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Development of Diagnosis Technique for Rotating Machines by Vibration Analysis

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The body can be viewed from the next page.

Development of Diagnosis Technique for Rotating Machines by Vibration Analysis*

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1 Introduction

In equipment-intensive industries such as steel, chemicals and petroleum, various rotating machines such as fans, pumps and motors are widely used, and in an integrated steelworks, they reach more than 10 000 units, even counting only major units. On the other hand, their stabilized operation is indispensable for the industry, and their trouble results in a serious drop in production, leading also to process disturbance. In addition, periodical over-haul and the preparation of spares are costly.

To cope with this situation, proposals have been made for introducing machine diagnosis techniques which will permit foreseeing and predicting anomaly and future adverse effects through quantitative grasping of machine conditions.[1] Among these proposals, the field which has been most thoroughly studied and is highly practical is the rotating machine diagnosis technique.[2]

At Kawasaki Steel, introduction and development of machine diagnosis techniques have been positively promoted since the latter part of the 1970s, beginning with the rotating machine diagnosis (herein-after called the "vibration diagnosis."). Later, with the development of various vibration diagnosis instruments,[3] the vibration diagnosis technique was rapidly diffused and expanded. As a result, technical accumulation has been made, until today when systems implementation and intellectualization have come to be used in diagnosing. In this paper, the rotating machine diagnosis technique of the company will be described, centering around automation and systems implementation techniques.

2 Introduction and Expansion of Vibration Diagnosis Techniques

2.1 History of Vibration Diagnosis Techniques

Introduction of the vibration diagnosis techniques was started as a trial at various sectors in the latter part of the 1970s. At first, vibrometers sold on the market were used and the diagnosis level was mostly on the

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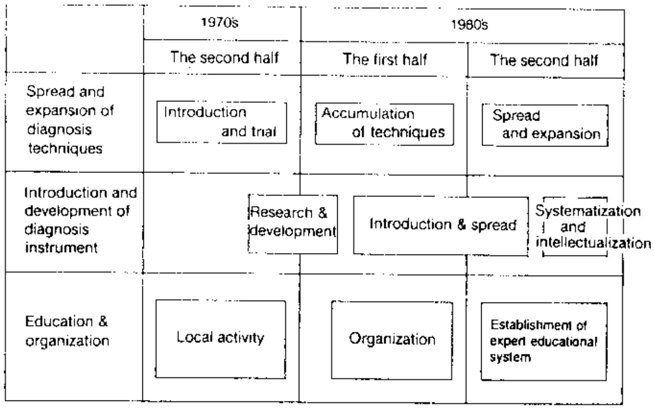

Fig. 1 Kawasaki Steel's history of machine diagnosis techniques

simplified diagnosis level. In the 1980s, however, portable disgnosis instrument was developed,[4)] opening the way for comprehensive field diagnosis covering both simplified and precision forms, thereby attaining rapid progress of techniques. However, these techniques were still in the hands of a small number of people who were called "diagnosis experts." In the latter part of the 1980s, the diagnosis setup was practically established and diagnosis technique was widely promoted through training and practice. At the same time, diagnosis instruments were also diffused, until at present, almost all maintenance crew have become able to operate diagnosis instruments and to perform a certain degree of analysis. On the other hand, in order to meet the maintenance control setup aimed with small-number but skilled crew, the systems inplementation and intellectualization of the vibration diagnosis were promoted. The history of the vibration diagnosis techniques of the company is shown in **Fig. 1**.

2.2 Examples of Vibration Diagnosis

Recently, the number of diagnosing cases such as predicting abnormality, preventing troubles or extending overhauling periods have exceeded 100 cases in a year. These examples have been summarized, one case per sheet, in diagnosis report for the purpose of accumulation of techniques. Of these examples, abnormality-predicting examples have been sorted out in **Table 1** by classifying them in "machine," "element" and "cause of abnormality." The "machine" includes mostly fans, pumps, gear boxes and rolls, the "cause of abnormality" includes many cases of unbalances, misalignments, coupling faults and bearing faults. Representative examples of diagnoses are summarized in **Fig. 2**.

Number 1 in fig. 2 shows an example of "unbalance," and its feature is a clear indication of a rotation reference frequency component f_0 (= $N/60$; N, revolution (rpm)) in the vibration spectrum. No. 2 is an example of "misalignment," and the clear showing of f_0, $2f_0$ and $3f_0$ is its feature. In general, attention should be paid to vibrations in the axial direction, but in many cases, it is too dangerous to measure such vibrations, and measurements in the radial directions are sufficient for making a decision. No. 3 shows an example of chain coupling teeth wear, and its feature is a regular showing of multiples of rotation reference frequency components for the number of teeth in the frequency spectrum such as "$f_0, 2f_0,$ and $3f_0, \ldots$". No. 4 is an example of the wear of the shaft and features irregular waveforms. No. 5 is an example of the outer-race of the roller bearing which has developed flaking, and features a peak distribution as shown in the frequency spectrum. There is also a method of obtaining a correspondence between

Table 1 Number of precise diagnosis cases

(◎: many ○: a few)

Element	Cause of fault	Fan, blower	Pump	Motor	Gear box	Roll
Rotor	Unbalance	◎	○			◎
Shaft	Bending	○	○			◎
Coupling	Wear of shaft	○	○			
	Misalignment	◎	◎	◎	○	○
	Wear of key				○	
	Loose bolt				○	○
	Wear of teeth	◎	◎	◎	○	
Bearing	Wear of bore				◎	○
	Wear of bearing	◎	◎	○	◎	◎
	Flaking of bearing	◎	◎	◎	○	◎
	Crack of bearing				○	
Base structure	Loose bolt	○			○	○
	Faulty setting	◎	○	○		◎
	Crack	○			○	
Others		Pressure pulsation		Electro magnetic unbal-ance	Wear of teeth Chipped tooth	

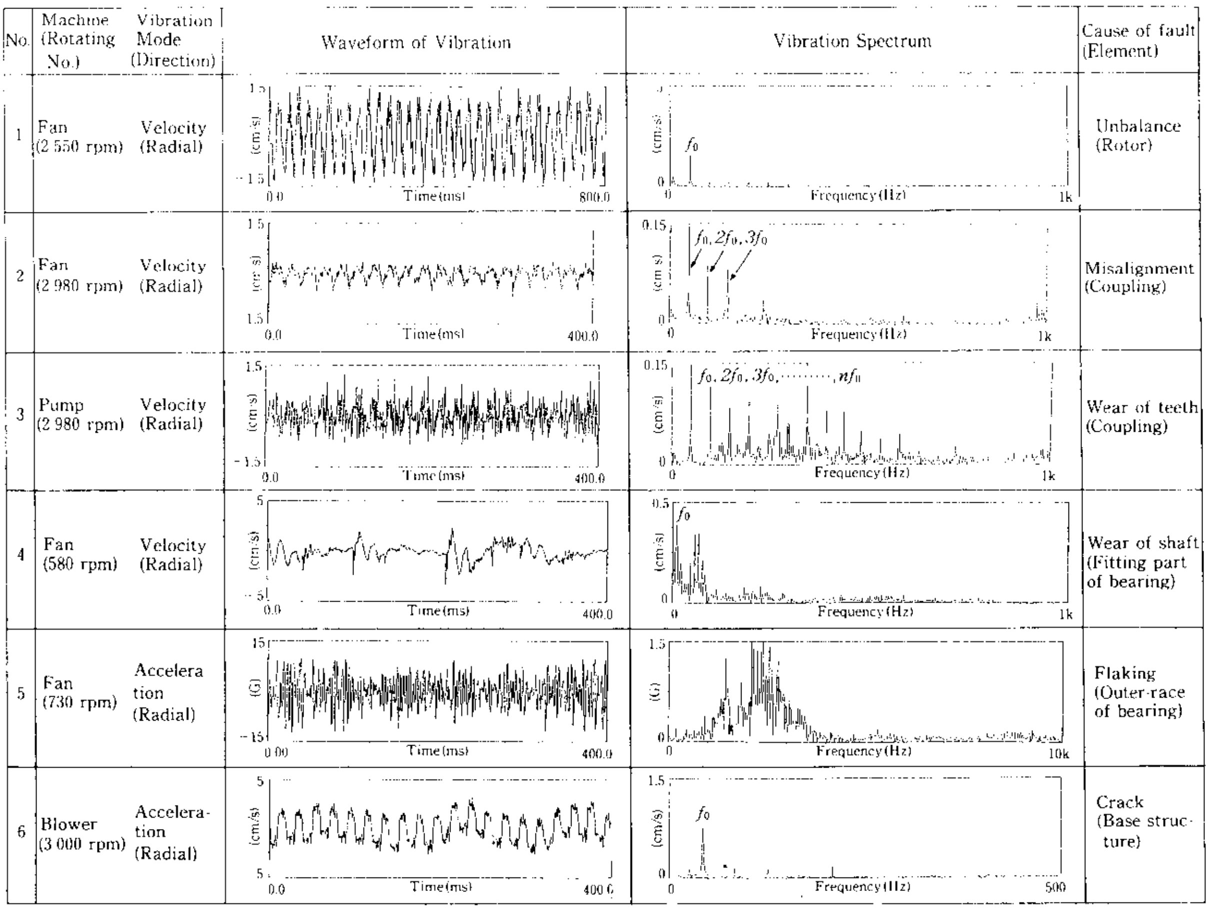

Fig. 2 Examples of vibration analysis

the frequency spectrum after envelope processing and the fault developing frequency,[5] but the above-mentioned method also can judge the abnormality of the bearing. No. 6 shows an example of detecting a crack on the base of the fan, has a special feature in the vibration waveform, and indicates that besides the regular vibration waveforms due to unbalance, there is another undulation of a much lower frequency synthesized in the regular vibration waveforms, but this is spectrum frequency and, as can be seen also by paying attention to the low-frequency spectrum, is too small and may be overlooked.

As mentioned above, Kawasaki Steel conducts a comprehensive diagnosis which includes not only the value, direction and mode of vibration but also the features of vibration waveforms and frequency spectra.

2.3 Organization for the Development of Diagnosis Techniques

The start of the program for developing diagnosis techniques at Kawasaki Steel was not very early, but the reason why the company was able to accumulate, diffuse and expand techniques and promote systems implementation and intellectualization of the diagnosis techniques in a short time lies in the way of the development organized at the company.

The diagnosis technique development organization of the company is shown in **Fig. 3**. Kawasaki Steel owns such subsidiaries as Kawatetsu Advantech Co., Ltd. for the development of diagnosis instruments, and Kawasaki Steel systems R&D Corporation for the research of

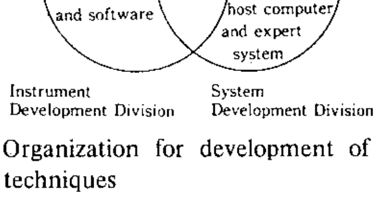

Fig. 3 Organization for development of diagnosis techniques

systems. They have been most useful in answering the needs of maintenance division through developing diagnosis instruments and the implementation of diagnosis systems. Further, they have facilitated the development of expert system and linkage with host computers. In addition, because the development has been promoted while listening to the opinions of the maintenance division as the user, developed items have frequently been utilized for commercialization. As a result, the above development-organizational setup consisting of the three features is still maintained intact.

3 Development of Expert System[6] Communicable with On-line System

3.1 Circumstances

When the training of the maintenance crew was completed as a first stage, next comes the training of specialists who can judge and process the cause of the abnormality. Chiba Works has endeavored to train specialists, about five specialists every year, through OJT (on-the-job training). However, abnormal phenomena which occur in the field are complicated, and it took at least one year of training to acquire the highly-advanced analysing ability to differentiate the direct cause from indirect causes. Thus it was difficult to bring up many experts in a short period. In view of the above, the company grappled with the development of expert system with the aims of making the non-expert able to operate on popular personal computers to a point of forming judgments as good as those by specialists and to develop systems that can be operated even by the unskilled.

3.2 System Configuration

3.2.1 Configuration of functions

The expert system can handle all the data from instruments used by the company such as vibrometers (**MK-10** series), portable vibration analyzers (**MK-300** series), vibrometer-equipped handy-terminals (**MK-20M** and **30M** series), and on-line diagnosis systems (**DM-2000** and **CMS 3000** series), thereby achieving multi-function operations. The configuration of functions is shown in **Fig. 4** and its out-line is explained below.

(1) Manual Diagnosis:
This is a diagnosis using only vibration values (simplified diagnosis), and data necessary for the diagnosis are manually inputted.

(2) Off-line Diagnosis:
This is a diagnosis (sub-divided into "simplified diagnosis" and "precision diagnosis") which uses vibration values, vibration waveforms and frequency spectra, which have been measured and stored through the portable analyser and handy terminal and whose data are transmitted to a personal computer through RS-232C Interface.

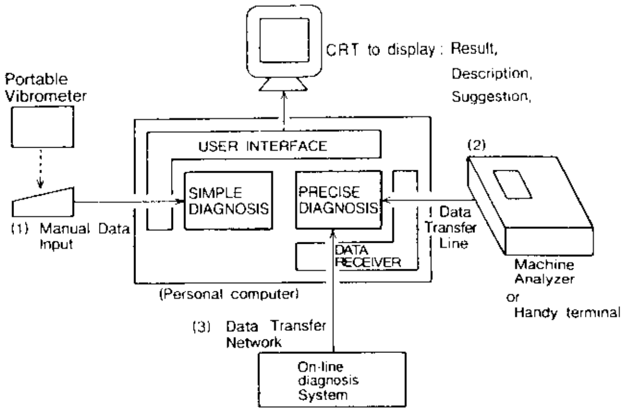

Fig. 4 Configuration of expert system

(3) On-line Diagnosis:
This is a diagnosis using various collected data in an on-line diagnosis system (sub-divided into "simplified diagnosis" and "precision diagnosis"). Its data are transmitted to the personal computer through RS-232C interface.

3.2.2 Hardware and selection of development-support tools

Necessary conditions for selecting the development-support tools are shown below.

(1) Operations shall be carried out on the popular personal computer.
(2) Interface with the file shall be possible.
(3) Displaying of diagrams showing vibration waveforms, frequency spectra, etc. shall be possible in the midst of inference.
(4) The development support tools shall be moderate in cost.

Due to the reasons mentioned above, the authors have selected the following as hardware and development-support tools:

Hardware: PC9800 series (made by NEC)
OS: MS-DOS
Development-Support Tool: TELL (made by Iwasaki Giken Corp.)

3.2.3 Acquisition of knowledge

The procedure of acquisition of knowledge is shown in **Fig. 5** and is explained below.

First, on the basis of examples so far obtained, the features of frequency spectra and waveforms have been extracted and sorted out. Next, they have been summarized into matrix forms according to respective features of measuring direction, vibration mode, characteristic frequency and waveforms. In addition, they have been re-written in the form of "IF, THEN." In particular, at this stage, data which can be coped with by numerical computation have been made into numerical formulas as far as possible, thereby reducing the number of ver-

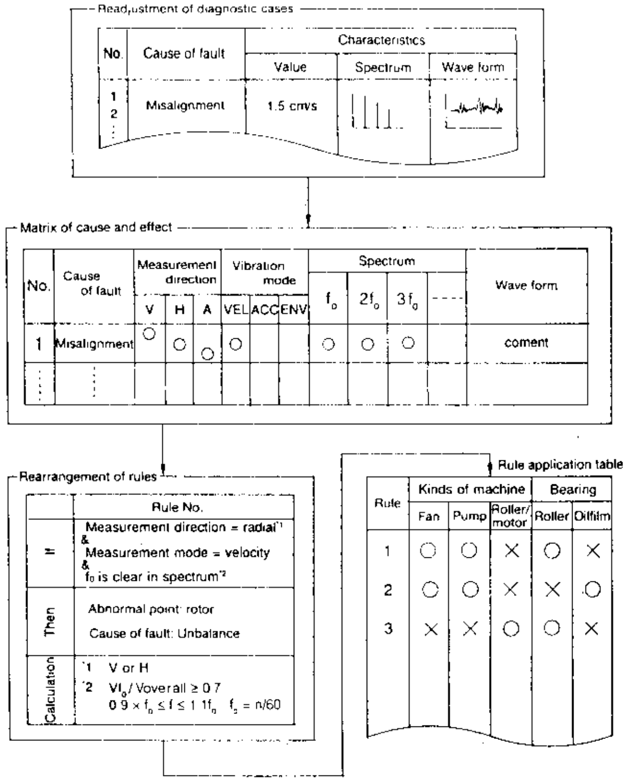

Fig. 5 Procedure of acquisition of knowledge

bal questions. Finally, the applications or rules have been classified according to each machine and element so that no conclusion, which is impossible to occur, will be deduced.

3.2.4 Configuration of software

The configuration of software of this expert system is shown in **Fig. 6**. As mentioned earlier, the development-support tool, TELL, is used. TELL is a tool based on the PROLOG language, and this PROLOG adds functions such as the window and the floating decimal

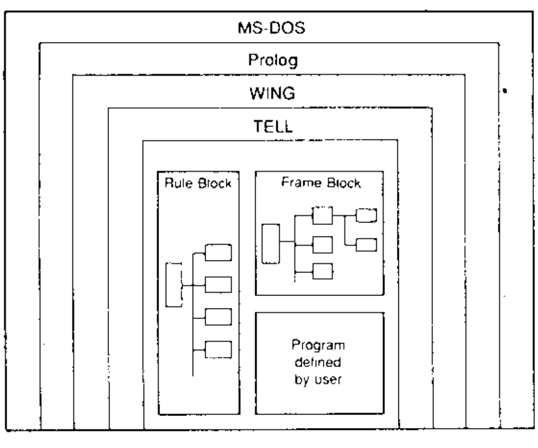

Fig. 6 Software configuration of expert system

point computation by means of the product called the "WING." The knowledge base is composed of the "rule," "frame" and "user defined predicate," and the "rule" and "frame" are divided into blocks. The "rule" is the portion which stores knowledge for diagnosis use in the form of "IF, THEN," and the total number of rules is about 240. The "frame" is the portion where the data for diagnosis use are stored, and the total number of frames is about 50. Processing like reading into the file, graph display and numerical computation are prepared as user-defined predicates, and registered. The total number of the user-defined predicates is about 60. Besides the above, about 60 predicates for the demonstration use have been prepared.

3.3 Operation Sequence of System and Display Examples

Operation sequence in the case of off-line diagnosis of the expert system is shown in **Fig. 7**. First, by selecting data No. and carrying out the designated transfer operation, data stored in the diagnosis instrument for off-line use are automatically transferred to the expert system side. Next, the machine type is selected, and revolution and motor power are inputted. Input operation ends here. Then ① the simplified diagnosis by the judgments of the deterioration degree after data reading and by combination of such judgments and ② the precision diagnosis by the magnitudes of vibration spectra

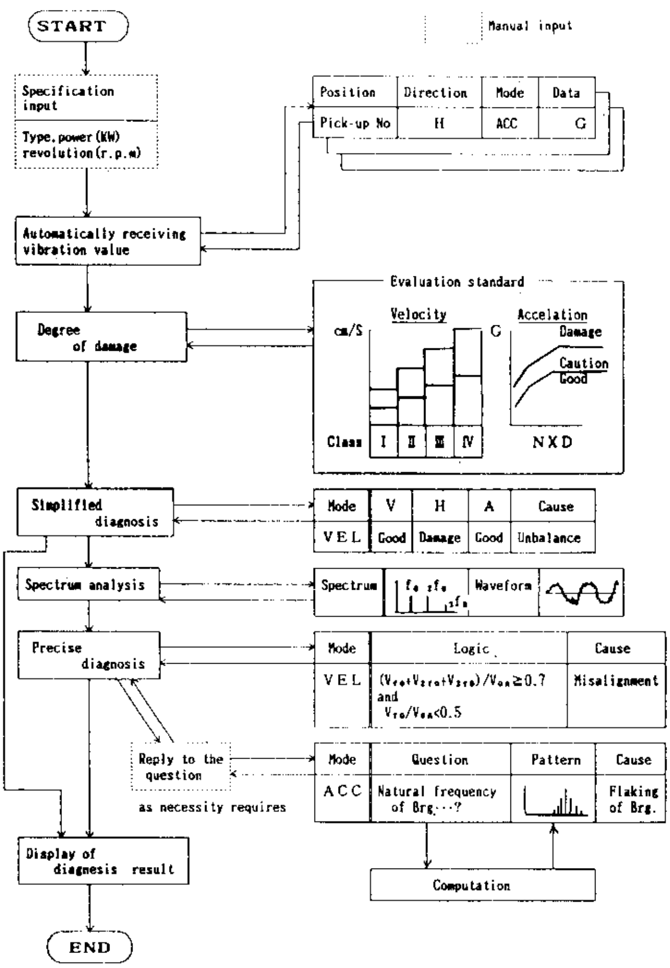

Fig. 7 Procedure of analysis

and their combination are carried out automatically. Provided, however, that when hitting a rule which cannot be processed by numerical computation, a verbal questionnaire is automatically issued. However, the verbal questions are all in the conversational mode, only requiring the selection among "yes," "no" and "unknown" using the mouse, thereby making the operation very simple. In addition, computations of ① the fault-developing frequency and natural vibration of the roller bearing and the ② critical speed of the spindle can be easily made. The diagnosis result is automatically displayed and printed-out as well. Examples of machine type selection, issuance of the questionnaire and display of the diagnosis result are shown in **Fig. 8**.

3.4 Features and Outcome

3.4.1 Features

The features of this expert system are shown below.

(1) Pliability of Communications Function
The linkage between the expert system and various diagnosis instruments of the company including the on-line system is possible.

(2) Highly-advanced Judging Function
Know-how has been structured on the basis of technical accumulation for many years, and is summarized into about 240 rules.

(3) Minimization of Human Intermediation
Theorization and quantitization are aimed at, and matters which can be solved by numerical computation are solved by using theorization and quantitization, thereby minimizing the human judgment.

(4) Low-Cost System Configuration
System design has been made so that operations can be made on popular personal computers.

(5) Guidance Function
Multi-windows have made it possible to display vibration waveforms and the result of spectral analyses.

3.4.2 Outcome

In the company, 16 systems (including 2 systems for on-line use) are working up to the present. Changes in the number of cases of the precision diagnoses before and after the introduction of the present expert system are shown in **Fig. 9**. Through the use of this system, the number of cases of the precision diagnosis has greatly increased, and it is seen that the number has increased about three times the pre-introduction number of cases. Through this introduction, a great contribution has been made to the prevention of troubles and the extension of overhauling periods.

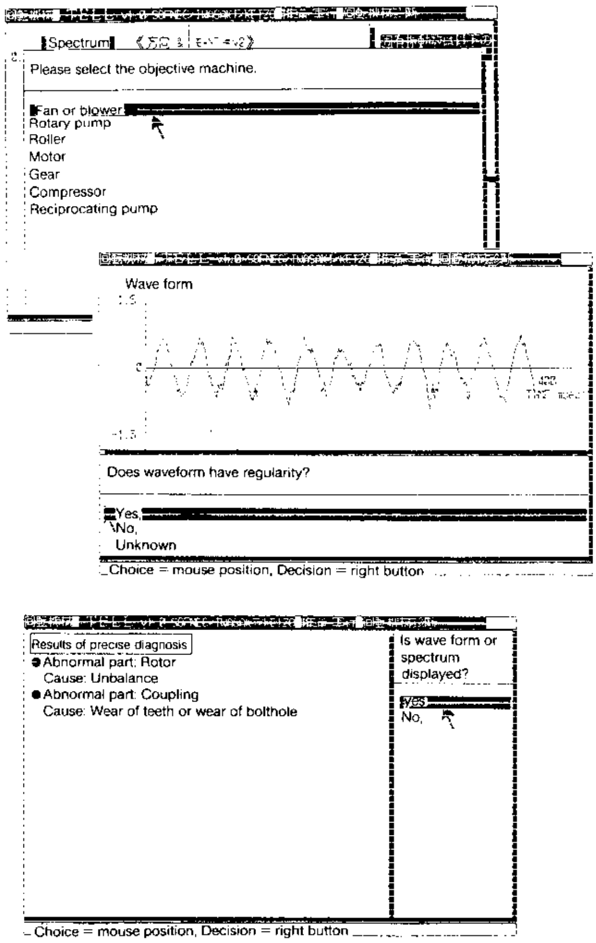

Fig. 8 Examples of CRT display

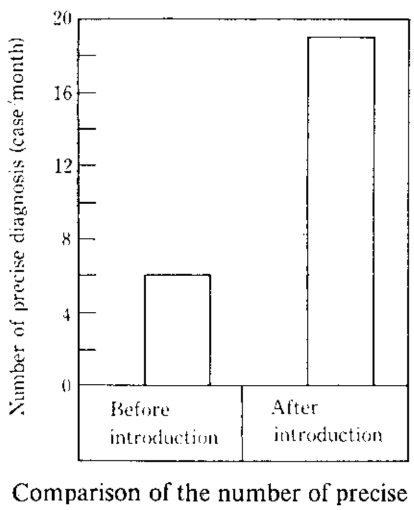

Fig. 9 Comparison of the number of precise diagnosis cases before and after the introduction of system

4 Development of On-line Machine Diagnosis System Having Automatic Diagnosis Function[7)]

4.1 Circumstances

Kawasaki Steel has since its early stage promoted the introduction of the on-line machine diagnosis system in order to establish equipment control setup to assure high efficiency and high quality by the small number of capable staff. Up to the present, about 20 systems are operating, and most of them are mainly concerned with the rotating machinery vibration diagnosis. As for the object portions of the measurement, however, priority has been given to difficult-to-inspect positions of key equipment in important facilities. However, when automation and mechatronics have progressed as in recent years, the object range has been expanded, and systems with their measuring points exceeding 200 points have come into being. As things have progressed this far, the man-machine interface has become more imporatant, which not only simply collects data for computation and judgment, but also saves human judgment and trouble so as to be intelligible to operators and maintenance crew to permit their quick response. Therefore, the company has developed an on-line machine diagnosis system which has automatic functions for diagnosing and report outputting.

4.2 System Configuration

4.2.1 Basic hardware configuration

Basic hardware configuration of the machine diagnosis system is shown in **Fig. 10**. The hardware mainly consists of vibration sensors, vibrometers, the controller and terminal units, and is equipped with the spectrum analyzer and signal multiplexer. The vibration sensor is

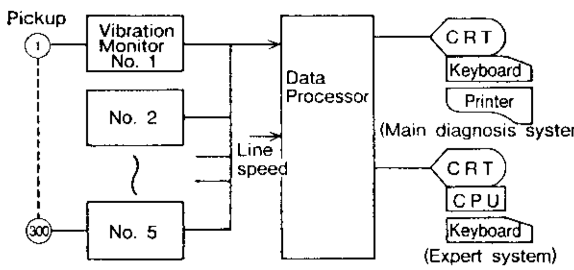

Fig. 10 Hardware configuration of on-line diagnosis system

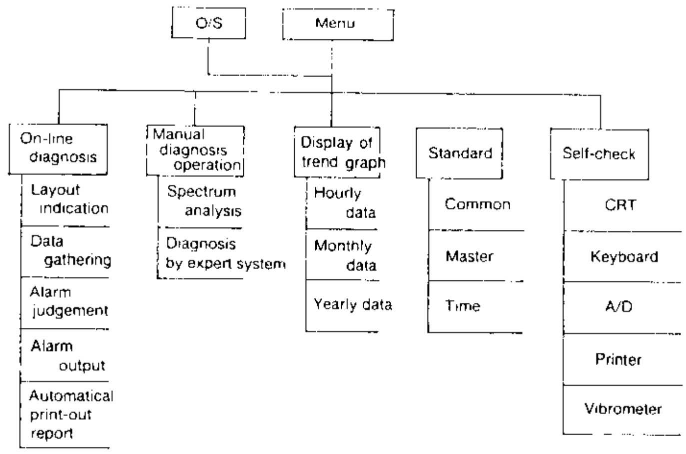

Fig. 11 Functions of on-line diagnosis system

ordinarily a pickup using a piezoelectric element of the insulation type and special waterproofing type. For the furnace, high-temperature-use pickup is used, and for the mill, a waterproof-type special pickup is used. A single unit of the vibrometer permits connection of 60 points of vibration sensors and changes over channels by external signals. Further, the vibrometer and the mode are selected by the singnal monitor. The controller controls the entire system and governs the selection, computation, storage and display of data, and also can input process signals such as line speed and condition signals such as ON-OFF signals. For terminal units, two units are used, one for the use of ordinary on-line system and the other for the exclusive use of the expert system.

4.2.2 Configuration of function

Functional configuration of the machine diagnosis system is shown in **Fig. 11**. The functional configuration is broadly divided into the on-line diagnosis function, manual diagnosis function, display function of stored data, criterion setting-up function, and self-diagnosis function. The on-line diagnosis function includes not only the functions of data collection and alarm judgment but also the automatic diagnosis function and automatic report compilation and printing-out functions. The manual diagnosis is used as and when necessary, and includes ① a precise diagnosis function equipped with an automatic diagnosis function and ② a diagnosis function by the aforesaid expert system. For stored data, it is possible to preserve and display data for two years' duration. The criterion setting-up function sets up sampling timing, constants for the purpose of computation and judging criteria. The self-diagnosis mainly self-checks wire breakage.

4.3 System Features and Display Examples

4.3.1 Alarm judgment and automatic diagnosis logic

What frequently poses problems, when setting up the criteria for the rotating machine vibration diagnosis, is the dispersion of vibration values due to changes in the number of revolution. To solve this problem, the company employs two methods. One is applied to the case of diagnosing the cold rolling mill and continuous annealing line, which are operated at speed near the maximum speed and whose operating time can be secured for a certain degree, and these reducers and rolls which rotate by being interlocked with the line speed, and this method samples data at speed above a certain speed (set speed). The other is applied to the case of diagnosing those machines whose revolution changes are wide and fluctuation width is also large, such as the reducer of the hot rolling mill and variable-revolution fans. In operating these machines, measured values are multiplied by correction coefficients matched with rotation (the so-called DN correction).

Another problem is concerned with dispersion of vibration values due to changes in load. To cope with this problem, an ingenious method is used on alarm processing. Namely, when alarm judgment is carried out on the basis of short-time data (for instance, 2-hour deta), the effect by load changes is exercised on most cases, and therefore, in order to ascertain that the alarm really indicates abnormality, the alarm is outputted only when the alarm criterion is exceeded several times continuously. When alarm judgment is to be performed on the basis of data for one day or for one month, it is possible to minimize the effects of dispersion due to load fluctuation by averaging these data.

On the other hand, when abnormality is judged (alarm is outputted), the position concerned on the layout screen of the CRT flickers, and the channel is switched over to the position concerned and an automatic diagnosis is performed. The automatic diagnosis carries out judgment on ① unabalance, ② misalignment, ③ faults on the bearing (inner and outer rings and rollers), and ④ faults on the tooth of gear (wear, and chipping). When there is no fault mentioned above, then ⑤ "other abnormalities" will be displayed. In many of ordinary cases, one of the above categories is applicable. When "other abnormalities" is displayed or when

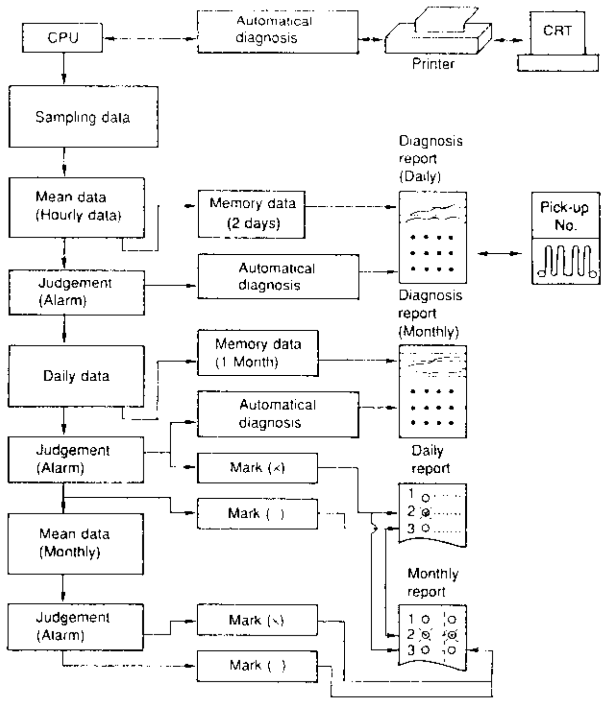

Fig. 12 Flow of automatic printing-out

a further detailed cause is to be searched, the above-mentioned manual diagnosis is used for analysis in linkage with the expert system.

4.3.2 Automatic report printing-out function

The automatic report printing-out function is explained according to **Fig. 12**. First, the average of sampled data for two hours and a judgment is made according to the aforesaid alarm logic. If there is abnormality, the automatic diagnosis result together with the trend graph for the nearest two days is outputted as the hourly anomaly report. The daily anomaly report is similarly prepared by averaging data for one day, and further, alarm judgments are performed. If there is any abnormality, the result of automatic diagnosis and the trend graph for the nearest one month are outputted. Besides the above, there is periodical outputs, namely, daily report to be outputted every morning and monthly report outputted at the beginning of a month. In all these reports, vibration levels are codified, and the abnormality developing position can be easily located, even if the number of measuring points is many. Examples of the hourly anomaly report and monthly report are shown in **Fig. 13** and **14**, respectively.

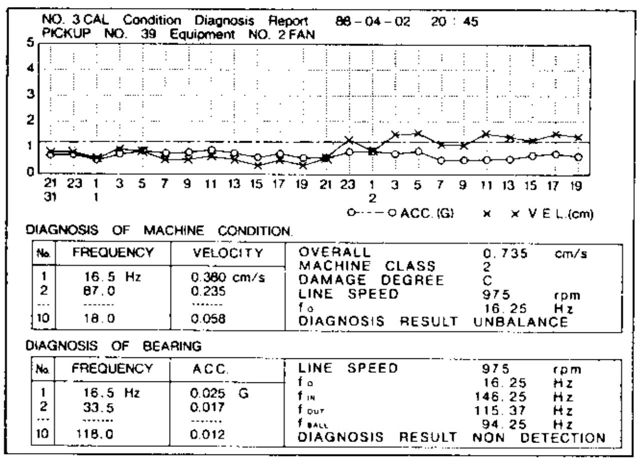

Fig. 13 An example of diagnosis report

NO. 3 CAL CONDITION DIAGNOSIS SYSTEM

MONTHLY REPORT 88. SEP. 01

O: GOOD X: WARNING — : DISCONNECTION

PU NO.	Machine	88. AUG. 123456789	1 01···	2 01···	3 01	M
181	CS- FAN01	OOOOOOOOO	OOOOO	OOOOO	OO	O
182	CS- FAN02	OOOXOXOOX	OOXOX	OXXOO	OO	X
183	CS- FAN03	OOOOOOOOO	OOOOO	OOOOO	OO	O
184	CS- FAN04	OOOOOOOOO	OOOOO	OOOOO	OO	O
185	CS- FAN05	OOOOOOOOO	OOOOO	OOOOO	OO	O
186	CS- FAN06	OOOOOOOOO	OOOOO	OOOOO	OO	O
187	CS- FAN07	OOOOOOOOO	OOOOO	OOOOO	OO	O
188	CS- FAN08	OOOOOOOOO	OOOOO	OOOOO	OO	O
189	CS- FAN09	OOOOOOOOO	OOOOO	OOOOO	OO	O
190	CS- FAN10	OOOOOOOOO	OOOOO	OOOOO	OO	O
191	CS-ROLL01 (OP)	OOOOOOOOO	OOOOO	OOOOO	OO	O
192	CS-ROLL01 (DR)	OOOOOOOOO	OOOOO	OOOOO	OO	O
193	CS-ROLL02 (OP)	OOOOOOOOO	OOOOO	OOOOO	OO	O
194	CS-ROLL02 (DR)	OOOOOOOOO	OOOOO	OOOOO	OO	O
195	CS-ROLL03 (OP)	OOOOOOOOO	OOOOO	OOOOO	OO	O
196	CS-ROLL03 (DR)	OOOOOOOOO	OOOOO	OOOOO	OO	O
197	CS-ROLL04 (OP)	OOOOOOOOO	OOOOO	OOOOO	OO	O
198	CS-ROLL04 (DR)	OOOOOOOOO	OOOOO	OOOOO	OO	O
199	CS-ROLL05 (OP)	OOOOOOOOO	OOOOO	OOOOO	OO	O
200	CS-ROLL05 (DR)	OOOOOOOOO	OOOOO	OOOOO	OO	O
201	CS-ROLL06 (OP)	OOOOOOOOO	OOOOO	OOOOO	OO	O
202	CS-ROLL06 (DR)	OOOOOOOOO	OOOOO	OOOOO	OO	O
203	CS-ROLL07 (OP)	OOOOOOOOO	OOOOO	OOOOO	OO	O
204	CS-ROLL07 (DR)	OOOOOOOOO	OOOOO	OOOOO	OO	O
205	CS-ROLL08 (OP)	OOOOOOOOO	OOOOO	OOOOO	OO	O
206	CS-ROLL08 (DR)	OOOOOOOOO	OOOOO	OOOOO	OO	O
207	CS-ROLL09 (OP)	OOOOOOOOO	OOOOO	OOOOO	OO	O
208	CS-ROLL09 (DR)	OOOOOOOOO	OOOOO	OOOOO	OO	O
209	CS-ROLL10 (OP)	OOOOOOOOO	OOOOO	OOOOO	OO	O
210	CS-ROLL10 (DR)	OOOOOOOOO	OOOOO	OOOOO	OO	O

Fig. 14 An example of monthly report

4.4 Outcome

Since the introduction of the machine diagnosis system, many cases of abnormality have been detected which are connected with serious troubles such as the bearing damage of the heavy-duty reducer, breakage of the coupling key-bolt, bending of the roll and insufficient toughness of the fan stand. As an example, **Fig. 15** shows the transitions of availability of No. 2 continuous annealing line and the downtime of the machine at Chiba Works before and after introduction of the machine diagnosis system. After the introduction, the downtime of the vibration-sensor-fitted portions has decreased, and at present, "zero" downtime is continued. Consequently, the total downtime of machine has decreased, and its availability has steadily increased. As the downtime of important units in important facilities decreases (or by prompt confirmation of important units being normal), the checking range by maintenance crew is expanded and work-planning accuracy is upgraded. Next, the total downtime also has decreased, and operation is stabilized. This seems to have resulted in enhancement of availability.

5 Conclusions

The rotation machine diagnosis technique of Kawasaki Steel has been described centering around the systematization technique. Its main points are summarized as follows:

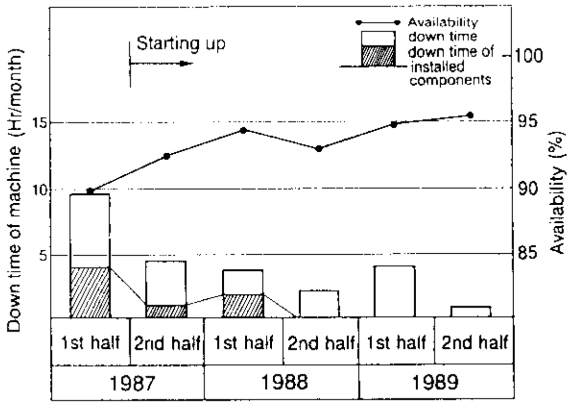

Fig. 15 change of availability and downtime of No. 2 CAL

(1) An expert system has been developed which can be operated on the personal computer, and is communicable to the on-line diagnosis system and which has minimized portions requiring human judgment and yet permits easy operation.
(2) An on-line diagnosis system has been developed which has automatic functions of diagnosis and report printing-out for an improved man-machine interface.

These technical developments have been greatly attributable to the fact that the company had groups such as the Diagnosis Instrument Development Dept., System Research Dept. and Maintenance Dept. (which is the user), and all these three departments have cooperated with each other. However, in the future, it is necessary to further promote the automation, systems implementation, and intellectualization of diagnosis. And, since the vibration diagnosis technique can be applied and expanded to the process diagnosis field, the authors would like to contribute to further advance of diagnosis techniques, with deep recognition of the values of such partnership.

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