Recent Trend on Nondestructive Material Testing Method and Its Application to Chemical Plant Equipment

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Newly developed methods for facility management like RBI (Risk Based Inspection) and FFS (Fitness For Service) have recently been adopted in industrial chemical plants for the purpose of enhancing safe, stable operation and extending their operational lives. These new methods introduced in this paper include an inspection method for stress corrosion cracks, an inspection method for parts with elevated temperatures during operation, an inspection method for reactor tubes under the baffle plates of carbon steel reactors, and diagnostic technology for ball bearings developed through collaboration between academia and industry on research. Non-destructive inspection technologies, which are very applicable to the protection of rotating machines from contamination by foreign objects are also introduced in this paper.

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Introduction

Sumitomo Chemical has various plants, such as petroleum related and bulk plants for petrochemical and basic chemicals, plants for finer products, such as pharmaceutical and agricultural plants, as well as assembly plants, such as those for information processing and electronic materials. There is a great diversity in the forms of products, from fluids to powders and molded products. Viewed from the standpoint of the years in which plants were built, on the other hand, there is a mixture of plants that were constructed in the era of high economic growth in the 1970's or before that and plants that were constructed recently in operation. Recently, Risk Based Inspection[1) (RBI) and Fitness For Service[2)] (FFS) have been incorporated as new facilities management methods for maintaining safety and stable operations and extending the plant life in a variety of plants. Among these facilities management methods are the selection of optimal inspection methods based on techniques for accurately detecting defects and techniques for precisely quantifying defect dimensions and the determination of inspection intervals according to facility conditions, or applying or developing conventional nondestructive inspection techniques based on dynamic safety evaluations and examining whether continued operation is possible allowing for the defects in the facility.

Since our group has developed an inspection method for stress corrosion cracks, an inspection method for parts operating at elevated temperatures, as well as an inspection method for reactor tube under baffle plates in carbon steel reactors and diagnostic techniques for ball bearings developed through the collaboration between academia and industry on research, we will introduce them in this paper. Non-destructive inspection technologies, which are very applicable to the protection of rotating machines from contamination by foreign objects, are also introduced in this paper.

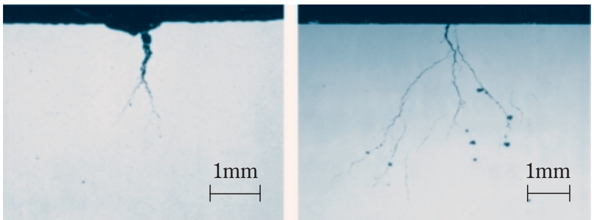
Stress Corrosion Crack Inspection and High Temperature Testing Using Ultrasonic Testing

Sound waves with frequencies above the audible sounds (20 Hz – 20 KHz) for humans are called ultrasound, but for testing, a frequency range on the MHz order or higher is used for testing applications. Since this testing method can make internal inspections of materials nondestructively with good precision, it is often used in the detection of material defects. Here, we will introduce examples of stress corrosion crack inspections in plant facilities and high-temperature testing in operating facilities.

1. Stress Corrosion Crack Inspection

(1) Crack Detection by TOFD

Since there is not only the handling of corrosive fluids inside equipment at chemical plants, but also the scattering of corrosive substances (seawater and the like) from the outside of the equipment, stress corrosion cracks (SCC) may occur both on the inside and outside of the equipment. Examples of SCC are shown in **Fig. 1**, but in both the carbon steel and SUS304 stainless steel, there are multiple cracks that have developed into a branched shape. Therefore, in conventional angled ultrasonic testing experiments, the beam was interrupted by the neighboring crack and the depth could not be estimated, regardless of the inspection being from the opening side or the side without the opening. Therefore, we focused on the new time-of-flight diffraction technique (TOFD) in ultrasonic testing and ascertained the detection performance.



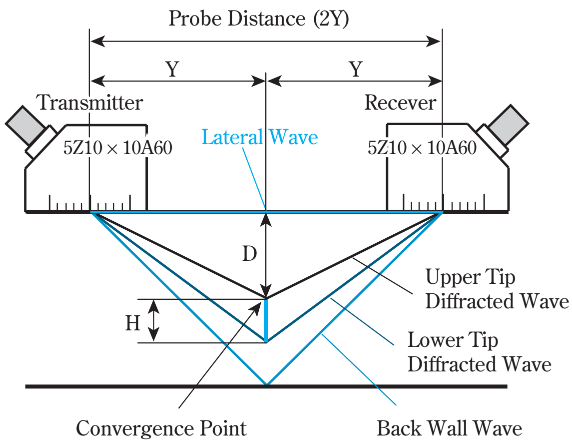
(a) Carbon Steel (b) SUS304 Stainless Steel

Fig. 1 Cross Section View of SCC Specimen

(2) Principles of the TOFD Technique

With the new TOFD ultrasonic testing, the transmitter probe and the receiver probe are positioned in opposition at a fixed distance as is shown in **Fig. 2**. If the probes are positioned on the side of the crack opening, a weak diffracted wave is generated from the end of the crack, when the ultrasound (vertical wave) emitted by the transmitter probe hits, and the method is one that the position and dimensions of the crack are quantified when that is received by the other probe.

Since the display screen of the tester can read the distance between the two probes (2Y in Fig. 2) and the beam path (W_U and W_L in Fig. 2) for the diffracted wave from the end of the crack, it is possible to estimate the depth by calculations. Along with confirming the practicality of these measurement principles using samples with stress corrosion cracks (see **Table 1**) that occurred in materials with a thickness of 10mm or less which make up the majority of structural materials in chemical plants, we evaluated the estimation precision for the depth. The TOFD technique that has disseminated in general is one developed for testing thick materials, so we devised improvements to the measurement precision by fabricating small probes (3mm in diameter) with special specifications and carrying out measurements in this evaluation so that the technique could be applied to materials of 10mm or less, which are used for the most part in chemical plants.



• Equation to calculate Flaw Depth ; D

$$D = \sqrt{\left(\frac{W_U}{2}\right)^2 - Y^2} \quad \text{(Eq. 1)}$$

• Equation to calculate Flaw Height ; H

$$H = \sqrt{\left(\frac{W_L}{2}\right)^2 - Y^2} - \sqrt{\left(\frac{W_U}{2}\right)^2 - Y^2} \quad \text{(Eq. 2)}$$

W_U : Path Length of Top Tip Diffracted Wave (Upper)
W_L : Path Length of Top Tip Diffracted Wave (Lower)

Fig. 2 Reflection Echo Path and Flaw Size Estimation Method With TOFD Technique

Table 1 SCC Specimen for TOFD Measurement

Material	Equipment	Thickness (mm)	Cause of SCC	Photo
Carbon Steel	Tower Body	8.1	Caustic Solution	Fig. 1(a)
SUS304 Stainless Steel	Tower Body	9.0	Chloride Enrichment under Insulator	Fig. 1(b)

(3) Depth Estimation Accuracy and Application in Actual Plants

Fig. 3 shows the TOFD testing signal from the side opposite to the opening in a carbon steel sample where a SCC has occurred. Fig. 3 (a) shows the display screen for the A scope (propagation time on the horizontal axis and echo height on the vertical axis), but this is the display screen for a conventional ultrasonic depth tester, and numerical values, such as the echo height and beam path are recorded. We must construct a figure for displaying the position and dimensions of the flaw, using a trigonometric function based on these numerical values. Fig. 3 (b) shows the display screen of the D scope (flaw mapping diagram in the direction of the cross-section when the probe is moved in a direction corresponding to the lengthwise orientation of the flaw or weld line), and since, unlike the A scope, the flaw is drawn in the cross-section and output, it is easy to get an image of the position and height (length in the width orientation of the flaw arising internally in the material) of the flaw even without constructing a figure. Since waves that can be thought of as diffracted waves from the end of the crack are received by both the A and D scopes, the depth D to the end of the crack was found using Wu and Y shown in Fig. 2 (Eq. 1). Furthermore, observations were made of the cross-section, and the results were brought together and are given in **Table 2**. The error in measurements with testing from the side opposite to the opening with carbon steel was ±0.2mm, and with SUS304 stainless steel was ±0.4mm.

Since the TOFD technique uses diffracted waves from the end of the flaw, it is a superior testing method for quantifying the dimensions of flaws. However, for small flaws with a depth of 2mm or less, bottom waves overlap each other as shown in Fig. 3 (a), so estimation of depth becomes difficult, and in the worst cases, it is missed. Therefore, the conventional method of shear wave testing using one probe and the TOFD technique are used together, because nothing is missed by observing the echoes reflected by the corners from flaws with strong reflection intensities using shear wave testing.

Table 2 TOFD Measurement Result of Branched Crack Caused by SCC

Material	Test Surface	Convergence Point	Error*1 (mm)	Detecting Limit (mm)
Carbon Steel (8.1t)	Non Opening Side	2/3t	± 0.2	(> 0.5)*3
	Opening Side	2/3t	NA*2	NA*2
SUS304 Stainless Steel (9.0t)	Non Opening Side	2/3t	± 0.4	> 0.5
	Opening Side	2/3t	± 0.3	> 3
	Opening Side	Minimum	± 0.3	0.5 < d <3

*1 : Deviation from Average of Measurement Data
*2 : Due to a lot of Pitting (0.5mm Deep) on the Inside Surface of the Specimen
*3 : Shallow Crack Specimen to specify the limitation was not available

2. Development of High Temperature Ultrasonic Testing Techniques

(1) Necessity for Inspections During Operation

In recent years, it has become possible for facilities approved even by The High Pressure Gas Safety Law and Boilers and First Class Pressure Vessels under the Ordinance on Safety of Boilers and Pressure Vessels to operate for two to four years without regulated periodical maintenance. Much of this equipment is in the high temperature region of 100°C or greater, but there are cases where SCC arises from the inside surfaces in equipment and pipes at 100°C or greater, because a wet environment is possible if there is pressure. In addition, thinning arises because of erosion and corrosion, and cracks may arise because of fatigue

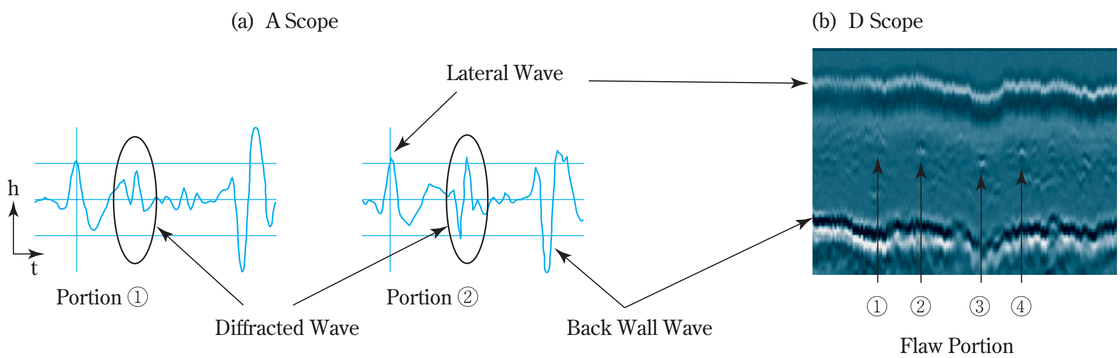


Fig. 3 Test Result of TOFD Technique Testing with Carbon Steel Specimen

damage in places where loads are repeatedly applied. Inspection during operation is one of the required items for achieving continuous operation.

(2) Ultrasonic Testing Performance

1) Standard Samples and Air Cooling Probe Unit

The carbon steel sample (200mm × 300mm × 20mm thick, slit width 0.3mm × length 10mm, depth of 40% of the thickness) shown in **Fig. 4** was placed on a hot-plate and on top of it the air-cooled TOFD test probe fabricated by this group. A heat resistant resin was used for a wedge, and air cooling made it possible to use a commercial ultrasonic probe for ambient temperature. The contact area of the test surface of the wedge was 12mm wide × 17mm long, and that is almost the same dimensions as a small commercial ultrasonic probe for ambient temperature. A commercial high temperature contact medium was used for the contact medium.

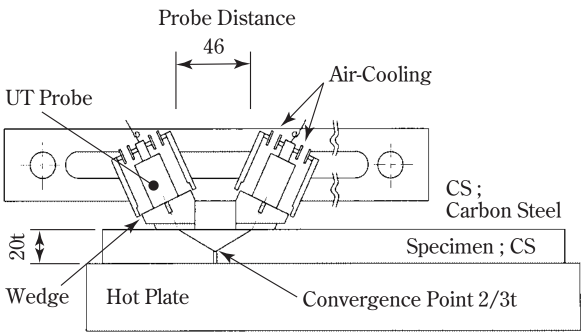


Fig. 4 Schematic Illustration of TOFD Tecnique Probe Setting on Hot Plate

2) Test Results

The test waveforms shown in **Fig. 5** are ones where the angle of incidence (angle of the slant of the direction of ultrasonic wave transmission in the wedge) was determined using a heat resistant resin for the fabrication of the wedge and the carbon steel test specimen at 300°C, but both the lateral wave and the base wave have a large amount of damping at 350°C compared with ambient temperature. Though a high temperature contributes to the increase in damping, the deviation in the point of convergence has a greater effect than this. With a probe wedge for a 45° shear wave, a wedge fabricated using the speed of sound at 200°C for both the carbon steel and heat resistant resin could be used in a temperature range from 25°C to 350°C. However, with a 60° probe wedge for a longitudinal wave, the angle of refraction (angle of the slope in the direction of ultrasonic transmission in the sample) was also large at 60°, and the variations given to the angle of refraction by the variations in the angle of incidence were also large. We determined that it was necessary to fabricate several wedges in 50°C steps in a temperature range of 200°C or greater.

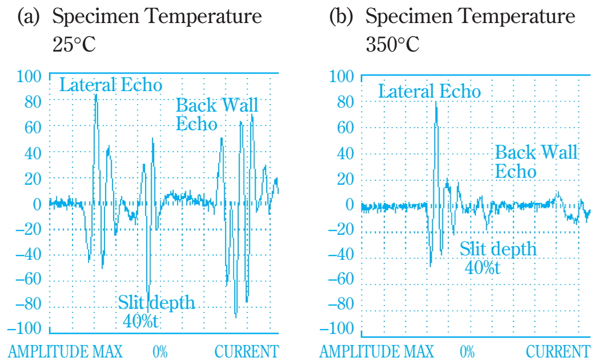


Fig. 5 Echo Pattern from TOFD Technique on Hot Plate

3. Development of Quantification Techniques for the Amount of Air Mixed into Heat Transfer Salts

(1) Mixing of Air in a Vertical Multi-tube Reactor Vessel

Heat transfer salt (HTS) is used as a heating medium for multi-tube reactor vessels. If for some reason air gets mixed into the heat transfer salt in a vertical multi-tube reactor like that shown in **Fig. 6**, it is retained under the upper tube plate and the baffle and inhibits the transfer of heat, so it may cause an extreme increase in the reactor tube temperature.

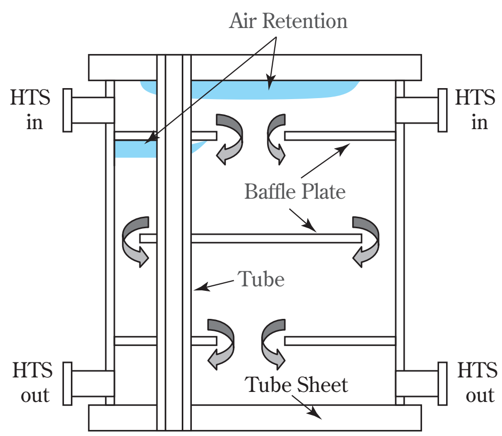


Fig. 6 Air Retention under Upper Tube Sheet and Baffle Plate of Reactor

(2) Air Quantification Techniques and Applications in Actual Plants

Applying the high temperature ultrasonic testing techniques introduced in the previous section, we developed techniques for detecting and quantifying air bubbles mixed in the heat transfer salt tubes around 300°C, and it is being used for safe operation in the plants of a Sumitomo Chemical affiliate. As is shown in **Fig. 7**, the principle is placing transmitter and receiver ultrasonic probes facing each other, with the target of measurements, such as the tube, between them. The ultrasonic beam transmitted by the transmitter probe passes through the heat transfer salt and is received by the receiver probe. The ultrasonic beam is scattered by the bubbles if there is air mixed in the heat transfer salt, so the intensity of the ultrasound received by the receiver probe after passing through the heat transfer salt is weakened. Thus, it is possible to determine if there is air mixed in the heat transfer salt by the presence or absence of changes to the intensity of the ultrasound received. Furthermore, as is shown in **Fig. 8**, it is possible to quantify the amount of air mixed in by the predetermining correlation function between the average value for the ultrasonic intensity passing through during 10 seconds and the amount of air and the ratio for the HTS flow rate.[3), 4)]

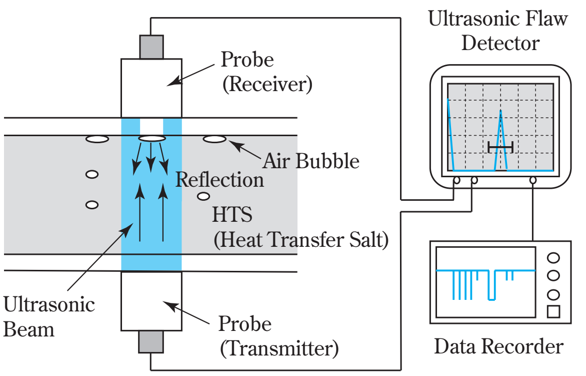


Fig. 7 Principle of Air Bubble Measurement in HTS

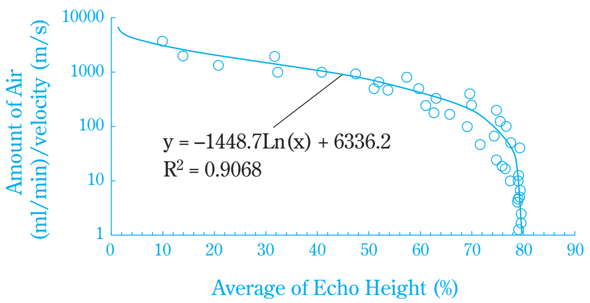


Fig. 8 Relation between Average of Echo Height and Amount of Air

Through the establishment of this technique, it is possible to monitor the mixing of air into HTS easily and accurately, and by suppressing abnormal increases in temperature in reaction tubes, it is possible to have more stable and safer plant operations.

Gap Monitoring and Carbon Steel Reactor Tube Inspection by Eddy Current Testing

The inspection speed of eddy current testing is high, and there is no need for a contact medium like water for ultrasonic testing, so it has the merit of being easy to handle. On the other hand, since it is affected by changes in material characteristics and changes in the contact surface other than flaws, the inspection precision is not as good as the ultrasonic methods. However, if there is air on the other side of the material for ultrasonic testing, everything is reflected back by the back side of the material. However, with eddy current testing, the lines of magnetic force pass through the air, and the other conductive material that is across from the near conductive material can be detected. Therefore, we developed a gap monitoring technique using the passage of the lines of magnetic force through two conductive materials.

1. Development of Gap Monitoring Technique for Rotating Vanes in Table Feeder

(1) Table Feeder Structure

The table feeder is installed at the bottom of a hopper or silo, and as is shown in **Fig. 9**, the content is sent to the outside of the cylinder through the rotation of large, thin, flat rotating fins over a bottom plate. The content on the periphery is discharged by the small rotating vanes. The large rotating vanes have a cantilevered structure centered on the axis of rotation, and drooping arises in the vanes because of the load of the content. If the gap between the large rotating vanes and the bottom plate, which changes according to this drooping is not maintained accurately, the two may come into contact, and foreign objects, such as metal shavings may be generated. When these are designed in detail, the design is done to incorporate sufficient strength and dimensions, but if obstructions and the like arise in the discharge part, a phenomenon where the large rotating vanes sink toward the bottom plate arises, so there is a need to confirm that this gap is being maintained sufficiently. We examined the eddy current testing that has conventionally been used in flaw inspection in materials and in the measurement of gaps between two materials as a method for measuring this gap.

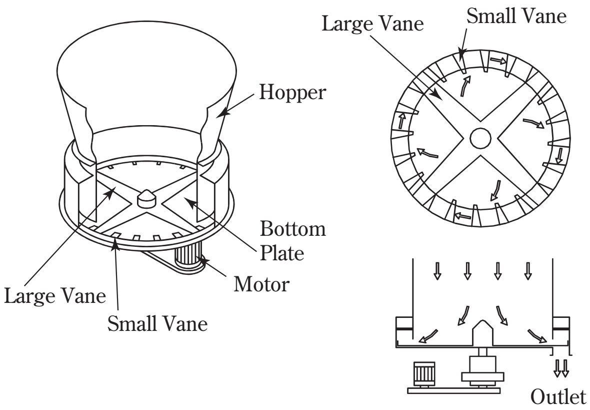


Fig. 9 Schematic Illustration of Table Feeder

(2) Eddy Current Testing

1) Principles and Types of Eddy Current Testing

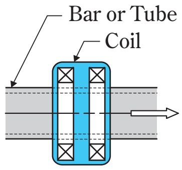
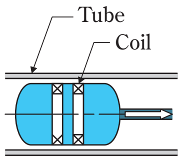
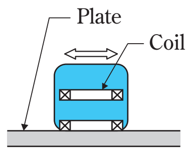
If alternating current flows through a coil, magnetic flux is generated, and if this coil is brought into proximity with a conductor, an eddy current is induced. If there is a defect or a part where the material characteristics (conductivity, magnetic permeability) change, the magnetic flux changes, and the current flowing in the eddy current coil changes. Typically, inspections such as the detection of defects are carried out using this change.

Table 3 gives the types of eddy current coils. Uses of the eddy current coils are divided into three types according the targets of the inspection. Encircling coils are used for inspections during the manufacturing materials for rods and heat transfer tubes by material manufacturers. Inner coils are used for maintenance inspections of heat transfer tubes in heat exchangers installed in chemical plants, power plants, nuclear power plants and the like, and surface coils are used for maintenance inspections of the wall surfaces in the tower tanks, heat exchangers tubes and the like in these plants.

2) Eddy Current Coil Signal Output

As is shown in **Fig. 10**, a Wheatstone bridge circuit is incorporated into commercial eddy current testers. Each of the impedances Z_1 and Z_2 (AC resistance) from the eddy current coils in a differential system is set so as to be in equilibrium with the characteristic resistances ZM_1 and ZM_2 of the eddy current tester . If the inner coil moves along the axis of the tube in this state, the eddy current is disturbed if there is a defect or the like, and the change in the impedance is displayed as a resurge waveform on the tester as shown in Fig. 10 (1) – (5).

Table 3 Type of Eddy Current Coils

Encircling Coil	Inner Coil	Surface Coil
 Bar or Tube, Coil	 Tube, Coil	 Plate, Coil
For use of production inspection at material supplier	For use of equipment maintenance and inspection	For use of equipment maintenance and inspection

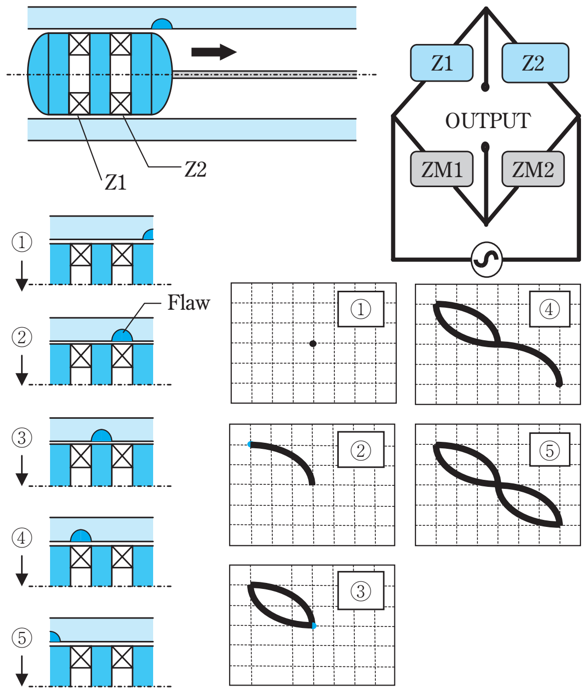


Fig. 10 Eddy Current Inpedance Plane Signals from Differential Coil

(3) Surface Coil for Gap Measurement and Application in Actual Plant

1) Surface Coil for Nonmagnetic Materials and Application in Actual Plant

The bottom plate of the table feeder is made of 9mm thick SUS316, and on the other side are SUS304 large vanes and small vanes with a gap of 5mm or more that have to be detected. Therefore, we made prototype 50mm and 90mm surface coils and compared the detection sensitivities.

As is shown in **Fig. 11**, the surface coil made as a prototype was positioned underneath a SUS316 simulated bottom plate with a thickness of 9mm. To create a gap above that simulated bottom plate, an acrylic plate with a varied thickness and further a trapezoidal shaped SUS304 simulated small vane were placed on top of the plate. The center of the surface coil was adjusted so as to pass through the position of the 50mm width of the simulated small vane and the variations in voltage were measured. **Fig. 12** shows the test results. The output voltage was greater with the coil with the larger diameter, and the detection signal with a gap of 5mm was 2.2 V. It was 1.5 V with a gap of 10mm. From the fact that the simulated small vane was sufficiently detected using the sample to the actual equipment, we decided to use the 90mm surface coil, which had the larger detection sensitivity.[5)]

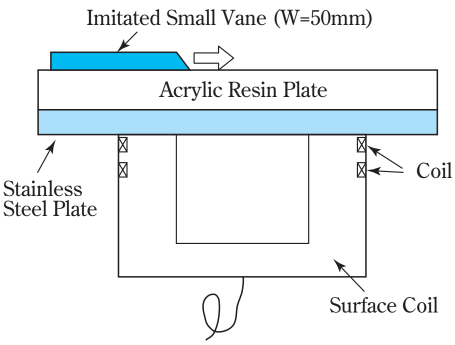


Fig. 11 Test Configuration of Imitated Small Vane and Surface Coil Without Permanent Magnet

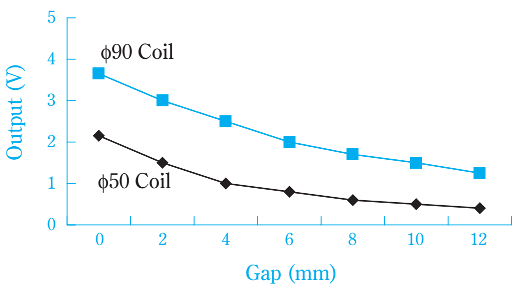


Fig. 12 Relation of Output Signal with Gap between Bottom Plate and Small Vane

2) Surface Coil for Ferromagnetic Material

With a table feeder made of carbon steel, it is necessary for the carbon steel of the bottom plate to be magnetized and the magnetic permeability must be close to 1. It is possible to use an electromagnet to magnetize a carbon steel bottom plate with a thickness of approximately 10mm. However, in consideration of the space on site, we used a magnetization system that uses a rare earth magnet, and we examined an arrangement with a magnet having approximately the same dimensions (90mm outside diameter × 40mm high) as the surface coil for nonmagnetic materials for confirming the magnetization thickness for the carbon steel plate.

To attach the ring-shaped rare earth magnet on outside of the coil, the outside coil diameter was set at 70mm, and a column shaped rare earth magnet was also inserted inside of the coil. A magnetic circuit was formed between these magnets inside and outside of the coil.

The center of the surface coil was set so that a 100mm portion of a carbon steel imitated large vane passed through, and the voltage variations were measured. As a result, the detection voltage with a gap of 5mm and with a carbon steel plate having a thickness of 5mm was 1.5 V, and it was 1 V with a gap of 10mm. A detection sensitivity that presents no practical problems was obtained.

When the rare earth magnets fabricated this time are placed in contact each other, there is an attractive force arised and handling is difficult with human strength. When the table feeder bottom plate is thicker than 5mm, it is necessary for the installation location to be made thinner with hole gouging, or the surface coil dimensions made larger to use the electromagnet system.

2. Development of Inspection Techniques for Reactor Tubes under Baffles in Carbon Steel Reactors

(1) Parts Where Inspection Is not applicable with Eddy Current Testing

In inspections of the reactor tubes and heat exchanger tubes (“tubes” in the following) in carbon steel reactors up to now, magnetic saturation eddy current testing and remote field eddy current testing were used as inspection methods where the inspection speed was fast, but the inspection accuracy was not as good as ultrasonic testing and radiographic testing. With these inspection methods, inspection of tube parts underneath the baffle was impossible. Therefore, inspections have recently often been done by ultrasonic water immersion testing, which can carry out inspections under baffle plates, but is faster than previous methods. Even though this ultrasonic immersion testing is faster than previous one, the inspection speed is still slower than eddy current testing (50 – 100 tubes per day), and inspecting all tubes is impossible. Therefore, the maximum reduction in thickness that may be present in the tubes is often estimated, by extreme value statistics used.

As was described earlier, in vertical multi-tube reactors that handle heat transfer salt, abnormal temperature increases arise in the tubes below the baffle plate and tube sheat and in their neighborhood if air gets mixed in, and there is a fear that corrosion will arise on the outside surfaces of the tubes. In addition, even in vertical and horizontal heat exchangers where water passes over the outside surfaces of the tubes, it is easy for sludge to be piled up collect in places under the baffle plate, and local corrosion often occurs. Because of this, we are under development of a combined probe capable of inspecting parts underneath baffle plates is under development as a rough testing method for inspecting as many tubes as possible within the limited inspection time.

(2) Combined Probe under Development

The combined probe, with an eddy current coil and a Hall element is shown in **Fig. 13**. The eddy current coil is one with the coil wound around a rare earth magnet bobbin, and the Hall element (gallium-arsenic Hall element with an active area of 70 × 70μm) is attached to the outside surface of this bobbin. If current flows in this Hall element as shown in **Fig. 14** and it is placed in a magnetic field, an output voltage that is in proportion to the intensity of the magnetic flux is obtained.

Since the wall thickness of heat transfer tubes is most often around 2mm, we found the magnetizing force capable of detecting flaws arising on the inside and outside surfaces of heat transfer tubes with a thickness of around 2mm and also capable of detecting baffle plates by experiments. As a result, a magnetic flux density of as much as 0.7 – 1.4T (the magnetic saturation density of carbon steel being 1.8T) in the tube thickness was necessary. The stronger the magnetizing force is the more the detection for flaws improved, but the contact force of the tube wall increases and is difficult to handle. Conversely, with a weak magnetizing force, handling becomes easier, but the tube outside surface flaw detection capabilities decrease.

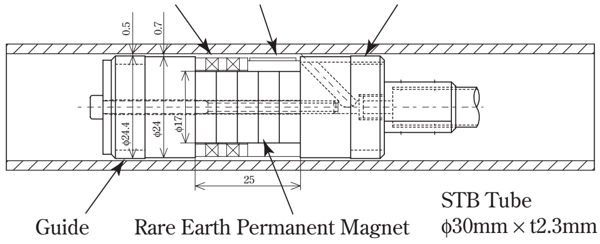


Fig. 13 Component of Eddy Current Coils and Hall Element

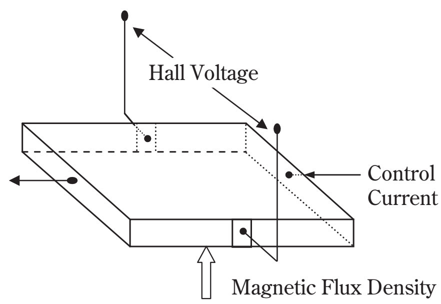


Fig. 14 Voltage generation of Hall Element

(3) Defect Signal Distinction and Study of Application in Actual Plant

1) Eddy Current Coil

Conventionally, the differential method has been used for the inspection of localized corrosion and the standard comparison method has been used for the inspection of general corrosion in maintenance inspections. **Fig. 15** shows the inspection conditions for an artificial defect. When the baffle plate signal, artificial defect signal and the signal (phase) from the artificial defect under the baffle plate are compared visually, the baffle plate and defect cannot be distinguished. A detailed explanation is given below.

The signal from the baffle plate using the differential method is shown in Fig. 15 (1). This signal looks similar to the signal from the 0.5mm step groove under the baffle plate as shown in Fig. 15 (3) and the signal from the 5mm diameter × 1.3mm flat bottom hole under the baffle plate shown in Fig. 15 (5), and cannot be distinguished at the site. In addition, with the standard comparison method, the signal from the baffle plate is shown in Fig. 15 (6), but since it is very similar to the signal (phase) from the 5mm diameter, 1.3mm deep flat bottom hole shown in Fig. 15 (10), they also cannot be distinguished at the site.

2) Hall Element

The signal from the baffle plate with the Hall element is shown **Fig. 16** (1), but it is a positive peak signal. The signals for the artificial defects alone and the signals from the artificial defects under the baffle plate are shown in Fig. 16 (2) – (5), and a clear difference in the signals (phases) can be observed.

The signal for both the baffle plate and the artificial defect from the Hall element moves to between the positive phase when the probe moves to thicker side and to the negative phase when it moves to the thinner side, so it is easily understood intuitively. With the step-shaped artificial defect in Fig. 16 (2), the signal becomes positive when the probe is moved to the thicker side that is the opposite side from that in the figure, and it cannot be distinguished from the baffle

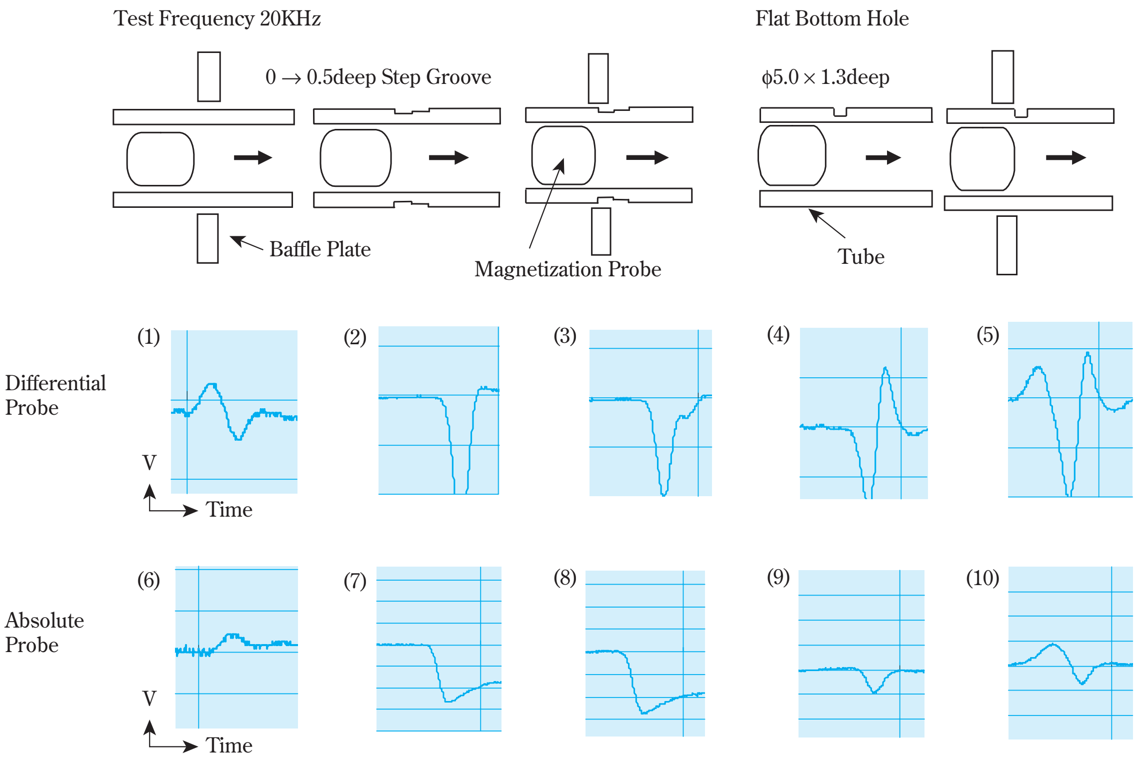


Fig. 15 Artificial Defect Signals of Eddy Current Test with Internal Probe under Magnetic Baffle Plate (STB340 × ϕ30 × t2.3, Density of Magnetic Flux in Tube Wall ; 1.0 Tesla, Carbon Steel Baffle Plate Thickness ; 15.5mm)

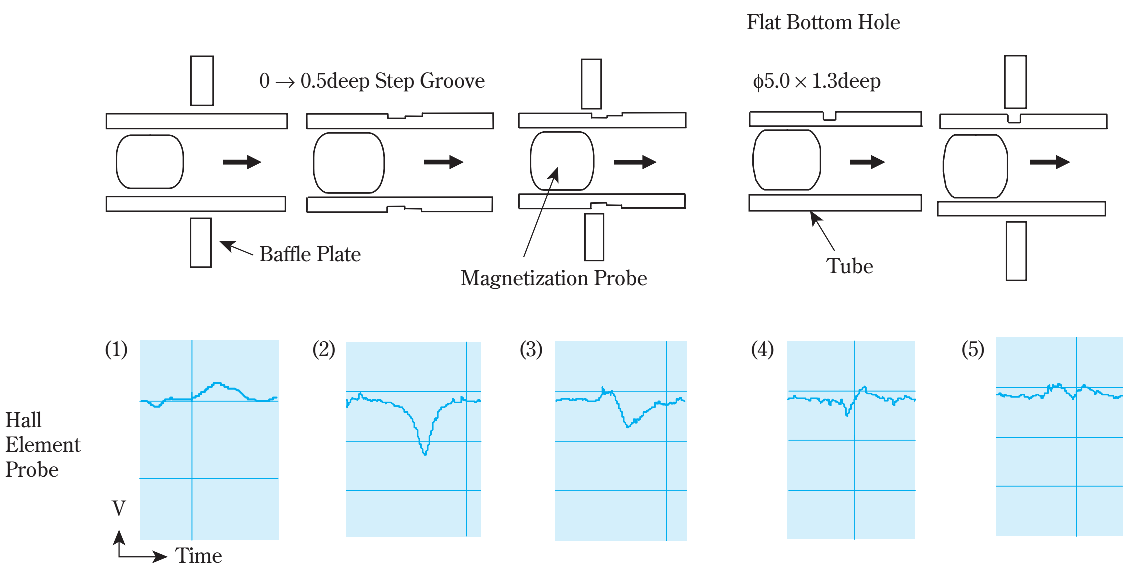


Fig. 16 Artificial Defect Signals of Hall Element with Internal Probe under Magnetic Baffle Plate (STB340 × ϕ30 × t2.3, Density of Magnetic Flux in Tube Wall ; 1.0 Tesla, Carbon Steel Baffle Plate Thickness ; 15.5mm)

signal. However, since the baffle plates are positioned at the same interval, it could be distinguished. It is easy to distinguish the defect signal if it moves to the negative side when the probe is put in from the opposite end in the tube as an assured method.

With only one Hall element, the inspection range in the direction of the tube periphery is limited, so it would be preferable to have inspections with two or three elements or if possible four placed at a 90° pitch. In the near future, we would like to complete this technique for applications at sites.

Ball Bearing Wear and Diagnostic Method Application

To achieve safe and continuous operation of dynamic equipment among the pieces of equipment that constitute chemical plants over long periods of time not only maintains stable operation of the plant, but also improves quality and reduces the cost of products. In addition, this is an important task for the communication with the local residents as a safe plant. Therefore, along with confirming early detection methods for damage to ball bearings, which are seen frequently in small rotating equipment, we confirmed the effectiveness of the ultrasonic method as a new diagnostic method.

1. Progress of Wear in Ball Bearings and Diagnostic Method

Conventionally, temperature measurements, vibration techniques (speed, acceleration), shock pulses and the AE technique have been used as methods for diagnosing damage to ball bearings. Adding an ultrasonic method to these, we made a new bearing life tester and carried out verification of operation. **Fig. 17** shows the conditions for the verification test equipment and the peripheral equipment.[7)]

The time stage that can be detected by these various diagnostic methods when abnormal wear arises are shown in **Fig. 18**. The vibration (acceleration) technique and shock pulse method are widely used methods which have standards for determining bearing damage, but they cannot detect damage until the last stages of bearing damage. However, the newly added ultrasonic technique[8), 9)] has been confirmed to be a diagnostic method capable of detecting abnormal wear in its initial stages. The AE technique has an earlier bearing wear damage detection period than the vibration (acceleration) technique, but it can be used when the noise from the bearings and other sources can be reduced, and there are many practical problems .

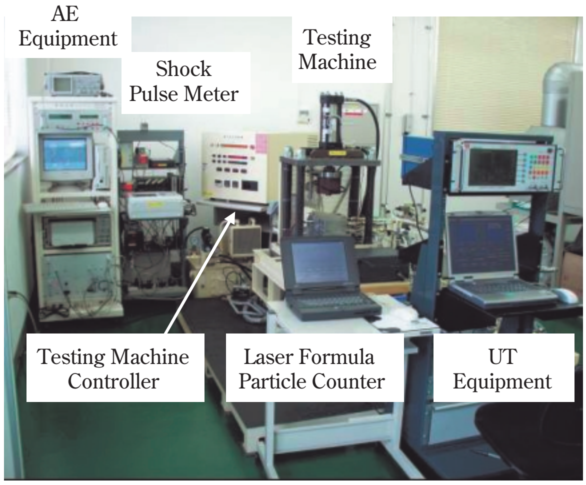


Fig. 17 Panoramic View of Testing Machine and Life Measurement System of Ball Bearing

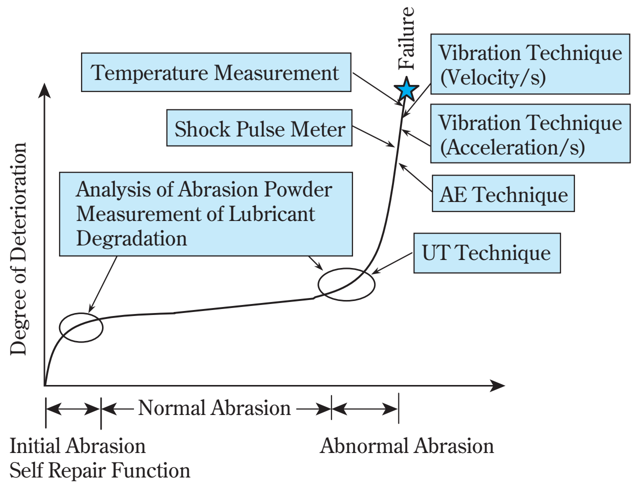


Fig. 18 Wear Progression and Diagnosis Method for Ball Bearing and Detection Availability Stage of each Method

2. Development of Diagnostic Technique Using Ultrasonic Method

Fig. 19 shows a schematic structure of the apparatus used in the tests, and the damage to the bearings (single-line deep groove ball bearings 6210) was examined by making a lateral ultrasonic wave incident to the surface between the housing and the outer ring using a 5 MHz ultrasonic lateral wave probe attached to the periphery of the housing. Part of the sound wave that is made incident passes through according to the surface conditions for solid contact mainly in the illuminated area, and the remainder is reflected.

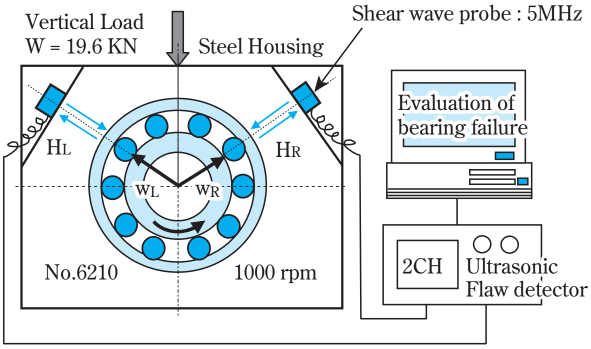


Fig. 19 Outline of Experiment Apparatus

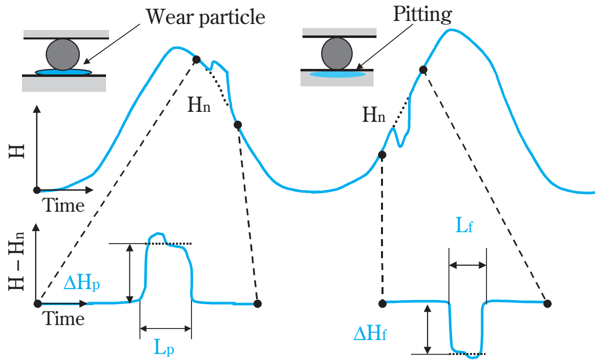


Fig. 20 Schematic Diagram of Echo Height Variation

Furthermore, a reflected echo proportional to the sound pressure received is observed on the tester screen. In this measurement method, evaluations are carried out using the echo height ratio $H = [(1 - h/h_0) \times 100]$ defined by the ratio of the echo height h (position of the moving body in Fig. 19) from the surface where the housing and outside ring meet when a rolling element directly under the probe moves, the echo height h_0 when the probe is positioned in the middle of two adjacent rolling elements.

Now, we will consider the case where the rolling element moves directly under the probe. At this time, stress on the surfaces that meet increases, and since the stress of the surface area with solid contact increases, the height of the echo decreases from h_0 to h. Furthermore, because of the changes in stress accompanying the movement of the rolling element, the echo height increases and decreases, and when bearings without damage are operating with good lubrication conditions, it repeatedly varies in something close to a sine wave pattern.

On the other hand, if eroded dust that has been come out is mixed in or the rolling element passes through a damaged area with pitching or the like, the load on the rolling element temporarily increases or decreases. As a result, a local disturbance arises in the echo waveform as in the pattern diagrams in **Fig. 20** (vertical axis being the echo height ratio H, so the position of the rolling element in Fig. 19 is the peak of the variation of the sine wave shape), and it is possible to evaluate the condition of the lubricant including bearing deterioration.[8, 9] The length of the damage from flaking that arose in the inner ring detected by estimating from the passage of time for dent shown in Fig. 20 is 0.9mm.[7] At this point in time, no abnormal shape is detected by the other diagnostic methods. Furthermore, using the analytical software we created as a prototype, there was low-speed rotation (500 rpm), but it was possible to detect a Vickers impression with a 0.5mm width.[10]

This ultrasonic method has the merit of being able to detect damage to ball bearings from the early stages, but the places it can be applied are limited to vibration dryers and places where the housing and bearings have a tight fit. In the future, it would be desirable to have designs where direct ultrasonic probes could come into direct contact with the outer ring for the purpose of earlier diagnosis of bearings in dynamic equipment.

Summary

The ultrasonic time of flight diffraction (TOFD) technique was used to measure the depth of stress corrosion cracks with a branched shape that arise in carbon steel with a thickness of 8 – 9mm and SUS304 stainless steel. As a result, it was confirmed that an accuracy of ±0.2mm for carbon steel and ±0.4mm for SUS304 stainless steel was confirmed. Therefore it is applied to on-site equipment integrity evaluations. In high temperature ultrasonic testing, TOFD testing was applicable for both compression wave and shear wave inspection up to 350°C using an air cooled wedge and a normal temperature type probe. Using this high temperature ultrasonic testing technique, a technique for quantifying the amount of air mixed into heat transfer salt around 300°C was established using a technique for ultrasonic transmission from the outside of the tubes, and has already been applied on-site.

By measuring and monitoring the gap between the rotating vanes and the bottom plate of a table feeder, it became possible to prevent the mixing in of surplus foreign matter due to contact between the two. Thus, since the gap between a nonmagnetic material

(SUS304 or the like) and a strongly magnetic material (carbon steel or the like) of the rotating fins and bottom plate was measured using a surface coil for the eddy current technique, we studied coil design, and carried out on-site applications. Reactor tube (heat transfer tubes) parts that are under baffles in carbon steel reactors have areas that cannot be inspected by magnetic saturation eddy current testing and remote field eddy current testing, but it was possible to distinguish defects by combining a magnetized eddy current coil and a Hall element. At present, we are studying to apply on-site applications.

To establish a diagnostic technique that can make early detection of ball bearing damage, we made a bearing life tester and verified its effectiveness. As a result, among the diagnostic methods carried out from the outside surface of the bearing, the ultrasound technique gave the earliest detection, and the order was the AE technique, shock pulses and vibration technique after that. The new ultrasonic inspection technique made wear particle analysis and diagnosis of lubricant deterioration possible at about the same early stage, but applications are limited to vibration dryers and the like and bearings where the housing and bearings are joined tightly. In the future, and it would be ideal to make a design such that an ultrasonic probe could directly come into contact with the outer ring of bearings for early diagnosis.

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