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Steam Generator Tubing Inspection

Development of an Eddy Current Probe for Detecting Outside Circumferential Cracks near an Expansion of Heat Exchanger Tubes

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ABSTRACT

Eddy current testing (ECT) is a conventional inspection method of heat exchanger tubes. Many types of probes have been developed depending on such tube conditions as tube shapes and materials. However, the vicinity of a tube expansion is still a difficult area to inspect. This is because there is a step-shape variation circumferentially on the inside surface and there is a ferromagnetic tube sheet around the outside surface so that large noise is observed. A high signal to noise ratio (S/N) is required to inspect the area because fatigue cracks can occur near the tube expansion.

In this study, we chose test pieces having an outside circumferential notch with a depth of 20% tube thickness (20%t) and set the target of the detection performance at S/N= 3. In order to realize this target, we utilized the difference of eddy current flows at a local notch and a tube expansion, and devised a new arrangement for exciting and pick-up coils. In our arrangement, the pick-up coil having a winding direction along the circumference is placed at the center of two exciting coils. The exciting coils induce an eddy current flow in the axial direction at the center and the pick-up coil can detect only a circumferential component. By using this probe, large noise having an axial component is suppressed and only a notch signal having a circumferential component can be detected.

In order to confirm the probe performance, we compared it with a general bobbin type probe. In the sensitivity evaluation for an outside circumferential notch with 20%t, the signal amplitude was improved 5.7 times. In the noise evaluation test using a test piece with tube expansion, the noise amplitude was decreased 1/8 times. We could successfully detect the outside circumferential notch (20%t) near a tube expansion at S/N=3.5, verifying the detection performance.

INTRODUCTION

Heat exchangers are widely used in power plant systems. In the heat exchangers, hundreds of tubes are regularly arranged to keep effective heat transfer between circulating water flows. However, tube conditions such as surface morphology can vary depending on the environment of use. Therefore, regular inspection of heat exchangers is needed.

Eddy current testing (ECT) is well known inspection technique for heat exchanger tubes. In ECT, a conventional bobbin probe arranged with an exciting coil and a pick-up coil is inserted into a tube at one end by using an air gun and then a winder pulls the probe through the tube at a speed of about 1m/s by winding up an attached cable[1]. Signals from the probe are acquired during the scan and inspectors check the signal waveform. Even though the ECT has been successfully applied to straight or U-shape areas of tubes, the vicinity of a tube expansion is still a difficult area to inspect. This is because there is a step deformation circumferentially on the inside surface and there is a ferromagnetic tube sheet around the outside surface which results in large noise being observed. However, fatigue cracks can occur and extend circumferentially from the outside surface near the tube expansion. Therefore, a new probe making it possible to detect outside circumferential cracks near the tube expansion is required.

In order to solve this problem, we utilized the difference of eddy current flows at a local crack and a tube expansion, and devised a new arrangement for exciting and pick-up coils. In this study, we chose test pieces having an outside circumferential notch with a depth of 20% tube thickness (20%t), and set the target of the detection performance at S/N= 3.

INSPECTION METHOD NEAR A TUBE EXPANSION

Figure 1 shows a cross section of an inspection object. The tube sheet, made of a ferromagnetic material, has a through hole with a diameter of □16.1mm. The tube is made of a non-ferromagnetic material (SUS316) and has an outer diameter of □15.9mm and a nominal tube thickness of 2.3mm. The tube is inserted into the through hole and mechanically expanded from the inside surface so that it sticks at the sidewall of the through hole. Therefore, at the tube expansion, there is the circumferential step deformation appears on the inside surface.

Detailed of principle of ECT have been published[2,3]. Here, we describe the detection properties of a bobbin probe (Figure 2). In the bobbin probe, an exciting coil and a pick-up coil are arranged with the coil axis parallel to the axial direction of the tube. Here, the coil axis is defined as the centerline of the winding axis of the coil. When AC voltage is supplied to the exciting coil, an electric field E is induced along the circumferential direction of the tube.

$$\nabla \times E = -\frac{dB}{dt} \tag{1}$$

Here, B is the induced flux density. An eddy current J is also generated along the electric field E in the tube having a conductivity of □.

$$J = \sigma E \tag{2}$$

The pick-up coil placed in the neighborhood of the exciting coil detects the magnetic flux and then produces an induction voltage V according to the amount of flux linkage □and the number of turns N.

$$V = -N\frac{d\Phi}{dt} \tag{3}$$

Equation (3) can be expressed using equations (1) and (2) and Green’s theorem.

$$\begin{aligned} V &= -N\frac{d\Phi}{dt} = -N\frac{d}{dt}\left(\int_S B \cdot dS\right) = N \cdot \int_S \left(-\frac{dB}{dt}\right) dS = N \cdot \int_S (\nabla \times E) dS \\ &= N\left(\oint E \cdot dl\right) = \frac{N}{\sigma}\left(\oint J \cdot dl\right) \end{aligned} \qquad (3)’$$

Here, dS and dl are the differential cross section and the line segment of the pick-up coil, respectively. Equation (3)’ shows that the induction voltage depends only on the eddy current component parallel to the line segment of the pick-up coil and the vertical component does not contribute to it.

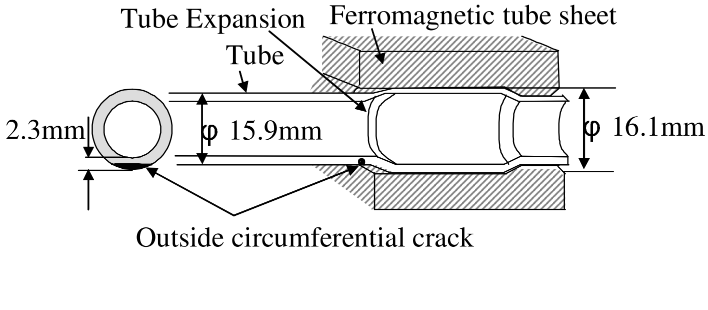


Fig.1 - Schematic cross section of inspection object

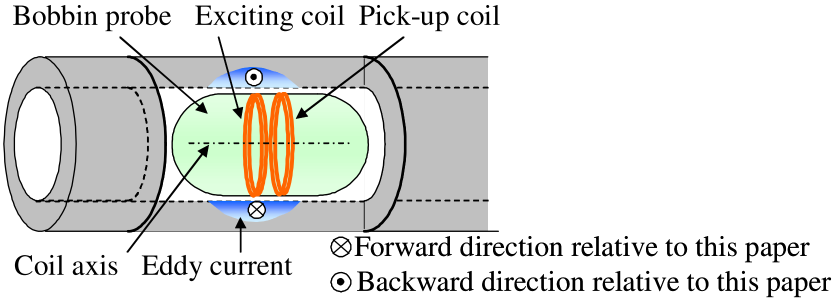
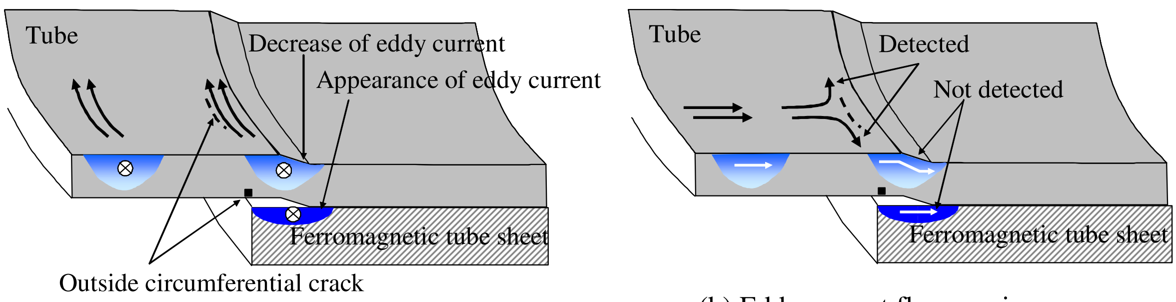


Fig.2 - Coil arrangement and eddy current flows of a bobbin probe

Figure 3(a) shows eddy current flows near the tube expansion when a bobbin probe is used. Arrows shown on the surface denote the eddy current flows. As described in the previous section, the eddy current produced by a bobbin probe has a circumferential flow and only the circumferential component is detected. Therefore, all variations in the eddy current profile are detected including the decrease of eddy current at the step deformation and the appearance of eddy current in the ferromagnetic tube sheet. Because the position of the outside circumferential crack is assumed to be close to that of the tube expansion, the signal cannot be seen in the waveform overlapping the noise components.

For this problem, we proposed to induce an eddy current flow in the axial direction of the tube and to detect only the circumferential component. Figure 3(b) shows the eddy current flows. From viewpoint of this proposal, the axial components formed at the step deformation and in the ferromagnetic tube sheet cannot be detected. On the other hand, the circumferential component passing around the crack can be detected.

In order to realize this idea, we devised a new arrangement for exciting and pick-up coils as shown in figure 4. In our arrangement, the pick-up coil having a coil axis parallel to the axial direction of the tube is placed at the center of two exciting coils. The exciting coils can induce an eddy current flow in the axial direction at the center and the eddy current has a relatively high density even at deeper positions[4]. The pick-up coil detects only the circumferential component. By using this probe, large noise having an axial component is suppressed and only a crack signal having the circumferential component is detected.



(a) Eddy current flows: circumference
Detection direction: circumference

(b) Eddy current flows: axis
Detection direction: circumference

Fig. 3 - Schematic views of eddy current flows around an outside circumferential crack near a tube expansion

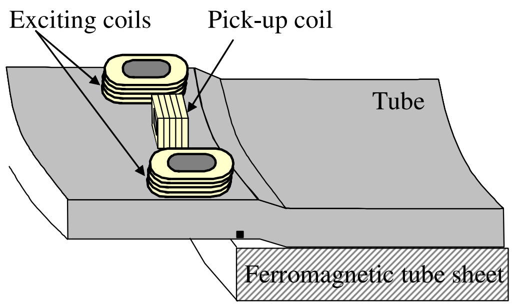


Fig. 4 - Schematic view of a coil arrangement for realizing the eddy current flows and detection direction shown in Fig.3(b)

EXPERIMENTAL SETUP AND MEASUREMENT CONDITION

Figure 5 shows the structure of the new test probe. The probe length is 100mm and the diameter is □10mm. Exciting and pick-up coils are placed along the circumference at intervals of 45 degrees. Each of exciting coils is formed into a track shape using an enamel wire (diameter, □0.04mm). The length, the width and the height are 6mm, 2mm and 2mm, respectively. The pick-up coil has a cubic shape with each length of 2mm. The number of turns is 400. Ferrite cores are inserted for the exciting and pick-up coils.

A bobbin probe is used for comparison of detection performance. One exciting coil and a pick-up coil (diameter of both, □10mm) are arranged at an interval of 5mm and the number of turns is 121 for the bobbin probe arrangement.

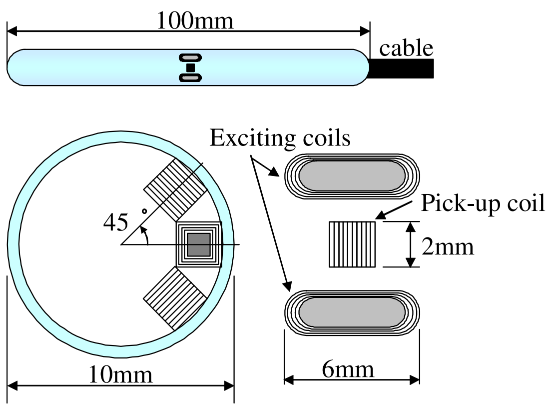
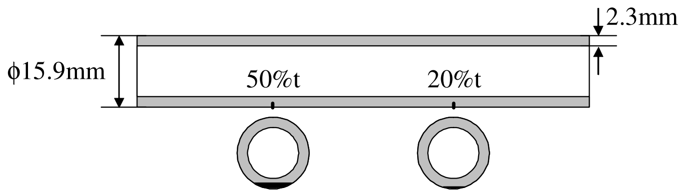
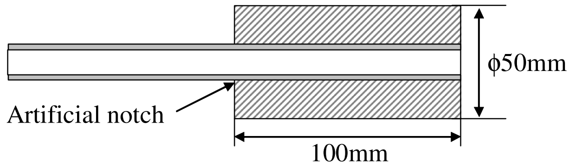


Fig. 5 - Structure of the new test probe

Figure 6 shows the sample test pieces without a tube expansion (a) and with a tube expansion (b). In Fig.6(a), the outside diameter of the tube is □15.9mm and the nominal tube thickness is 2.3mm. Artificial notches of 50%t and 20%t are mechanically processed on the outside surface. In Fig.6(b), a ferromagnetic ring having an outer diameter of □50mm is used as a substitute for the ferromagnetic tube sheet. An artificial notch is made for each test piece and then the process of tube expansion is carried out.



(a) Test piece without a tube expansion



(b) Test piece with a tube expansion

Fig. 6 - Sample test pieces

In the experiments, the test probe is scanned by pulling the attached cable. The scan speed is 30mm/s and the scan length is 300mm. Eddy Station MWII (ACTUNI, Inc.) is used for data acquisition and parameter setting. The signal gain is fixed at 50dB. The phase shift values are set at each frequency as liftoff noise appears in the X-component of a Lissajous graph. Figure 7 shows an example Lissajous waveform in the case of a tube expansion. The angle □ varies depending on the depth of the signal source and the penetration depth. For example, the noise from the step deformation surely appeared in the X-component because it is a surface component similar to the liftoff noise. On the other hand, the signal from the outside circumferential crack and the noise from the ferromagnetic tube sheet originate from distant positions and both X-component and Y-component are included. Because the surface noise is large in principle, high S/N cannot be obtained from the X-component. Therefore, the Y-component is used to evaluate S/N in the experiments.

In the Y-component, the signal from the outside circumferential crack and the noise from the ferromagnetic tube sheet appear, but the waveforms are different as shown in Figure 8. This is because the ferromagnetic tube sheet is at a more distant position from the probe and larger than the outside circumferential crack in size so that the waveform becomes broader. To improve S/N by utilizing the difference between the signal and the noise waveforms, the amplitudes of the signal and the reversed signal having a shift length L are simply added in the offline calculation. According to the shift length L, the signals are overlapped and the noise is suppressed. The optimum shift length L is determined from measurement results because it depends on exciting frequency f.

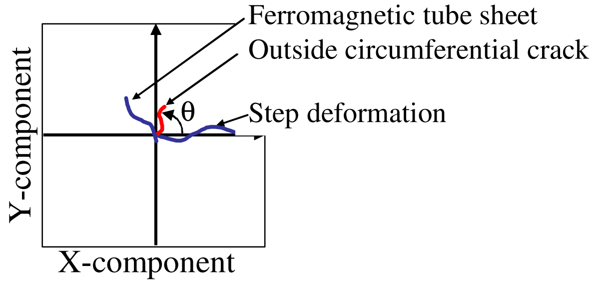


Fig. 7 - Example Lissajous waveform in the case of a tube expansion

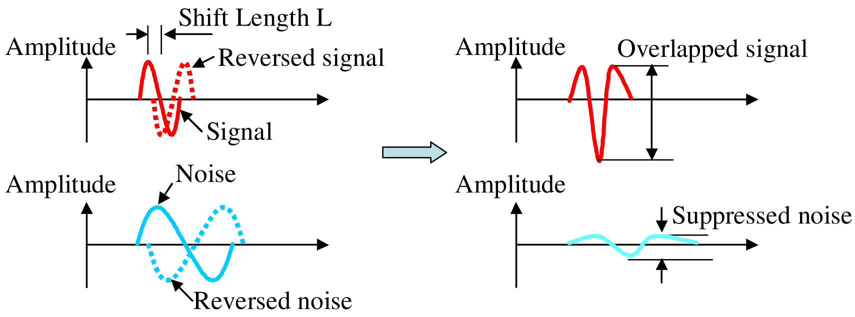
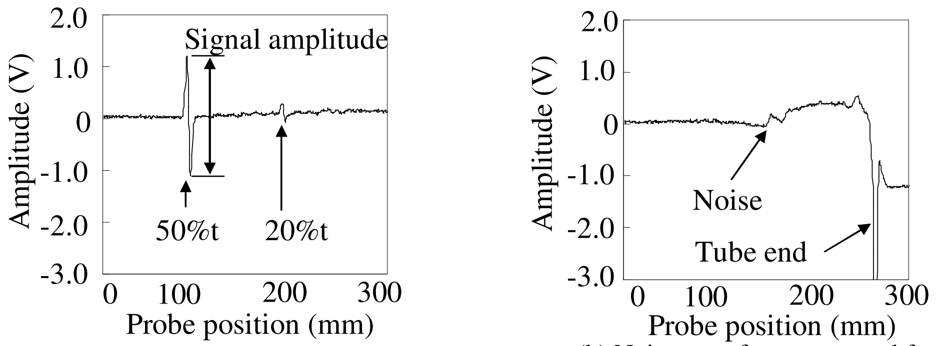


Fig.8 - S/N improvement utilizing the difference between signal and noise waveforms

EXPERIMENTAL RESULTS

Figure 9 shows the waveforms measured at a frequency of 50 kHz. The horizontal axis is the probe position and the vertical axis is the amplitude. In Fig. 9(a), the signals from 50%t and 20%t notches are observed at 100mm and 200mm. In Fig. 9(b), the noise from the ferromagnetic tube sheet is appreciably suppressed, but it can be seen at 170mm. As mentioned in the previous section, the waveform difference between the signal and the noise can be confirmed. To optimize the conditions of the frequency f and the shift length L, S/N was evaluated from the measurement results. In the evaluation, the values from peak to peak of the amplitude are used.



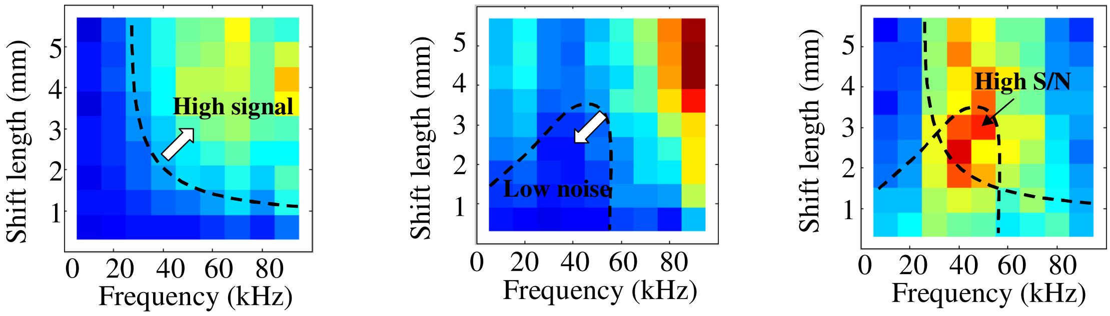
(a) Signal waveform measured for notches with 50%t and 20%t.

(b) Noise waveform measured for a expansion without a notch.

Fig. 9 - Sample signal and noise waveforms measured at a frequency of 50kHz

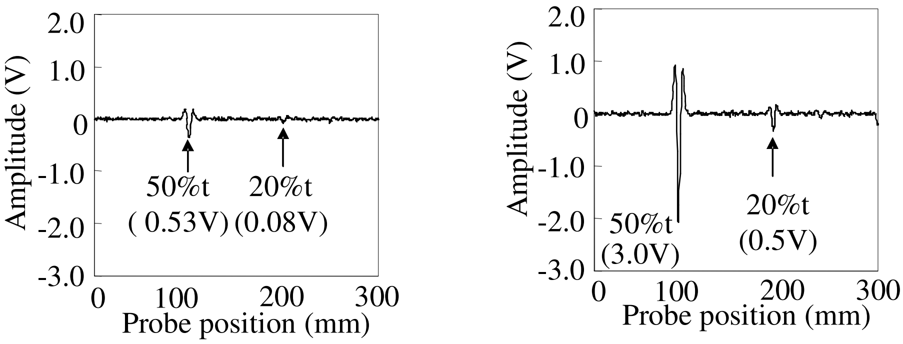
Figure 10 shows the color maps of the signal amplitude of the 20%t notch, the noise amplitude and the S/N of the 20%t notch. The horizontal axis is the frequency f from 10kHz to 90kHz with a step of 10kHz and the vertical axis is the shift length L from 0.6mm to 5.4mm with a step of 0.6mm. In Fig.10s(a) and (b), the signal amplitude and the noise amplitude show a tendency to increase as the frequency f and the shift length L increase. The reasons are that the sensitivity of the test probe itself becomes high in the high frequency area, and the signal and the reversed signal match better in the area having large shift length. Consequently, high S/N area appears at the center as shown in Fig.10(c). From these results, the frequency f and the shift length L are determined to be f=50kHz and L=3.0mm.

In order to confirm the performance of the new probe, we compare it with the bobbin probe. Figures 11 and 12 show the measurement results obtained at f=50kHz and L=3.0mm. In the sensitivity evaluation for outside circumferential notches with 50%t and 20%t, both signal amplitudes are improved 5.7 times. In the noise evaluation test using a test piece with tube expansion, the noise amplitude is decreased 1/8 times. The S/N is improved 46 times by using the new probe.



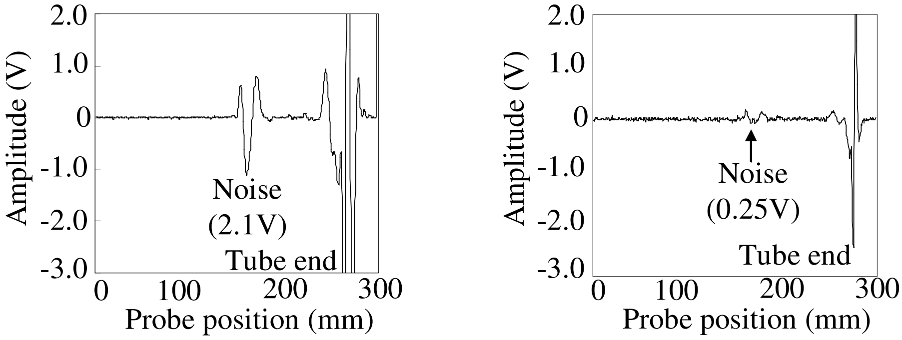
(a) Signal amplitude (b) Noise amplitude (c) S/N

Fig.10 - Color maps of signal amplitude, noise amplitude and S/N for a 20%t notch



(a) Bobbin probe (b) New test probe

Fig.11 - Sensitivity comparison between a bobbin probe and the new test probe



(a) Bobbin probe (b) New test probe

Fig.12 - Comparison of noise amplitude between a bobbin probe and the new test probe

Figure 13 shows the measurement results for the outside circumferential notches of 50%t and 20%t with a tube expansion. The signals from both notches are clearly measured and the amplitudes are 4.8V for 50%t and 0.7V for 20%t. Consequently, we can successfully detect the outside circumferential notches with 50%t and 20%t near a tube expansion at S/N=16 and S/N=3.5, verifying the detection performance of the new test probe.

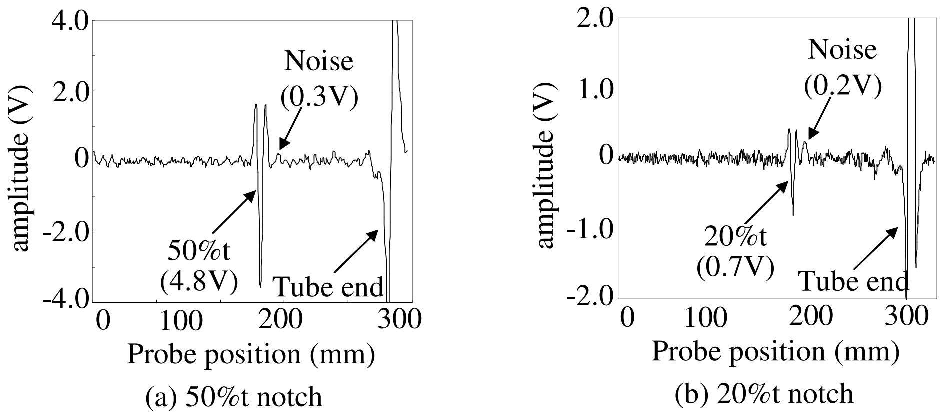


Fig.13 - Measurement results of 50%t and 20%t notches near a tube expansion

CONCLUSION

In this study, we chose test pieces having an outside circumferential notch with 20%t and set the target of the detection performance at S/N= 3. In order to realize this target, we utilized the difference of eddy current flows at a local notch and a tube expansion, and devised a new arrangement for exciting and pick-up coils. In our arrangement, the pick-up coil having a winding direction along the circumference was placed at the center of two exciting coils. The exciting coils induced eddy current flows in the axial direction at the center and the pick-up coil could detect just the circumferential component. By using this probe, large noise having an axial component was suppressed and only a notch signal having a circumferential component was detected.

In order to confirm the probe performance, we compared it with a general bobbin type probe. In the sensitivity evaluation for an outside circumferential notch with 20%t, the signal amplitude was improved 5.7 times. In the noise evaluation test using a test piece with tube expansion, the noise amplitude was decreased 1/8 times. We could successfully detect the outside circumferential notch of 20%t near a tube expansion at S/N=3.5, verifying the detection performance of the new test probe.

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