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Magnetic Shielding Analysis for Arrayed Eddy Current Testing

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Arrayed eddy current testing (AECT) has been widely applied in the field of crack detection, displacement measurement and many other fields due to its non-destructive and high efficiency. But the coupling interference of AECT exists objectively and leads to the detection error directly. In this paper, a magnetic shielding layer is proposed to reduce the coupling interference. The relationships between electromagnetic parameters of magnetic shielding material and coupled magnetic field are discussed theoretically. Furthermore, the simulation and experiments are carried out, the results are consistent. It shows that the application of magnetic shielding layer in AECT can reduce the mutual inductance of probe coils and increase the output voltage. Additionally, the most important factor to select material of magnetic shielding layer is the conductivity. Thus, the magnetic shielding layer with large conductivity will be suitable for AECT to promote the testing performance.

Keywords : magnetic shielding, eddy current, array, coupled

1. Introduction

Arrayed eddy current testing (AECT) is a widely used nondestructive testing method based on multiple coils [1-3]. The basic working principle is electromagnetic inductive law, same as the eddy current testing [4]. Due to the advantages of non-contact, non-pollution and robustness, the AECT has been applied in the field of displacement measuring, defect detecting, health monitoring and many other fields [5-8].

In AECT applications, the multiple coils are energized to generate the magnetic field in the air, so the coupled magnetic field between coils is inevitable and also called coupling interference [9]. Moreover, the coil mutual inductance can be regarded as the parameter reflection of the coupling interference [10]. The coupling interference will affect the coil equivalent impedance, change the coil output voltage, and then bring the testing errors. Thus, the study on some measures to weaken the coupling interference will be very meaningful and interesting.

In this paper, in order to ensure the normal work of AECT, a magnetic shielding layer is proposed. And the roles of different electromagnetic parameters of magnetic shielding material on weakening coupling interference are explained theoretically. Moreover, the simulation analysis and experimental verification are carried out. According to the results, it is found that the proposed magnetic shielding layer for AECT is effective; the most important factor to select magnetic shielding material is conductivity; the application of magnetic shielding layer in the AECT can reduce the coil mutual inductance and increase the coil output voltage.

2. Theoretical Analysis

As for the arrayed eddy current testing (AECT) with the positive polygon topology [9], the topological structure has good symmetry. The basic component of AECT can be regarded as any two adjacent coils, shown as Fig. 1. In which, the two coils are energized to create magnetic field to induce eddy current in the tested plate. Due to the AECT's demand of small size, the distance between two adjacent coils is quite small. For sure, the coupled magnetic field in the air between coils exists and brings testing errors. In order to analyze the influence of coupling interference, the coil mutual inductance is adopted to be parameter reflection of the coupled magnetic field.

As known, the traditional shielding layer can be used to wrap the target to cut off the connection of coupled

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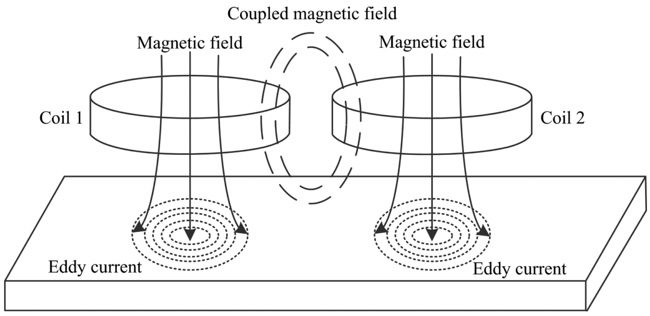

Fig. 1. The basic component of AECT.

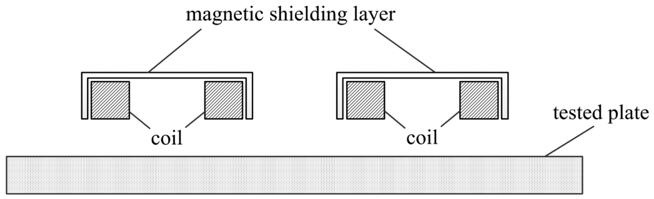

Fig. 2. The structure of proposed magnetic shielding layer.

magnetic field in the air. However, for the AECT, not all the magnetic field in the air could be cut off. Especially, the part between the bottom of coil and the tested plate must be retained. Otherwise, the basic working principle is broken. Thus, we propose a magnetic shielding layer to cut off the coupled magnetic field between adjacent coils while not affect the normal operation of eddy current testing. The structure of proposed magnetic shielding layer is shown as Fig. 2.

In Fig. 2, it can be seen that the magnetic shielding layer has no bottom, the magnetic field in the space working area is unaffected, which means AECT works normally.

The revised transformer analysis model [10] for AECT

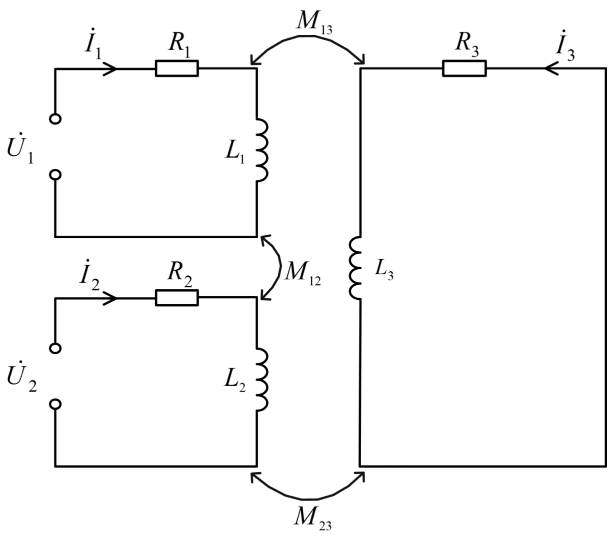

Fig. 3. The revised transformer analysis model.

is shown as Fig. 3. Where, U_1 and U_2 stand for the high frequency excitations, L_1 and L_2 are coil self-inductance, R_1 and R_2 are coil resistance, L_3 and R_3 are representative of the induced eddy currents in the plate, M_{13} and M_{23} represent the mutual inductance between coil and the tested plate, and M_{12} stands for the mutual inductance between the two coils.

After derivation, the coil equivalent inductance can be obtained as Eq. (1).

$$L_{eq} = L_1 - M_{12} - \frac{2\omega^2 {M_{13}}^2 L_3}{{R_3}^2 + \omega^2 {L_3}^2} \tag{1}$$

There are many different applications for AECT, but they mainly fall into two fields: displacement measurement and defect detection. Because the lift-off in defect detection is quite small, there is not much magnetic coupling interference. So, the paper will focus on the other field. However, in the displacement measurement, the large lift-off will lead to strong magnetic coupling interference between coils, which refer to the M_{12} in Eq. (1). Besides, the M_{13} is a coupling parameter between coil and tested plate corresponds to the normal working mode of eddy current testing and represents the electromagnetic induction. Hence, we propose the shielding scheme to reduce the coil mutual inductance M_{12}, not M_{13}. Surely, the precise detection results for different applications also require calibration of the arrayed probes and data post-processing.

Furthermore, it is important to consider the selection of material of magnetic shielding layer. The two main electromagnetic parameters of magnetic shielding material are the permeability μ and conductivity σ. Both two parameters will affect the magnetic shielding performance.

As for the permeability, the relationship between magnetic resistance R_m and permeability μ is shown as Eq. (2). Where, l is the length of magnetic path, and A is the area of magnetic path.

$$R_m = \frac{l}{\mu A} \tag{2}$$

From Eq. (2), the permeability μ is inversely proportional to the magnetic resistance R_m. The magnetic resistance R_m has an important effect on the magnetic path, which can be derived by Eq. (3). Where, F is the magnetomotive force, also called MMF for short.

$$F = \Phi \cdot R_m \tag{3}$$

Combine the Eq. (2) and Eq. (3), under the premise of same F, the larger permeability μ leads to the smaller magnetic resistance R_m, furthermore, leads to the more concentrated magnetic field. Because the relative permeability of air is very low, approximately equal to 1, the coupled magnetic field in the air will be reduced.

As for the conductivity, it can be analyzed from Maxwell's equation, as follows:

$$\begin{cases} \nabla \times E = -\dfrac{\partial B}{\partial t} \\ J = \sigma \cdot E \end{cases} \tag{4}$$

In Eq. (4), the $\nabla \times E$ represents the rotation of electric field E, the B is magnetic flux density, the J is the conduction current density. The magnetic field excited by the array coil is alternating, and an alternating electric field will be generated around. If the magnetic shielding material has large conductivity, the eddy current will be induced in the magnetic shielding layer. And then, the opposing magnetic field generated by the eddy current in shielding layer will weaken the coupled magnetic field in air.

To sum up, the permeability and conductivity both have some effect on weakening the coupled magnetic field in the air. In this research, the key is to analyze which one plays a bigger role.

3. Simulation Analysis

According to the theoretical analysis, for magnetic shielding layer, both permeability and conductivity are needed to be analyzed. The simulation modeling and analysis are carried out based on the ANSYS Maxwell. The materials of two coils and tested plate are set as copper and aluminum, respectively. The coil outer radius is 10 mm; the coil inner radius is 5 mm, the excitation frequency is set as 300 kHz and the solution region is 300 %. Besides, the mesh operations for coils and measured sample are set as inside subdivision and skin depth subdivision, respectively. The simulation models with magnetic shielding layer and no shielding layer are shown as Fig. 4.

In order to visually compare the spatial magnetic field distribution with or without shielding layer, the simulation analyses based on models in Fig. 4 have been carried out. The simulation results of magnetic field with and without proposed shielding layer are shown as Fig. 5. From the overall view and section view in Fig. 5, it can be easily found that the magnetic interaction between coils will be cut off with shielding layer, but the magnetic interaction between coils and tested plate will not be affected with shielding layer. So the proposed shielding scheme has two functions: one is to weaken the coil mutual inductance, and the other is to ensure the normal works of AECT.

Furthermore, in order to analyze the effect of permeability and conductivity of shielding material on the coil mutual inductance, three different materials are chosen, their electromagnetic parameters are shown in Table 1. Where, the relative permeability is the ratio of material permeability to vacuum permeability, and there is no unit.

The selected three materials are special, in details, ferrite

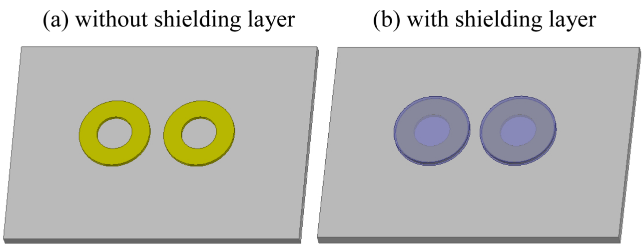

Fig. 4. (Color online) The simulation models.

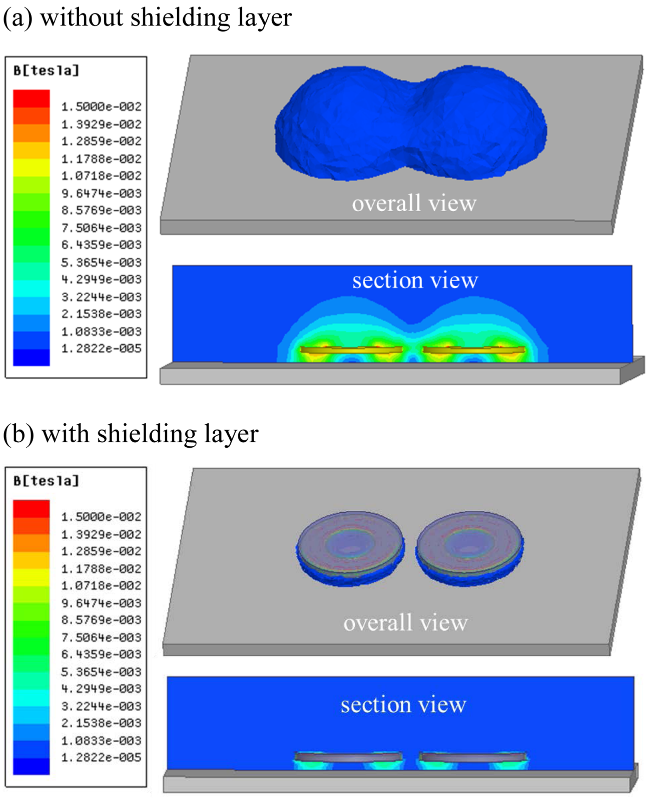

Fig. 5. (Color online) The simulation magnetic field.

Table 1. The electromagnetic parameters of magnetic shielding materials.

Materials	Relative permeability	Conductivity (S/m)
ferrite	1000	0.01
iron	4000	10300000
aluminum	1.000021	38000000

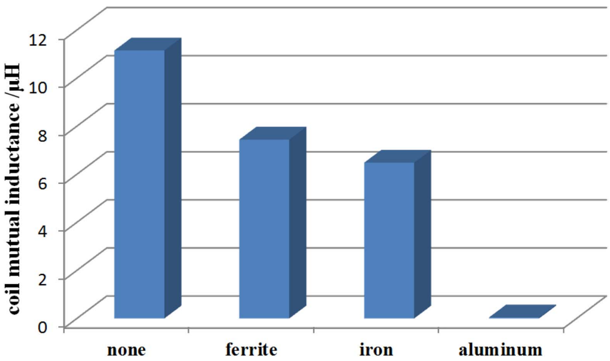

Fig. 6. (Color online) The coil mutual inductance under different shielding materials.

only has large permeability, aluminum only has large conductivity, and iron has larger permeability and smaller conductivity at the same time.

Take the unshielded layer as comparison, the coil mutual inductance under different magnetic shielding materials can be shown as Fig. 6.

It can be discovered that the coil mutual inductance all decreases under different magnetic shielding materials, which means the proposed magnetic shielding layer is effective, and the coupling interference can be reduced by the magnetic shielding layer. The rank of magnetic shielding performance among the three materials is that aluminum is best, ferrite is worst, and iron is middle. Thus, it is conductivity, not permeability, to play the most significant role to weaken coupling interference in the magnetic shielding layer for AECT.

4. Experimental Verification

The above simulation analysis has revealed the most significant factor in the selection of magnetic shielding material. Three typical materials are contrasted, in which

(a) without shielding layer (b) with shielding layer

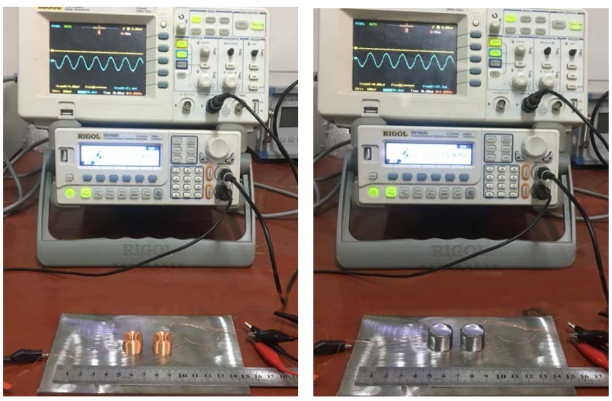

Fig. 7. (Color online) The comparison experiments.

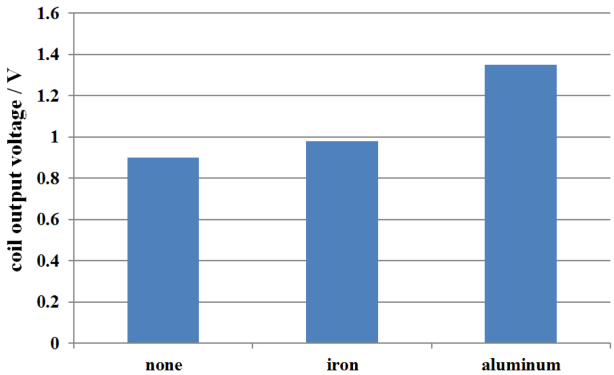

Fig. 8. (Color online) The coil output voltage under different shielding materials.

the aluminium and iron have achieved the relatively better performance. In order to verify its correctness, the magnetic shielding layer with aluminium and iron are made, and multiple groups of experiments are performed.

As the comparison group, the two coils energized without magnetic shielding layer are performed. The experiments with magnetic shielding layer under aluminium and iron are also carried out. The comparison experiments are shown as Fig. 7.

The experiment without magnetic shielding layer is considered as the reference with normal coupling interference. And the experiment with magnetic shielding layer is considered as the analyzed target with reduced coupling interference. The coil output voltages under different magnetic shielding materials are shown as Fig. 8.

It can be discovered that the coil output voltage will both increase with two magnetic shielding layers. In contrast, the output voltage of coil with iron shielding has been raised by about 10 %, while the output voltage of coil with aluminum shielding has been raised by about 50 %. According to the simulation analysis, with magnetic shielding layer, the coil mutual inductance should decrease. It is known that coil output voltage is affected by the coil mutual inductance, and less mutual inductance means less coupling interference, so the larger coil output voltage will be achieved. In simulation, it is shown that the aluminium shielding layer provides the least mutual inductance. In experiment, the aluminium shielding layer provides the largest coil output voltage, approximate 50 %. Thus, the simulation and experiments are verified by each other.

5. Conclusions

In this paper, a magnetic shielding layer to weaken coupling interference is proposed. And the theoretical discussions about the effect of permeability and conductivity of magnetic shielding material are carried out. The simulation and experiments are both performed, the results are verified each other. Thus, the conclusions can be summarized as follows:

The magnetic shielding layer is effective to weaken the coupling interference.

The main parameter to select magnetic shielding material is conductivity.

The application of magnetic shielding layer in AECT can reduce the coil mutual inductance and increase the coil output voltage.

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