Present Status and Future of Equipment Diagnosis Technology for Iron- and Steelmaking Plants

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Abstract

Nippon Steel & Sumitomo Metal Corporation started fundamental studies on diagnosis of equipment conditions and its field application more than 40 years ago as one of the first of the manufacturing industries in Japan. Varieties of devices have been developed and put into actual use for online and offline condition monitoring system. The technology and its system have been introduced to the plants of its steelworks ever since, and condition-based maintenance has permeated and firmly rooted in the production activities all over the company. Lately, the importance of condition diagnosis technology is increasing more than ever to maintain reliable and stable operation of plant equipment that have worked for decades.

1. Introduction

A steelworks comprises processes from unloading of raw materials, iron-making, steel-making, rolling, etc. down to product shipment, and is composed of a wide variety of plant equipment. The iron- and steel-making equipment is characterized as follows:

- (a) Being subject to intensive stress such as high temperature, high loads, corrosive conditions, and wear;
- (b) Working round the clock every day;
- (c) Dealing with many types of products of high dimensional accuracy and high material quality; and
- (d) Being large in size and complicated in structure and often not easily accessible for servicing.

To always keep the facilities in a stable working order and reduce the costs of maintenance under the above conditions, predictive maintenance, or condition-based maintenance (CBM, see **Fig. 1**), whereby equipment damage is kept under watch and the timing of repair is scheduled, is essential. ¹⁾ As the measures to quantitatively detect symptoms of equipment damage at an early stage, Nippon Steel & Sumitomo Metal Corporation has developed various technologies and devices for equipment condition diagnosis and applied them to daily field practice.

Such technology is based on diagnosis logics derived from verification of causal correlations between signals caught during monitoring of machines and secular damage of their components. The equipment diagnosis technology constitutes a general mechanical element technology that combines clarification of mechanical dam-



Fig. 1 Concept of condition based maintenance

age mechanisms based on failure physics, methods of measuring signals that may point to part damage symptoms, and signal processing technology to convert the signals into numerical diagnostic indicators. At Nippon Steel & Sumitomo Metal, these technologies have been proactively developed and accumulated by the organization responsible for mechanical engineering of the whole company.

2. Diagnosis Technology for Iron- and Steel-making Equipment

Repair work is the mainstay of the maintenance activities for iron- and steel-making equipment; its contents and timing are planned based on equipment management standards.²⁾ In addition, to make the repair work effective, plant equipment is inspected and their conditions judged in periodical cycles defined for each of

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Fig. 2 History of diagnostic technologies

them; maintenance personnel inspect and diagnose plant equipment according to prescribed schedules. Besides daily inspection by the five senses (visual inspection, contact sensing, auscultation, etc.), special tools are used for quantitative monitoring, such as the multifunction portable equipment diagnosis device and ELESMART[™]. Hydraulic fluids and lubricants undergo periodical sampling for contaminant analysis. Online diagnosis systems are provided mainly for vibration analysis for important units and those machines that work at changing rates. Thanks to these provisions making use of characteristics of different monitoring means, equipment damage is detected at an early stage and damaged parts are systematically replaced with sound ones at periodical maintenance work. These measures effectively comprise preventive maintenance.

3. Development and Advance of Equipment Diagnosis Technology

Nippon Steel & Sumitomo Metal began technical development for the field application of such plant diagnosis technology in the 1970s, and ever since, has introduced ELESMARTTM and other portable equipment diagnosis devices to different production lines at its steelworks. These facilities, more than 2000 in number, now constitute an indispensable tool for field maintenance activities. Based on equipment diagnosis technology obtained through the use of these portable devices, methods were developed for online diagnosis of plant equipment precisely and continuously around the clock in the 1980s, which were then refined in the 1990s for wider application and functions and lower costs and widely spread to the plant floors. Such online diagnosis systems now cover more than 100 plants at different works of the company, forming indispensable part of the field maintenance ^{3,4)} (see **Fig. 2**).

4. Application Examples of Equipment Diagnosis Technology

Some examples of equipment damage detection using online equipment diagnosis systems are presented below.

4.1 Drive systems for finishing mills of continuous hot rolling mill plant

At a blast-furnace-based integrated steelworks in Japan, the continuous hot rolling mill plant constitutes an obligatory process composed of a single production line, and an equipment trouble there has influence over the production of the entire works; a failure especially of any one of its rolling mill stand is likely to cause a long plant stop or a significant fall in production. For this reason, all the continuous hot rolling mill lines of the company have online continuous monitoring systems with vibration sensors provided for every mill stand, especially the drive system. **Figure 3** shows a monitor-



Fig. 3 Detection of bearing damage in main reduction gear box for finishing mill



Fig. 4 Flaking of outer ring raceway

ing system applied to the main reduction gear box of a finishing mill stand (F2). In a specific case given here, starting from six months before a scheduled change of a bearing, a diagnosis parameter on a monitoring device, say the Hi value, of the unit began to go up gradually, and at a direct inside inspection using a fiber scope, flaking was found at the raceway surface of its outer ring (see **Fig. 4**). In this case, the bearing was put under intensive control, the lubricant feed rate was increased, and it was kept in working order till the previously scheduled change up to its designed service life and without hindering production.

Figure 5 shows another example, diagnosis of the main reduction gear of a roughing mill stand. In this case, too, the Hi value of a









Fig. 6 Cracked bearing cage in main reduction gear box for roughing mill

bearing began to increase about two weeks before its scheduled change, and it was closely examined to find the cause, wherein acoustic signals of a specific frequency pointing to retainer damage were identified, and the bearing in question was replaced with a new unit at a periodical repair of the plant a few days thereafter. During the replacement work, a part of its retainer was found to have broken as had been suspected (see **Fig. 6**). As seen with these examples, an alarming signal makes it possible to prepare replacement parts and the personnel for repair in order to prevent secondary damage such as the failure of a gear or a shaft in the same gear box. More than 20 machine damage cases similar to the above are detected beforehand and taken care of at all the continuous hot rolling mill plants of the company every year, preventing roughly 120 hours of line stops.

4.2 Rolling mills of wire rod mill plant

Steel wire rods are rolled from square billets, more than 100 mm a side in section, to a diameter of several millimeters, and the rolling speed at the finishing stands of a wire rod mill is so high that many components of the drive system rotate at as high as 10000 rev/min. For this reason, when a defect develops in any one of the gears and bearings in a drive gear box, however small it may be, it aggravates



Fig. 7 Trend graph of speed increasing gear box



Fig. 8 Result of precise diagnosis



Fig. 9 Flaking of roller bearing

rapidly possibly leading to a stoppage of the entire driving system, which means that of the whole mill line. The finishing stands of Nippon Steel & Sumitomo Metal's wire rod mills are equipped with online monitoring systems to detect subtle signs of component damage at an early stage.

Figure 7 shows plotting of vibration trend monitoring of a speed-increasing gear box. The Hi value, which indicates damage of the bearing in question, went upwards from the base line; the MD value (mid graph), which indicates the acceleration in all frequency bands, rose to the caution level 14 days thereafter, and further to the danger level the following day; as a countermeasure, the lubricant feed rate was increased, and the cause of the anomaly was looked for using the online automatic precision diagnosis function. Eventually, signs pointing to damage of a bearing roller were detected as shown in **Fig. 8**, and preparations were made for replacement of the bearing. In the meantime, the Hi value (lower graph) suddenly began to rise rapidly, and the mill line was stopped for quick replacement of the bearing. The dismounted bearing was found to have flaking in one of the rollers as indicated in the precision diagnosis (see **Fig. 9**). In this example case, the part change before breakdown

effectively prevented secondary damage to the equipment and line stop, minimizing the decrease in production and avoiding an unnecessary increase in repair costs.

5. Development of New Equipment Diagnosis Technology

5.1 Equipment diagnosis technology applied to field practice

5.1.1 Acoustic monitoring using parabolic microphone

Vibration monitoring is widely applied to bearings of rotating parts in appreciation of higher detection sensitivity than by other methods, but, since it is necessary to monitor an object unit at two or more measurement points in direct contact, there are sometimes problems when an object equipment is not easily accessible. To solve the problem, an acoustic diagnosis method has been developed using a parabolic microphone and is being practically employed.

(1) Directional characteristics of microphone

The microphone used for the developed method is parabolic and has directional characteristics suitable for collecting desired signals, reducing the background noises from irrelevant sources and those of compressed air, cooling water and the like in the environment of plant floors. **Figure 10** shows the directional characteristics of the microphone, and **Fig. 11** the acoustic damping of sounds of different frequencies coming from different directions. A common microphone is not directional, and catches sounds coming from any directions with little damping, and the curves of Fig. 10 would be nearly circular for different frequencies with such microphones. In contrast, a parabolic microphone exhibits stronger directionality at higher frequencies. The parabolic microphone for the developed method was designed such that, with a sound source 1 m away, the



Fig. 10 Polar pattern of microphone



Fig. 11 Relation of angle value and acoustic damping

damping of a sound at 10 kHz frequency would be 3 dB when coming from 10° from direction 0, 10 dB, approximately, when coming from 20°, and more than 20 dB when coming from the back. (2) Acoustic diagnosis of bearings

An example of acoustic diagnosis of a bearing to detect damage using the developed microphone is explained below.

Figure 12 shows an acoustic measurement of a degraded bearing, and Photo 1 the appearance of the same bearing at an overhaul. A wave pattern characteristic of a defective bearing was captured among other sound patterns from a distance up to several meters from its housing in a noisy outdoor environment, and based on it, roughening of a raceway was found.

Through many times of verifications as the above and repeated field tests in equipment in commercial operation, the method has been brought up to daily practice worthiness; this function has been incorporated as an optional function of ELESMARTTM X (see **Photo 2**), a model of multi-function portable equipment diagnosis device commercialized by Nippon Steel & Sumikin Texeng. Co., Ltd. 5.1.2 Service life prediction of crane wires

According to the Industrial Safety and Health Law and the Safety Ordinance for Cranes, crane wires have to be recorded monthly in terms of the number of lifting, and inspected once in every two years periodically, but their replacement with new ones has been defined by the months in consideration of the period of use, the num-



Fig. 12 Sound frequency of defected bearing



Photo 1 Overhaul inspection of defected bearing



Photo 2 Parabolic microphone and compact data analyzer (By courtesy of Nippon Steel & Sumikin Texeng. Co., Ltd.)



Fig. 13 Wire rope residual life monitoring system (REXSTM)

ber of lifting and the evaluation of strand damage at periodical inspection. In the meantime, however, problems came to be felt increasingly strongly, and corrective measures were called for regarding the number of lifting exceeding the prescribed number of use due to increase in production at the plant in question, consequent increase in over-loading and excessive maintenance due to repair/discarding standards on a safety side. To solve the problems, a system to control the service life of steel wire ropes, REXS™, has been developed jointly with Tokyo Rope Manufacturing Co., Ltd., wherein cumulative fatigue of a wire is evaluated based on loading information from a load gauge installed in the wire route (see Fig. 13), brought up to practice worthiness, 5) and applied to some of important cranes. This system is capable of continuously calculating the remaining service life (number of lifting) of a crane rope based on the specifications of the crane, the rope, and sheaves and by connecting to the load gauge.

5.1.3 Structural analysis of operating plant equipment using laser displacement gauge

Most of the steelworks of Japan were constructed 40 to 50 years ago, and many of their production facilities, especially those comprising steel structures exposed to the elements, are aged and face problems of long-term damage due to corrosion, etc. In consideration of this, efficient secular diagnosis methods applying the latest dimensional survey and non-destructive inspection technology have been developed and practiced. For instance, the sag of aged support structures for belt conveyers or the displacement of the rails for coke oven machines is measured by 3D laser scanning to prevent conveyer meandering or correct the position accuracy of the machines with respect to coke oven chambers. Further, to evaluate the secular of moving machines in raw materials yards such as stackers and reclaimers, the combination of 3D laser scanning and numerical analysis is effective at quickly assessing the strength of structural members that have thinned through years of corrosion; this has been commercially applied to decide the priority of repair of machine parts and renewal of aged units (see Fig. 14).

- 5.1.4 Development of autonomous equipment diagnosis systems
- (1) Solar-powered autonomous diagnosis system for outdoor equipment

Many iron-making facilities are provided sparsely in wide areas of raw materials yards. Owing to considerable costs for the cabling for power supply and LAN, they were late in being provided with online equipment monitoring and diagnosis systems. To reduce the costs for the provision, Nippon Steel & Sumitomo Metal is develop-



Fig. 14 Structure diagnosis by 3D laser scanning and FEM



Photo 3 Solar-powered wireless condiiton diagnosis system

ing an autonomous diagnosis system for outdoor equipment with photovoltaic panels and wireless LAN devices and putting it into actual use (see **Photo 3**). The developed system is now under field tests with respect to the specifications of the power generation and consumption and the stability of wireless communication.

(2) Vibration sensor with self-contained power generation and wireless data transmission

In the condition diagnosis of moving machines, installing power supply and data transmission lines and maintaining them for a long period is a troublesome task. Especially in vibration analysis, wherein signals several kilo Hertz in frequency have to be collected, temporarily stored and processed, the diagnosing system including sensors consume considerable power, and continuous condition monitoring for a long period with primary batteries is extremely difficult. In consideration of this, the company is developing a practi-



Fig. 15 Energy harvest wireless vibration sensor

cally usable vibration sensor that includes power generation and wireless data transmission. **Figure 15** shows one such example: a vibration diagnosis unit equipped with an exclusive power generator and a wireless transmitter is monitoring a bearing for the vibrating screen of a sintering machine. Since the transmitter is capable of sending unprocessed original vibration waves several kilo Hertz in frequency, precision analysis of the vibration condition is possible using a fixed system for frequency analysis after a preliminary alarm has been given from the local unit based on simplified trend analysis. This system is being refined to unify the sensor and the auxiliary units into one package and making the package as compact as possible.

5.2 Development of advanced technology for equipment condition diagnosis

5.2.1 Application of motor current signature analysis (MCSA)

Online vibration monitoring requires a sensor fixed to the object machine, and for this reason, involves considerable costs for installation as well as for maintaining and controlling the reliability of the sensor and its cabling during use. As a solution, some sensor-less diagnosis methods for drive motors making use of past current signals are being studied. What is attracting attention at present is the motor current signature analysis (MCSA), which is considered effective at detecting the secular damage of electric motors by analyzing the frequency as well as the absolute value of the current.⁶⁾

(1) Principle of detecting motor damage by MCSA

MCSA is considered promising for detecting secular damage of motor bearing and unbalance of shaft; detecting bearing misalignment is more important. When the mass distribution of a motor is circumferentially unbalanced about the shaft, the shaft turns in a waggling manner, and the torque fluctuates, which leads to fluctuation of the motor current, and by monitoring the current fluctuation in a low frequency band (roughly 100 Hz or below) it is possible to detect unbalance of the shaft. As seen in **Fig. 16**, with a common induction motor, change in torque leads to change in the slip and the current, ⁷⁾ which causes formation of side bands about the operating frequency as seen in **Fig. 17**. The advantage in monitoring the fre-







Fig. 17 Waveforms under torque variation

quency of the voltage supplied to a motor (operating frequency) is that there are less noise peaks than in high-frequency bands and the side bands are identifiable more easily.



Fig. 18 Motor driven rotating simulator



Fig. 19 Signal variation caused by unbalance

(2) Test of detecting shaft unbalance based on MCSA

The sensitivity at detecting motor shaft unbalance based on MCSA was tested using the motor-driven rotating simulator shown in **Fig. 18**. The FFT curves of the motor current at 200 and 800 rev/min are given in **Fig. 19**. At either revolution, difference in peak heights is clearly seen in the side bands on both sides of the operating frequency, which indicates that it is possible to detect shaft unbalance based on MCSA.

5.2.2 Vibration diagnosis using laser Doppler vibrometer

The acoustic diagnosis method explained earlier as an example of a non-contact monitoring method uses high-frequency sound waves of high directionality and is suitable for detecting damage mainly of bearings. In contrast, low-frequency waves are less directional and easily diffracted, and when used for diagnosis of equipment damage of shafts and gears such as unbalance or misalignment, it is sometimes difficult to specify the unit in question. To avoid the problem, Nippon Steel & Sumitomo Metal is trying to establish a non-contact, low-frequency vibration diagnosis method applying laser vibration detection.

The laser Doppler vibrometer (LDV) is a vibration measurement device taking advantage of the fact that, when a laser beam is irradiated to a vibrating object, the frequency of the reflection from it is modified according to the Doppler effect. To evaluate its vibration detection capacity, a LDV was tested using an acceleration sensor as



Photo 4 Portable laser Doppler vibrometer



Fig. 20 Measurement object (bearing housing)



a reference. **Photo 4** shows the tested LDV, and **Fig. 20** the object machine (a bearing housing) used for the test. In the first place, to confirm how the laser reflection changed depending on the object surface condition, laser reflection was measured at two areas of the object machine, one polished and the other not polished. **Figure 21** compares the readings of the vibration (acceleration) by the LDV from a distance of 5 m with those by the acceleration sensor. The S/ N ratio by the LDV is very similar to that by the common acceleration sensor in the frequency range of 4 kHz or below, especially 1.5 kHz or below, which corroborates the applicability of LDV for trend monitoring of the defects of shafts such as unbalance and misalignment and that of some gears.

5.2.3 Development of structure diagnosis technology

(1) Non-destructive inspection of structures

Nippon Steel & Sumitomo Metal has been trying to apply the DC potential difference method to the non-destructive inspection of steel structures. The method is expected to be effective at scanning

and finding thinning of tank bottom plates and other structural members that have broad surface areas and often covered with heat insulating materials. Since the method is applicable while an object equipment is in operation, such as the examination of a tank bottom in actual use from the periphery shown in **Photo 5**, overhaul is not required. As is seen in **Fig. 22**, comparative tests have confirmed that thickness distribution measurement of a steel plate by the method yields results similar to that by ultrasonic measurement. The company intends to further improve the method in terms of resolution, accuracy, and reliability.

(2) Noise investigation by sound source visualization

Nippon Steel & Sumitomo Metal has been developing a method for identifying noise sources by visualizing possible sources in works areas using a sound source investigation device equipped with microphones and cameras. **Figure 23** shows an example of such investigation at an area near a dust collector of a steelmaking plant jumbled with pipes and ducts. This method employs the beam forming method, whereby sound waves from different sources are caught by two or more microphones and the direction of the source of a particular sound is identified relative to the device based on the time difference of its arrivals at different microphones. The direc-



Photo 5 Inspected object and partial view of inspection by direct current potential different method



Fig. 22 Example of thickness inspection of bottom plate by direct current potential difference method



Fig. 23 Sound source investigation by sound visualizing system

tionality of sound increases as the frequency becomes higher and the wave length shorter, and under such a condition, it is possible to calculate a prevailing arriving sound wave (main lobe) and identify its source accurately.

By visualizing the sound of the noisiest frequency band as in Fig. 23, it is possible to pinpoint the sound source and take measures to suppress the noise.

6. Closing

This paper has presented the application examples of Nippon Steel & Sumitomo Metal's equipment condition diagnosis technology and the outlines of their development studies. Equipment diagnosis is essential for stable operation of production facilities, and the company will continue to place emphasis on promoting R&D for innovative technology of equipment maintenance and quick field application of developed methods through cooperation with the group companies.

References

- 1) Fujii, A.: J. of Economic Maintenance Tribology. 534 (02), 6 (2010)
- 2) Murayama, T.: J. of Economic Maintenance Tribology. 504 (11), 18 (2007)
- 3) Murayama, T., Nakajima, S., Nagai, H., Yamamoto, T.: Shinnittetsu Giho. (362), 71 (1997)
- 4) Ohishi, N., Shia, Y., Kurisu, Y., Wada, K., Ishimori, Y.: Shinnittetsu Giho. (391), 113 (2011)
- 5) Ishii, H.: Crane (J. Japan Crane Ass.). 564 (03), 25 (2011)
- 6) Toyoda, T.: Introduction to Rotating Machine Diagnosis Technology Applying Motor Current Signature Analysis (MCSA). 2nd Conference on Latest Equipment Maintenance Technology of Soc. of Plant Engineers Japan (SOPE), Tokyo, Nov. 2009
- 7) Seto, T.: Plant Engineer (J. of SOPE). 505 (03), 33 (2011)



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