

Developments of Flat ∞ Coil for Defect Searching in the Curved Surfaces

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ABSTRACT

Previously we have succeeded in developing a new ECT sensor called ∞ coil. This new ECT sensor is a relatively high sensibility and has the high liftoff characteristics compared with that of conventional ECT sensor.

However, the ∞ coil confronts to a serious difficulty to apply the curved surface specimens. To overcome this difficulty, this paper has worked out a flat ∞ coil. This flat ∞ coil exhibits a high sensitivity not only to the curved surface but also to the flat surface specimens because of its highly shape flexibility to fit the curved target surface and widely spreader-able exciting coils.

Intensive numerical simulations employing 3D FEM have been carried to show the usefulness of the flat ∞ coil. The experimented results have verified the validity of the numerical simulations. Thus, we have confirmed the versatile capabilities of the flat ∞ coil.

KEYWORDS

Eddy current, Non-destructive Testing, Flat ∞ coil, curved surface

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1. Introduction

Modern engineering products such as air plane, automobile electric power plant and so on are essentially composed of metallic materials for forming the shape of product, suspending the mechanical stress and constructing the structural frames.

In particular, the mass transportation vehicles carrying a large number of people and various factories e.g. electric power plant and chemical plant are required the ultimately high safety as well as reliability.

To keep the high safety and high quality of their products, the non-destructive testing to the metallic materials is one of the most important technologies because most of the structure materials are composed of the metallic materials.

Various non-destructive testing methods, such as eddy current testing (ECT), ultrasonic testing (UT), radiographic testing (RT) and acoustic emission (AE) are currently used to the modern airplane, high-speed train and express high bus maintenance. Among these methods, ECT does not need complex electronic circuits and direct contact to the tested specimens.

To remove the noise caused by ferromagnetic materials and a circumferential step deformation on the inside surface, an eddy current probe with an original coil arrangement driven by a multi-frequency had been proposed and provided the successful results.[1]

Also, numerical and experimental analysis of eddy current testing for a Tube with Cracks had been carried with fruitful results. [2,3]

Operating principle of the separately installed sensing coil type ECT is fundamentally based on that the sensing coil catches the magnetic field intensity variation caused by the detour eddy currents flowing around a defect in the target metallic materials.[4-6]

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To realize this operating principle, three methodologies may be considered. The first detects the variation of entire magnetic fields caused by both exciting and eddy currents. In this case, the sensing coil has to detect only a change of the magnetic fields caused by the detour eddy currents around defects from the entire mixed magnetic fields. The second is that the sensing coil surface is installed in a perpendicular direction to the exciting coil surface. This coil layout suggests that the sensing coil never induce an electromotive force due to the exciting fields because the sensing coils are always directed in a parallel direction to the flow of exciting magnetic fields. Thereby, this type is capable of selectively detecting the magnetic fields caused by the detour eddy currents around a defect. The third one is one of the modifications of the second type, i.e., the sensing coil whose axis is perpendicularly crossing to the flow direction of exciting magnetic fields is installed in the zero exciting magnetic field space between the north and south poles of the two exciting coils. A deterministic difference between the second and third ones is exciting magnetic field intensity in the space where the sensing coil is installed. This difference essentially enhances the capability of catching ability only the magnetic fields caused by the detour eddy currents around a defect.

Our laboratory has succeeded in developing the third type ECT sensor called as “ ∞ coil”. This ∞ coil has the high liftoff characteristics compared with those of another type. [4]

However, the ∞ coil confronts to a serious difficulty to apply the curved surface target specimens. To overcome this difficulty, this paper proposes a flat ∞ coil whose exciting coils have a surprising flexibility to fit the curved surface of the target specimens. As a result, it is revealed that this flat ∞ coil has versatile capability, i.e., the defect searching ability not only the curved target specimens but also flat target specimens.

2. The ∞ coils

2.1. Structure of the ∞ coil

Figure.1 shows a typical conventional ∞ coil which is composed of the two finite length solid solenoid coils and one sensing coil wound around the ferrite bar. According to the shape of the two solenoid coils, we have named this sensor as “ ∞ coil”.



Fig. 1. Structure of the ∞ coil, where circular coils on both side are the exciting coils and the red rectangular boxes are the sensing coils wound around the ferrite bar

Table 1 Various constants used in the 3D simulation

Exciting coil		Sensing coil	
Outer diameter	22.4mm	Outer diameter	1.4×2.4mm
Inner diameter	20mm	Inner diameter	1.0×2.0mm
Length	10mm	Length	6mm
Number of turns	75	Number of turns	100
Input voltage(peak)	1V	Axis core	Mn-Zn/ferrite
Frequency	256kHz		(permeability:3000)

When an alternating current is flowing in series through these two solenoid coils, both coils yield magnetic fields. One becomes a south pole and the other becomes a north pole alternatively. Figure.2 shows an exciting magnetic field intensity distribution computed by the 3D finite elements.

In Fig.2, it is possible to find the zero magnetic field region between the two parallel exciting coils. According to this simulation result, we set a sensing coil wound around the ferrite bar at the bottom of the two exciting coils as shown in Fig.1. Setting the ferrite bar hardly disturbs the exciting magnetic fields because of the weak magnetic field strength location. Thus, the sensor coil wound around a ferrite bar displays an ultimately high sensibility.

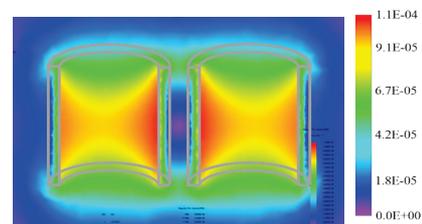


Fig. 2. Magnetic field intensity distribution, where the solid lines denote the parts of exciting coils

2.2. Operating principle of the ∞ coil

The ∞ coil is capable of catching only the magnetic fields caused by the detour eddy currents around a defect. To evaluate the validity of our ∞ coil performance, we have worked out a 3D simulation model as shown in Fig.1. Table 1 lists various constants used in the 3D simulations.

The eddy currents in a plane target specimen (copper plate) located under the two exciting coil surfaces are shown in Fig.3, where the two adjacent exciting coils face to the no-defect, 0 degree, 90 degree and 45 degree line defects as shown in Figs.3(a),3(b),3(c) and 3(d), respectively. Also, Fig.3 shows that the magnetic flux density vector distributions along the axial cross section of the ferrite bar equipped sensor coil are corresponding to that of eddy currents in Figs.3(a),3(b),3(c) and 3(d).

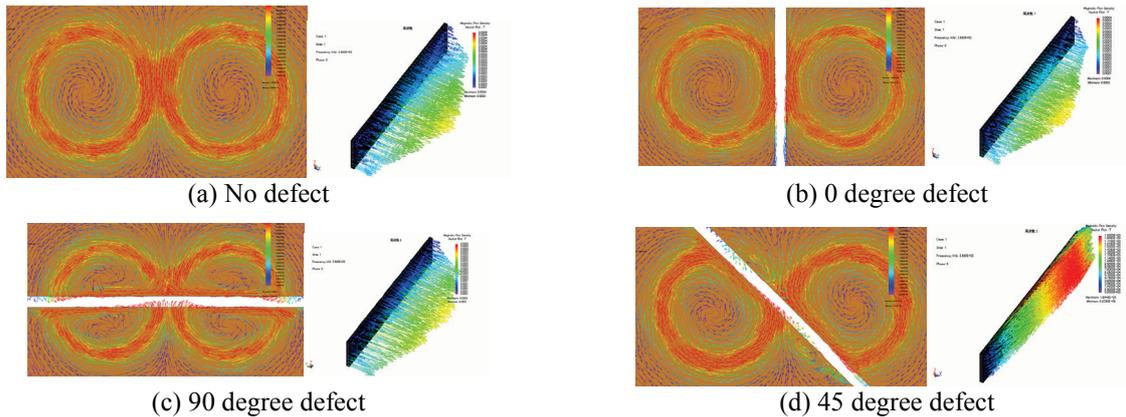


Fig. 3. Eddy currents in a plane copper plate and magnetic flux density vectors in the ferrite bar are shown on the left and right sides in each of the figures (a)-(d), respectively
Color bars in each figures reveals that the uppers and lowers are large and small in values, respectively

Observing the magnetic flux density vector distributions in Fig.3 reveals that the sensing coil wound around the ferrite bar could not induce the electromotive force in the cases of Figs. 3(a), (b) and (c) but induces the electromotive force in the case of Fig.3(d). The induced voltages in the sensor coil under the conditions in Figs. 3 or 3(a)-(d) are shown in Fig.4, whose result reveals that the case (d) yields the highest sensor output voltage.

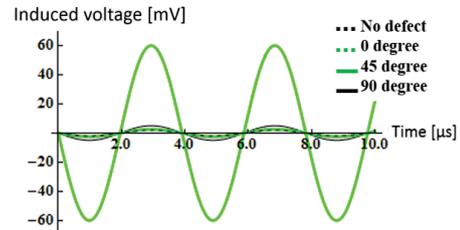


Fig. 4. Induced voltages in the sensing coil

3. The ∞ coil composed of flat and flexible exciting coils

Because of the solid shape of the two solenoid coils, the conventional solid type ∞ coil confronts to a serious difficulty to apply the curved surface target specimens.

To overcome this difficulty, we propose the flat ∞ coil whose exciting coil shape is possible to fit any of the curved surface target specimens. Figure.5 shows a typical shape of the flat ∞ coil.

Figure.6 shows an exciting magnetic field intensity distribution of the flat ∞ coil computed by the 3D finite elements. In Fig.6, it is also possible to find the nearly zero magnetic field strength location between the two parallel flat exciting coils.



Fig. 5. Both of the left and right circular planes are the ∞ coil with flat flexible exciting coils, respectively

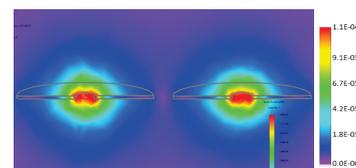


Fig. 6. An example of magnetic field intensity distribution by the flat ∞ coil shown in figure 1

Figures.7(a) and 7(b) show the eddy current distributions caused by the conventional solid and flat ∞ coils, respectively. Observe the results in Fig. 7 suggests that the eddy currents caused by the flat ∞ coil distribute to wider regions compared with those of the conventional solid ∞ coil. This reveals that the flat ∞ coil has larger searching area.

In addition, the eddy current density of the flat ∞ coil takes higher in magnitude than those of the conventional one because the highest exciting magnetic field strength points caused by the flat ∞ coils exist nearly target piece points as shown in Fig.6. This means that the flat ∞ coil may have ultimately higher sensitivity.

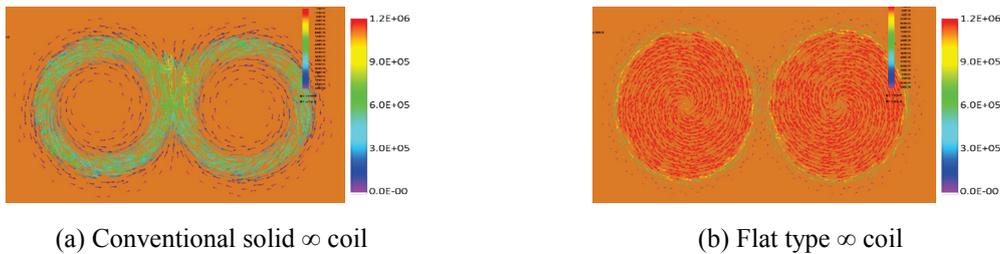


Fig. 7. Eddy current density distributions on the target pieces by the ∞ coils, where the left and right side vectors denote the eddy current density vectors due to the conventional and flat exciting coils, respectively

4. Simulations and Experiments

4.1. Defect searching in a flat surface

We have implemented the sensitivity comparison between conventional solid and flat ∞ coils by simulations as well as experiments. We employed a coppers plate having 1mm thickness and 2mm width defect as a target metal plate specimen. Further, we worked out the two prototypes of the ∞ coils. One is the conventional solid ∞ coil and the other is the flat ∞ coil. Both of these ∞ coils were made with the same conducting coils for the exciting coils having the same number of turns. Table 2 lists various constants of these ∞ coils. Figure.8 shows the pictures of these ∞ coils.

Table 2 Various constants of the tested ∞ coils

(a) Solid type exciting coil		(b) Flat type exciting coil		(c) Sensing coil	
Coil outer diameter	21.0mm	Coil outer diameter	22.0mm	Outer diameter	1.4×2.4mm
Coil Inner diameter	17.0mm	Coil Inner diameter	3.0mm	Inner diameter	1.0×2.0mm
Coil length	8.0mm	Coil length	0.4mm	Length	6mm
Number of turns	20	Number of turns	20	Number of turns	100
Input voltage(peak)	1V	Input voltage(peak)	1V	Axis core	Mn-Zn/ferrite
Frequency	256kHz	Frequency	256kHz		(permeability:3000)

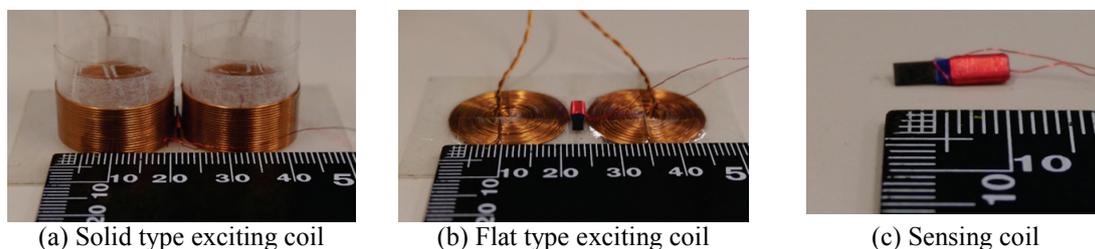


Fig. 8. The pictures of tested ∞ coils, where the left, centre and right denote the conventional, flat ∞ coils and sensing coils wound around a ferrite bar

We measured the induced voltages in the sensing coil when the ∞ coils are located at the No.1, No.2, No.3, No.4 and No.5 points on the target specimen shown in Fig.9. The exciting frequency is 256kHz and exciting voltage is $1V_{Max}$.

We calculated the signal-noise ratio (S/N) from the measured induced voltages by means of equation (1).

$$S/N = \frac{\text{Induced voltages at defect}}{\text{Induced voltages at no defect}} \quad (1)$$

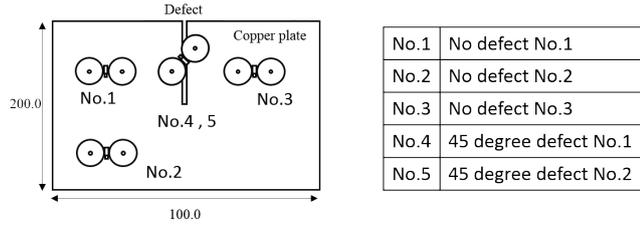


Fig. 9. Schematic diagram of a flat surface searching
 The ∞ coil is located at the center of a perpendicular slit defect. No.4 and No.5 are measured twice at this position to confirm the recoverability of experimented values

Figures 10 and 11 are the simulation and experimental results for the flat surface searching, respectively. Comparing the induced voltages of flat with those of the conventional solid ∞ coils reveals that the induced voltage of the flat ∞ coil is larger than those of the conventional solid one.

In addition, it is found that the S/N ratios of the flat type ∞ coils take higher in values than those of the conventional solenoid solid one, i.e., experimented S/N ratios of the flat type are 10.89~12.30 and those of the solid type are 7.93~10.79.

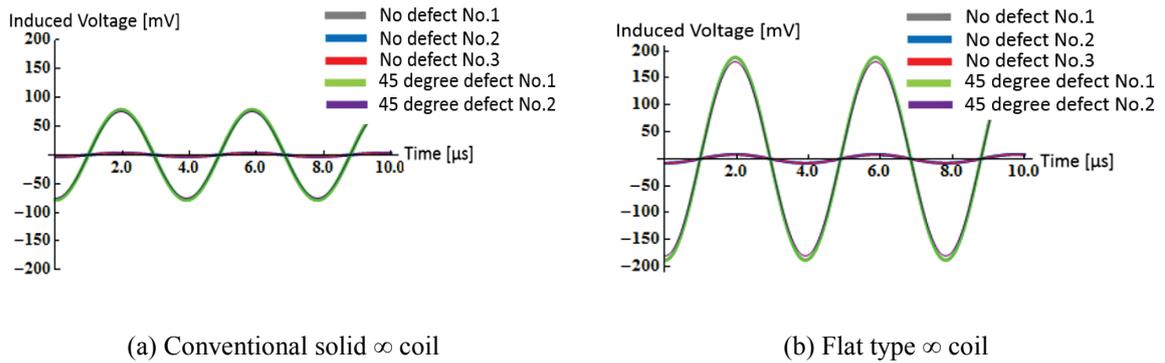


Fig. 10. Simulation results for a flat surface searching

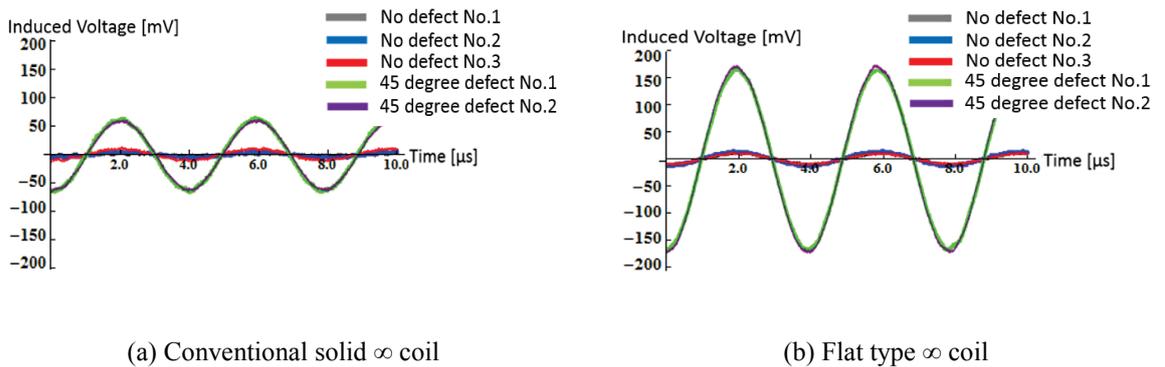


Fig. 11. Experimental results for a flat surface searching

4.2. Defect searching in a curved surface

We employed a seamless pipe having 82mm outer and 54mm inner diameters as a curved surface example. This tested pipe has a 0.3mm width curved line defect as shown in Fig.12.

A 0.3mm width curved line defect shown in Fig.12 is searched by the two distinct sensors. One is

the conventional solid ∞ coil as shown in Fig.8 (a) and the other is the flat ∞ coil as shown in Fig.8 (b).

Figures.13 and 14 show the simulation and experimental results for the curved surface, respectively. Observe the results in Figs.13 and 14 reveals that both of the solid and flat types of ∞ coils obtained by the experimented take the large in valued to that of simulated ones. This may be caused by the idealized simulation and practical measured conditions, i.e. there are many devices and instruments covered as iron case which works as the magnetic flux paths. Also, it is obvious that the flat type ∞ coil has higher sensitivity compared with those of the conventional solid ∞ coil.

The S/N ratios 7.33 and 3.62 by (1) are respectively calculated from the experimented results of the flat and the solid ∞ coils in Fig.14. Because of the fitting property, the S/N ratio 7.33 of the flat ∞ coil is much greater than 3.62 that of solid type ones. This means that the newly developed flat ∞ coil has the versatile capabilities compared with the conventional one.

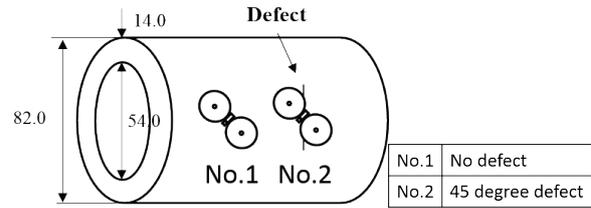


Fig. 12. Schematic diagram of the defect searching of a curved surface

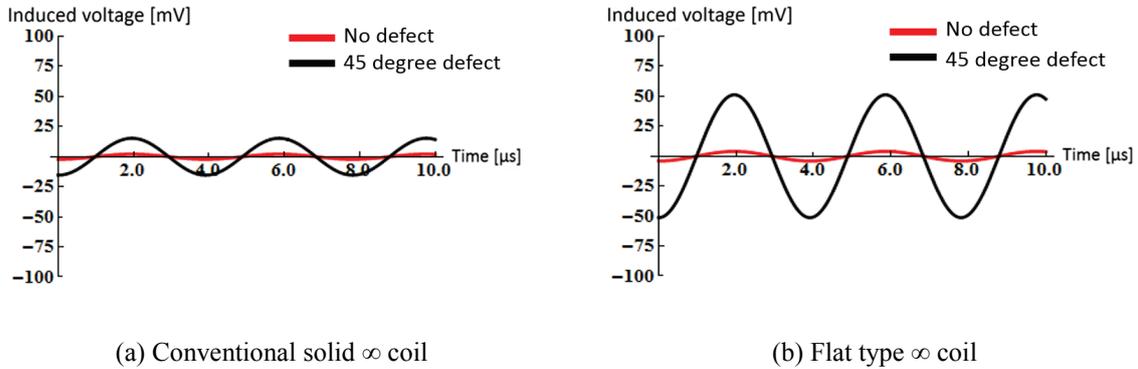


Fig. 13. Simulation results for a curved surface searching

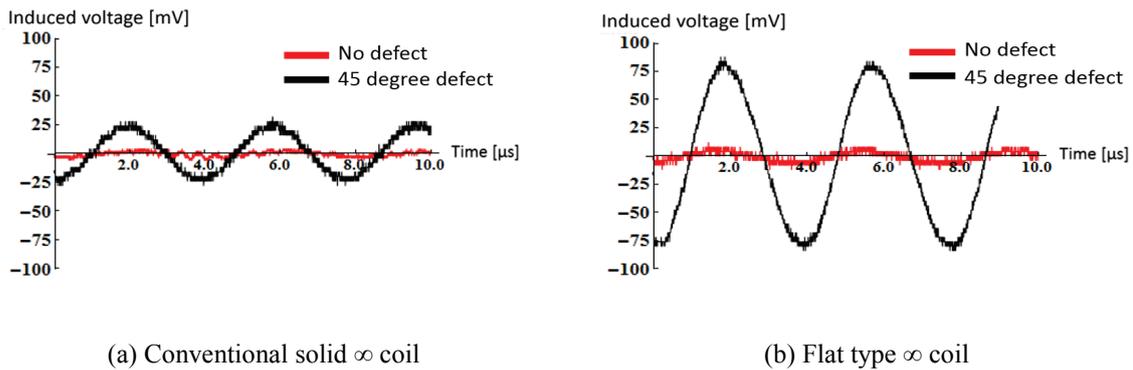


Fig. 14. Experimental results for a curved surface searching

5. Conclusion

We have proposed the new ∞ coil which is composed of the flexibly flat exciting coils. Intensive numerical simulations as well as experimental results have elucidated that this newly developed flat ∞ coil has the versatile capabilities compared with the conventional one.

Thus, we have succeeded in developing the new ∞ coil, which has a reasonable capability to detect not only the curved but also flat surface defects in the target.

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