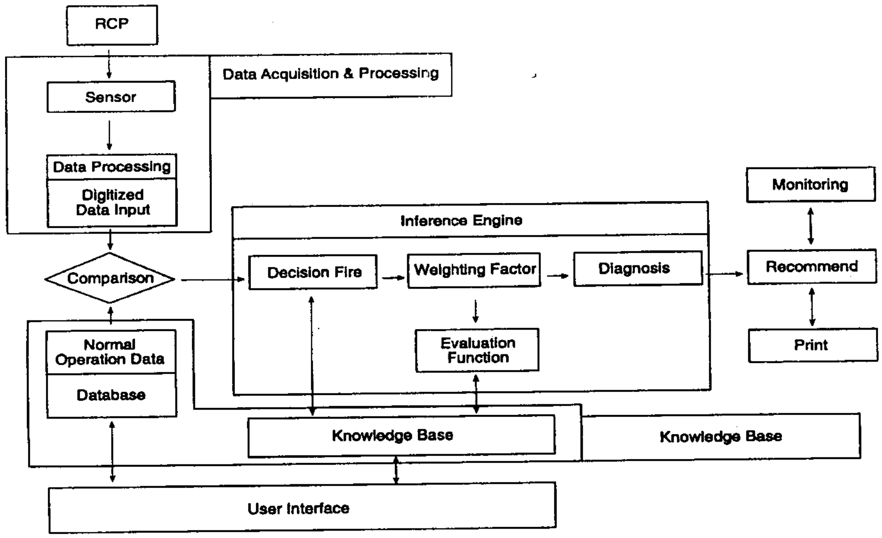

Fig. 7 Procedure for weighting factor calculations

based on the change in temperature in relationship to normal temperature can be used to evaluate the truthfulness of the fact. To use this method, the fact-evaluation functions should be designed individually for each RCP to account for unique pump characteristics. These functions are present under normal conditions but increase as anomaly progresses. Additional certainty factors based on input from users and experts can be defined for each fact.

The brief explanation of abnormal vibration diagnostic procedure (for example, unbalance) is as follows.

- Evaluate the current data to determine if it matches up to each fact in knowledge base for vibration/operating data such as spectrum, orbit, phase, bearing oil temperature, etc.
- Determine the weighting factor for each evaluation function to find the quantitative value of certainty : $WF_U f_i^{(j)}$ ($i=1\sim n$, $j=1\sim m$, where, n is number of facts, m is number of evaluation functions)
- Calculate the weighting factor for each fact using an algebraic treatment : $WF_U f_i$ ($i=1\sim n$)
- Finally, estimate the probability of unbalance as the cause of abnormal vibration using the min-max method : Pu. The feasible root cause of each type of abnormal vibrations and the data on the probability of the cause being accurate can then be displayed.

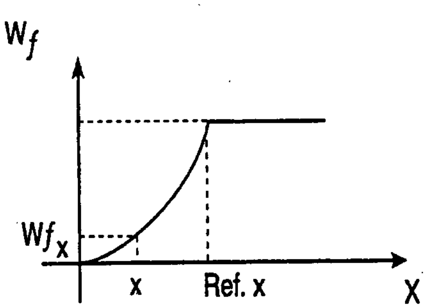

Fig. 8 Example of evaluation functions

Figure 9 shows the flowchart for a diagnostic system that was programmed in C++. The system uses a two-phase approach to diagnose problems. In the initial diagnostic phase, the system analyses the following attributes of the vibrations: amplitude, phase, trend, spectral value, dc position, phase variation, and critical speed. When abnormal vibrations are detected

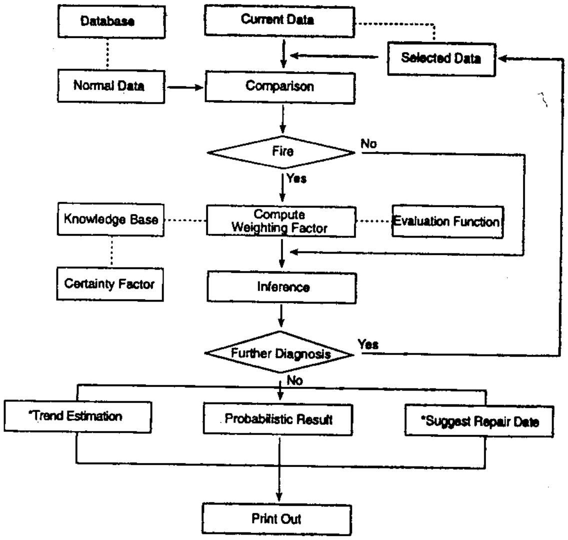

Fig. 9 Flow chart of a diagnostic system

from the primary diagnostic results or when additional diagnosis is required, the analyzed data is combined with the operating data and the orbit vibration data for secondary diagnosis, but this data can automatically be provided to the system once further research on pattern recognition has been completed.

Finally, the diagnostic system determines the cause, calculates the probabilistic results for each type of abnormal vibrations, and displays a recommendation on the monitor as shown in Fig. 10. Although this paper did not cover how to estimate trends or optimal times for repairing RCP problems, probabilistic theory can be used to do this.

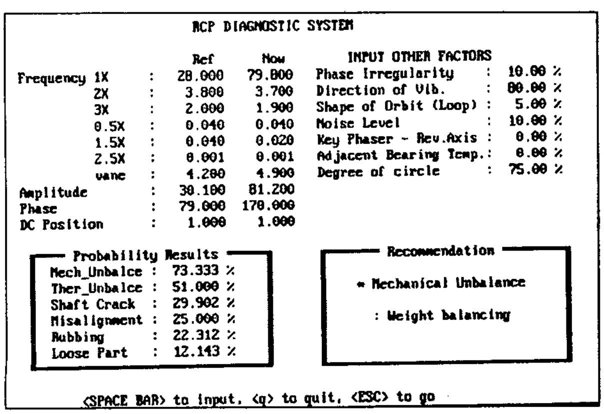

Fig. 10 Example of diagnostic system output

6. Conclusion and Recommendation

To ensure the safety and the availability of the RCPs being used in nuclear power plants, we searched the NPRDS database for information on RCP problems, constructed a knowledge base on RCP abnormal vibration characteristics, and provided a diagnostic algorithm. Knowing the relationship between vibration causes and associated symptoms is the key to diagnosing RCP problems.

In order for nuclear power plants to develop a better diagnostic system based on the suggested diagnostic algorithm, some further studies such as the experimental verification of actual pump vibration characteristics due to the change of process condition, pattern recognition, etc. are recommended.

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