Evaluation of magnetic field inside spiral search coil using evolution strategy in mutual induction eddy current testing

Yuji Gotoh and Yuta Motoyasu

Department of Mechanical and Energy Systems Engineering, Faculty of Engineering, Oita University, 700 Dannoharu, Oita 870-1192, Japan

Abstract- The mutual induction type eddy current testing using a spiral type search coil is one of the eddy current testing (ECT). In this type ECT probe, since the thickness of a spiral search coil is very thin, the distance (lift-off : L_o) between the ECT probe and the specimen is able to set small. Therefore, the high detection sensitivity is obtained. However, since the wire is coiled in the shape of spiral, the evaluation of the flux density inside the spiral search coil is made difficult by experiment. Moreover, the phenomenon elucidation of inspection using this ECT probe is not carried out. In this paper, the inspection characteristic of a surface defect on an aluminum plate using this probe was investigated by 3-D alternating electromagnetic finite element method (FEM). Moreover, the evaluation in consideration of the characteristic of the spiral search coil in this ECT probe is also investigated by (1+1) evolution strategy. It is shown that high detection sensitivity is obtained using the spiral search coil.

***Index Terms*— Mutual induction type eddy current testing, spiral search coil, (1+1) evolution strategy, 3-D FEM**

I. INTRODUCTION

THE eddy current testing (ECT) is one of the electromagnetic inspection methods [1,2] of surface defect in a nuclear power generation plant structure. In the mutual induction ECT, since a large magnetic field is able to impress to the inspection specimen, high detection sensitivity is obtained. In order to increase the detection sensitivity of the defect in the inspection specimen, it is necessary to decrease the distance (lift-off : L_o) between the ECT probe-coil and the specimen [3]. In recent years, the manufacture technology of a semiconductor was applied, and the spiral search coil film with the ECT probe was created. Since the thickness of the spiral coil is very thin, the distance L_o is able to set small. However, since the wire is coiled in the shape of spiral, the evaluation of the flux density inside the spiral search coil is made difficult by experiment. Moreover, the phenomenon elucidation of inspection using this ECT probe is not carried out.

In this paper, the inspection principle of the ECT probe was investigated by 3D electromagnetic finite element method (FEM). Moreover, the measured flux density inside the spiral search coil is calculated by the inversion method using the (1+1) evolution strategy [4-6], and it is compared with the calculated result of 3-D FEM.

II. MODEL AND 3D ELECTROMAGNETIC ANALYSIS

A. Inspection Model

Fig.1 shows the inspection model of the mutual induction ECT probe using a spiral search coil. The structure of the proposed mutual induction ECT probe is a rectangle exciting coil and a spiral search coil. The diameter, the thickness and number of turns of the spiral search coil are 2mm, 0.1mm and 44 turns, respectively. As for the search coil, the z-direction flux density (B_z) on the surface of specimen is detected. An aluminum plate of specimen is impressed by exciting coil of 25 kHz and 0.1A, and a surface defect is inspected by the thin spiral search coil. The distance (lift-off : L_o) from the bottom of the spiral search coil to the surface of the aluminum plate is equal to 1mm. The conductivity of the aluminum specimen is 3.5×10^7 S/m.

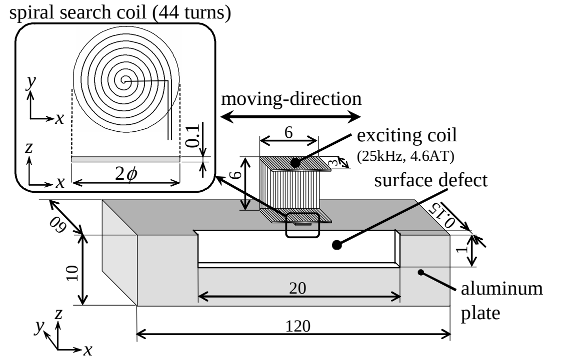


Fig.1. Inspection model for surface defect on aluminum plate (1/2domain).

B. Distribution of Magnetic Flux and Eddy Current

Fig.2 shows the vector distribution of magnetic flux near a surface defect on the aluminum plate when the ECT probe is located in the centre of the defect. This figure illustrates that the impression magnetic field from an exciting coil is distributed in the about x-directions. Therefore, the output voltage is not generated by a search coil.

Fig.3 show the vector distribution of magnetic flux and eddy current near a surface defect on the aluminium plate when the ECT probe is located in the edge part of the defect. Fig.3(a) illustrates that the impression magnetic field is hardly distributed inside the edge part of the aluminium plate. The impression magnetic field is hardly distributed inside the edge portion, and is bypassed to z-direction. This is, because the eddy current is generated inside the edge portion as shown in Fig.3 (b). Therefore, since the magnetic field of the z-direction is distributed near the edge portion of the defect, the output voltage is generated by a search coil.

III. INSPECTION EVALUATION OF SURFACE DEFECT ON ALUMINUM PLATE

A. Output Signal Analysis using Evolution Strategy

The comparison with verification experiment and calculation by 3D FEM is evaluated by flux density inside the spiral search coil (44 turns) in the ECT probe. In the verification experiment, since the shape of the search coil is spiral, the conversion to flux density from the output voltage V_e of the search coil is difficult. In this research, the

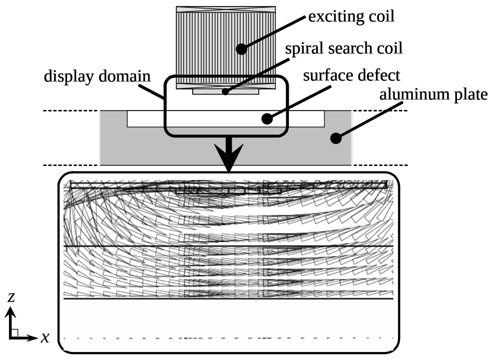
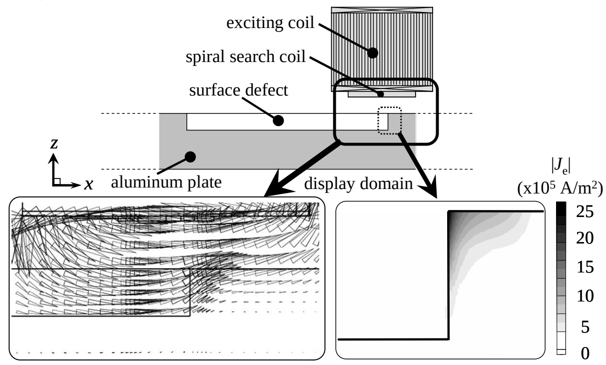


Fig.2. Distribution of magnetic flux near a surface defect when the ECT probe is located in the centre of the defect (B_{max}=5.98x10^{-4}T).



(a) flux distribution (B_{max}=6.16x10^{-4}T) (b) eddy current distribution

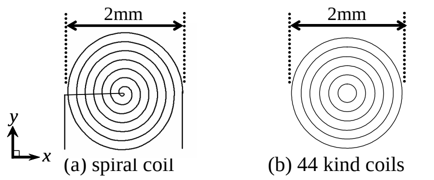
Fig.3. Distribution of magnetic flux and eddy current near a surface defect when the ECT probe is located in the edge part of the defect.

spiral search coil is assumed to be the coils with 44 kinds of diameter as shown in Fig. 4. Then, the measured flux density inside the spiral search coil is calculated by the (1+1) evolution strategy. The flux density in 44 kinds of coils is chosen as design variable. The normal random number N (0, σ^2) (σ: standard deviation) with weight value is added to each flux density in 44 kinds of coils. Then, total output voltage V_c is calculated. The residual of the measured output voltage V_e and the calculated output voltage V_c is an objective function W. If the calculated objective function W is less than the previous one, W is updated. The initial value of the standard deviation σ and the convergence criterion of the objective function W are 2.25 and 1x10^{-3} mV, respectively.

B. Inspection of Surface Defect

Fig.5 shows the distribution of calculated and measured values of B_z in the spiral search coil. The calculated result B_z by 3D FEM is shown in the "calculated (□)" inside this figure. And, the "measured (◆)" in this figure is the value which changed measured output voltage V_e into flux density B_z using the (1+1) evolution strategy. B_z is obtained by moving the ECT probe in the x-direction on the aluminum plate with surface defect. The figure denotes that each peak value is obtained near two edges of the defect. The calculated result is in agreement with measurement.

Moreover, the calculated result (△) of a usual search coil is also shown in this figure. The diameter, the thickness, and number of turns of the usual search coil are the same as the spiral coil, and are 2mm, 0.1mm, and 44 turns, respectively.



(a) spiral coil (b) 44 kind coils

Fig.4. Spiral search coil (44 turns) and assumed coils with 44 kinds of diameter.

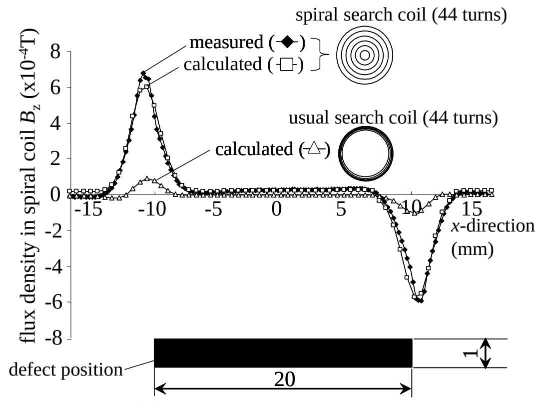


Fig.5. Distribution of flux density in spiral search coil (25 kHz, 6.22AT).

The structure of the usual coil is that the wire is rolled 44 times with the same diameter of 2mm. The result denotes that the magnetic-flux detection sensitivity of the spiral coil is higher than that of the usual search coil.

IV. CONCLUSIONS

The results obtained are summarized as follows:

(1) In this mutual induction ECT probe, the impressed magnetic field is distributed to bypass the edge portion of the surface defect on aluminum plate, since eddy current is generated inside the edge portion of the defect. Therefore, output signal in the search coil is obtained near two edges of the defect.

(2) It is possible to estimate the magnetic flux density from measured output voltage in the spiral search coil of this ECT probe using evolution strategy. Moreover, it is shown that the detection sensitivity of a spiral search coil is higher than that of a usual search coil.

REFERENCES

[1] N. J. Goldfine, “Magnetometers for improved materials characterization in aerospace applications”, *Materials Evaluation*, The American Society for Nondestructive Testing, pp.396-405, 1993.

[2] R.C.McMaster, P.Mclntrire, and M.L.Mester,”Electromagnetic testing”, Nondestructive testing handbook, American Society for Nondestructive Testing, vol.5, Third Edition, 2004.

[3] Y.Gotoh, A.Matsuoka, and N.Takahashi, “Electromagnetic inspection technique of thickness of nickel-layer on steel plate without influence of lift-off between steel and inspection probe”, *IEEE Trans. Magn.*, vol.47, no.5, pp.950-953, 2011.

[4] T.Bäck, ”Evolutionary Algorithms in Theory and Practice”, Oxford University Press, 1996.

[5] M.Horii, N.Takahashi, and T.Narita:”Investigation of evolution strategy and optimization of induction heating model”, *IEEE Trans. on Magn.*, vol.36, no.4, pp.1085-1088, 2000.

[6] Y.Gotoh, H.Fujioka, and N.Takahashi, “Proposal of electromagnetic inspection method of outer side defect on steel tube with steel support plate using optimal differential search coils”, *IEEE Trans. Magn.*, vol.47, no.5, pp.1006-1009, 2011.