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Procedia Engineering 130 (2015) 1649 – 1657

Procedia Engineering

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14th International Conference on Pressure Vessel Technology

Study on the Optimization of Eddy Current Testing Coil and the Defect Detection Sensitivity

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Abstract

As an essential component in the eddy current testing system, the detection sensitivity of eddy current probe affects the performance of the system. Different probes such as cylindrical differential probe, single orthogonal rectangular probe and biorthogonal rectangular probe were modeled using Comsol Multiphysics in this paper. The electromagnetic characteristics of probes were analyzed through the finite element simulation. Comparing the different probe detection signals, the new biorthogonal rectangular probe was found to have a better inhibition effect on the lift-off effect. The detection capability of probes according to flaw's width, length and depth were also studied. Based on the results of simulation, a new type of biorthogonal rectangular probe with higher detection sensitivity was designed.

Peer-review under responsibility of the organizing committee of ICPVT-14

Keywords: Eddy current testing; Biorthogonal rectangular probe; Defect; Simulation;Sensitivity

1. Introduction

Eddy current testing technology which is based on electromagnetic induction principle, is one of non-destructive testing (NDT) methods. It had been widely applied in various NDT instruments in the early 20th century. In the 1970's, the rapid development of computer technology and electronic technology led the improvement of eddy current testing instruments. The noncontact, high-sensitivity and anti-interference capability of eddy current testing system makes it important in many fields such as aerospace, metallurgy, electric power, machinery, nuclear and so on.

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Peer-review under responsibility of the organizing committee of ICPVT-14
doi:10.1016/j.proeng.2015.12.331

According to different testing purposes and application objects, eddy current testing instruments are divided into many types with same working principle and basic structure. The detection coil generates an alternating magnetic field when a signal generator supplies alternating current to the detection coil (probe) in the eddy current testing instrument. Then the magnetic field induced by eddy current induced in the inspected material reacts on the detection coil. The energy coupling between the detection coil and the inspected material causes the change of detection coil impedance, which changes the output signal of testing system. Through the analysis of the output signal, the information about material propriety, defects, lift-off distance and others is obtained.

As the key part of a testing system, the detection coil has a great impact on the performance of the eddy current testing system. Sensitivity and linearity range are important parameters for measuring the performance of a detection system. The sensitivity and linearity range are decided by the magnetic field distribution [1-5] which is directly affected by the shape and geometrical parameters of the detection coil [6-9]. Hence, except for optimizing the detection coil parameters [10], the study of the shape and geometrical parameters of the coil has an important practical significance for the high sensitivity and detection range of high performance probe.

Based on previous researches [11,12], three types of probe models were established on the COMSOL MULTIPHYSICS platform. The output signals of three models were obtained by finite element (FE) simulation analysis. The output signals of the probes were worked out at the 20kHz. The effect of shape on the sensitivity and linearity range of the defect detection was studied when the magnetic line of force distribution and the energy distribution were obtained by the numerical simulation. Additionally, the detection performances of the probes on the inspected material defects in three dimensions were further studied and the effects of detection objects on the detection sensitivity and linearity range were analyzed, which provides a certain theoretical basis for further rational optimization of the detection coil.

2. Establishment of FE models

By using the COMSOL MULTIPHYSICS FE software to compute the models, the coupling of magnetic field and electric field excited by alternating current was studied. The basic equations of electromagnetic field are presented as follows:

$$\left(j\omega\sigma - \omega\varepsilon\right)\mathrm{A} + \nabla \times \left(\mu^{-1}\nabla \times \mathrm{A}\right) = J_e \tag{1}$$

$$\mathrm{B} = \nabla \times \mathrm{A} \tag{2}$$

j is the imaginary unit, ω the angular frequency of the applied alternating current, μ and σ the relative magnetic permeability and conductivity of the inspected material, ε the dielectric constant, **A** the magnetic vector potential, J_e the excitation current intensity, **B** the magnetic flux density.

Basing on the previous researches, the simulation model was built, as shown in Fig. 1. The material of the inspected material was SUS304 stainless steel. The geometrical dimension was 100 mm×100 mm×20 mm. The conductivity of the inspected material was 1.35×10^6 S/m. And the relative permeability of the inspected material was 1. The excitation current intensity and the frequency of the applied excitation current were respectively 1×10^6 A/m^2 and 10 kHz. The size of computational domain, including the air around the specimen, was Φ16 mm×120 mm. Boundary condition was imposed so that the tangential component of magnetic vector potential was zero.

According to different testing purposes and applications, the detection coils are divided into three types: outside through type, inside through type and placed planar type. The research object was the placed planar probe used for the detection of plane parts. The shape and geometrical parameters of the probe are shown in Fig. 2. In this paper, the cylindrical coil, single orthogonal rectangular probe and biorthogonal rectangular probe, as shown in Fig. 3, were studied.

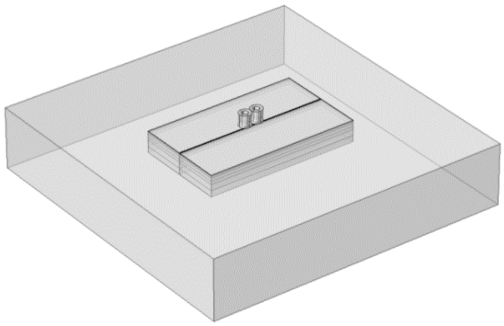
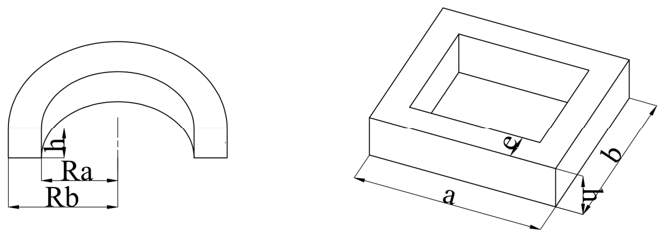
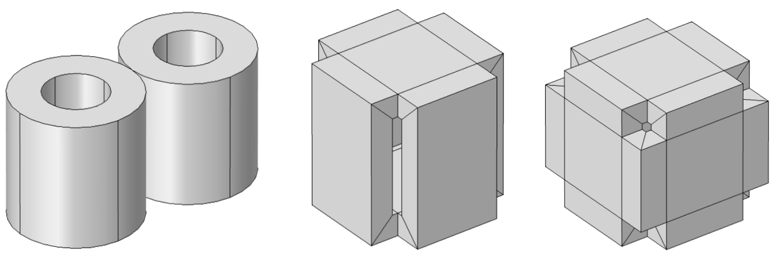


Fig. 1. The simulation geometry model.



(a) (b)

Fig. 2. (a) Cylindrical coil; (b) Rectangular coil.



(a) (b) (c)

Fig. 3. (a) Cylindrical differential probe; (b) Single orthogonal rectangular probe; (c) Biorthogonal rectangular probe.

3. Rationality of the FE models

The finite element analysis results include the total error caused by the model error and the computational error [13]. In order to obtain the simulated error and verify the feasibility of the FE simulation model, the magnetic field distribution of a single coil model was simulated. The model is shown in Fig. 4. The relationship between the magnetic flux intensity on the axis of the coil and the lift-off distance was derived by the Biot-Savart law [14]. The theoretical solution is shown as follows:

$$B = \frac{\mu_0 NI}{2(R_b - R_a)h}\left\{(z+h)\ln\frac{R_b + \sqrt{R_b^2 + (z+h)^2}}{R_a + \sqrt{R_a^2 + (z+h)^2}} - z\ln\frac{R_b + \sqrt{R_b^2 + z^2}}{R_a + \sqrt{R_a^2 + z^2}}\right\} \quad (3)$$

The theoretical computational results of the model and the FE simulated results are shown in Table 1. Apparently the FE model is reasonable with a computational error less than 2% and proves the accuracy of the model.

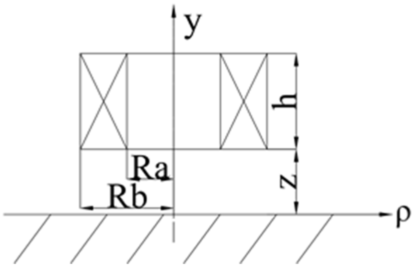


Fig. 4. The solving model in theory.

Table 1. The comparison between theoretical calculations and finite element analysis results of model.

z/mm	Theoretical result (*mT*)	Simulated result (*mT*)	Result error (*%*)
0.3	50.5111	50.4377	0.15
0.9	29.1066	28.9568	0.51
2.0	10.9277	10.9648	0.34
2.7	6.4300	6.4522	0.35

4. Optimization of the eddy current coils

4.1. The influence of coil shape on the magnetic field distribution

The influence of coil shape on the testing performance is affected by the magnetic field distribution. For optimizing the detection coil to improve the testing performance of the coil, the cylindrical coil, single orthogonal rectangular probe and biorthogonal rectangular probe, which were constructed in COMSOL MULTIPHYSICS platform, were studied. Fig. 5 shows the magnetic line of force distributions and the magnetic flux density distributions on the inspected material surface actioned under three types of probes, which were analyzed by FEM.

The results reveal that the orthogonal rectangular probe has a smaller magnetic line of force distribution range and a less magnetic energy loss compared with cylindrical differential probe. Compared with single orthogonal rectangular probe, biorthogonal rectangular probe has a more concentrated distribution of magnetic line of force, a larger change of magnetic energy, higher detection sensitivity and wider linearity range. Hence, the FE simulation results reveal that the biorthogonal rectangular probe is a new type of probe with higher testing performance.

4.2. The inhibition effects of coil shape on the lift-off

The distribution of the induced vortex flow field is affected by the lift distance between probe and inspected material, which is called the lift-off effect. In the eddy current testing of material defects, the lift-off signal is one kind of interference signal and should be separated or eliminated [15]. For improving testing performance of the system, the study of the inhibition effect of each probe is extremely important.

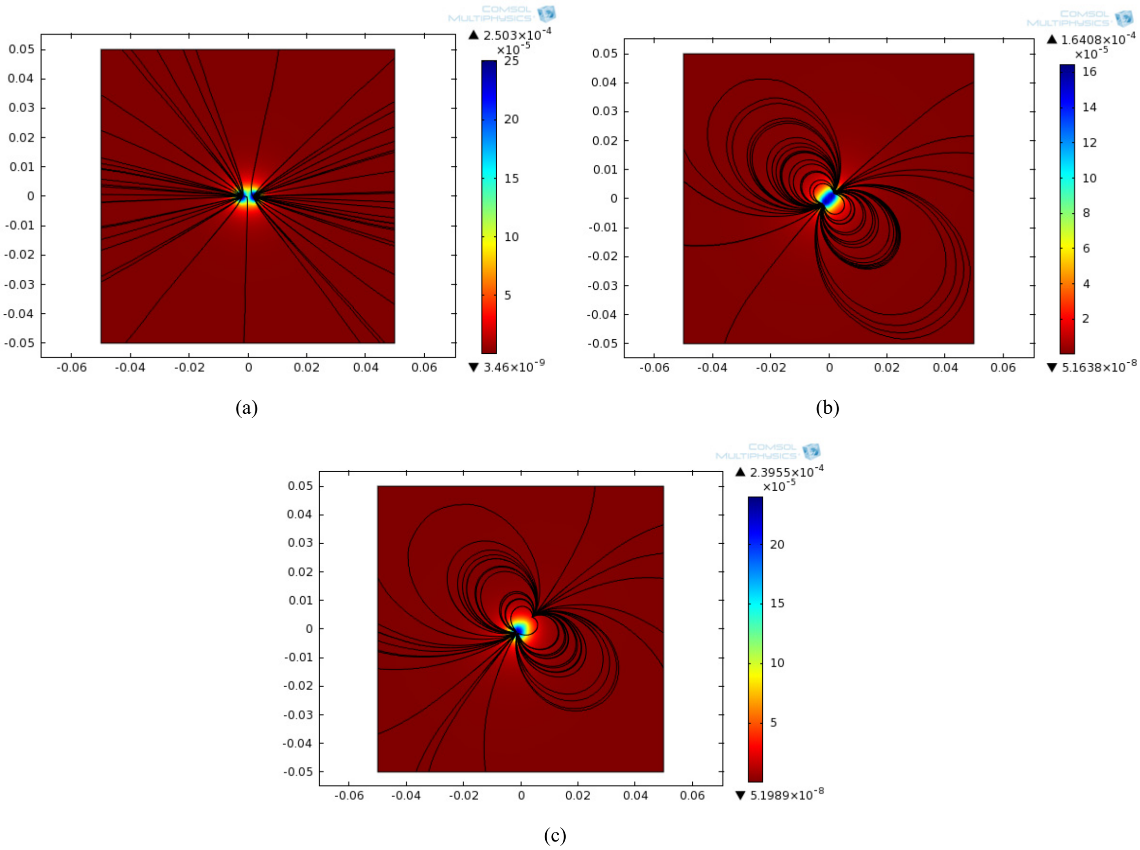


Fig. 5. The effect of coil shape on the magnetic induction intensity (a) Cylindrical differential type; (b) Single orthogonal rectangular type; (c) Biorthogonal rectangular type.

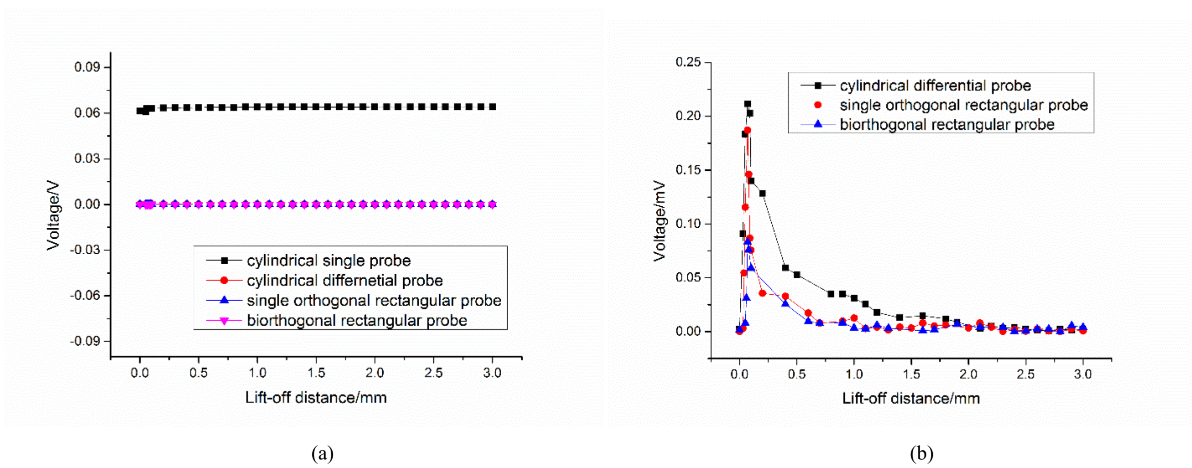


Fig. 6. The voltage variations caused by the lift-off: (a) Four coil shapes; (b) Three coil shapes.

The FE analysis of different models was established to analyze the inhibition effect of coil shape on the lift-off effect. The conductivity of inspected material was 1.35×10^6 S/m. The relative magnetic permeability was 1. The values of lift-off distance considered in the simulation were 0.05 mm, 0.5 mm, 1 mm, 1.5 mm, 2 mm, 2.5 mm, 3 mm, and other parameters of the model were kept in constant. The output voltages of the detection probe computed by FEM is shown in Fig. 6.

The results shown in Fig. 6 present that the Lift-off effect has an apparent inhibition effect on the output signal of cylindrical single coil probe; cylindrical differential probe, single orthogonal rectangular probe and biorthogonal rectangular probe are less affected by the Lift-off effect, and these probes have a certain inhibition effect on the Lift-off effect. The output signal change of biorthogonal rectangular probe affected by the Lift-off effect is significantly decreased and the inhibition effect on the Lift-off effect is most obvious.

5. The influence of coil shape on defect detection performance

5.1. Crack depth variation

Simulation was carried out using a model with a preset crack. The values of the width and length of crack were 0.2 mm and 6 mm. The values of crack depth considered in the simulation were 0.1 mm, 0.5 mm, 1 mm, 2 mm, 3 mm, 5 mm, 7 mm. Solved on COMSOL MULTTIPHYSICS platform, the magnetic induction intensity distribution and the eddy current distribution under the probe were obtained, and the real and imaginary voltages of the detection coil were also obtained. The output voltages of models with different crack depths under cylindrical differential probe, single orthogonal rectangular probe and biorthogonal rectangular probe reflect the impedance of the coils. Then the effect of coil shape on the detection performance of crack depth is obtained, as shown in Fig. 7.

Figure 7 shows that the output voltages of the probes are increased with the increase of crack depth but the voltage gradient values are decreased. Compared with two rectangular probes, the cylindrical differential probe has smallest voltage gradient values and lowest detection sensitivity. The detection sensitivity of rectangular probes is significantly improved. Compared with single orthogonal rectangular probe, biorthogonal rectangular probe has larger voltage gradient values with the increase of crack depth, higher detection sensitivity and wider detection range.

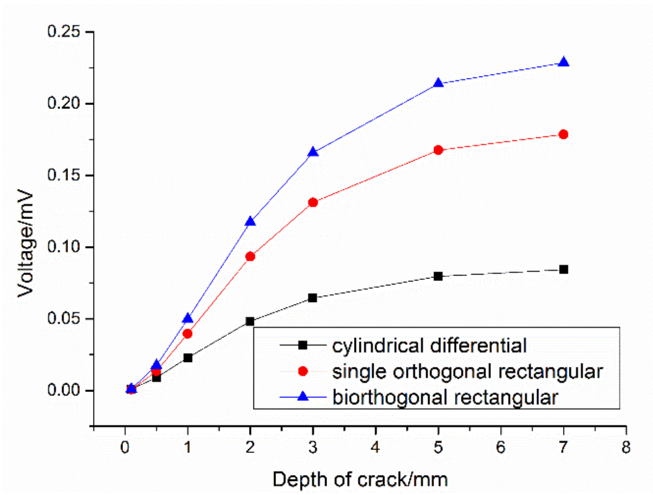


Fig. 7. The voltage variations of three probes caused by the crack depth variation.

5.2. Crack width variation

Simulation was carried out using a model with a preset crack. The values of the depth and length of crack were 4mm and 3mm. The values of crack width considered in the simulation were 0.1mm, 0.2mm, 0.3mm, 0.4mm, 0.5mm. The real and imaginary voltages of the detection coil respectively actioned under cylindrical differential probe, single orthogonal rectangular probe and biorthogonal rectangular probe were also solved. And the output voltages of models with different crack widths were calculated. Then the effect of coil shape on the detection performance of crack width is obtained, as shown in Fig. 8.

Figure 8 shows that the output voltages of the probes are in approximately linear growth with the increase of crack width. Compared with single orthogonal rectangular probe, the cylindrical differential probe has a larger voltage gradient value and higher detection sensitivity. Compared with single orthogonal rectangular probe, the biorthogonal rectangular probe has larger voltage gradient values with the increase of crack width. The biorthogonal rectangular probe is a kind of probe with highest detection sensitivity and widest detection range.

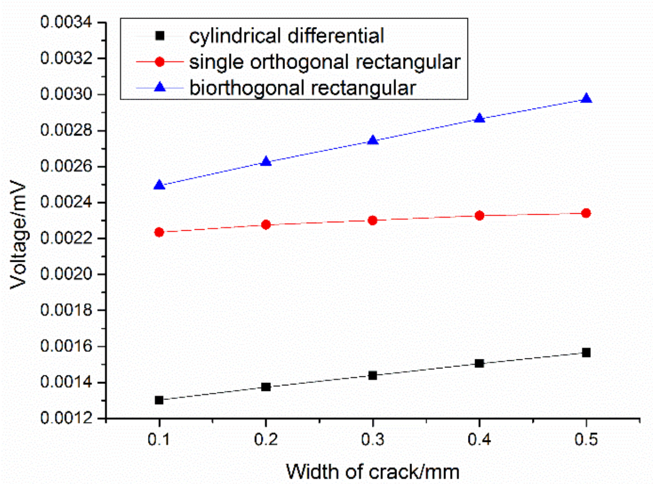


Fig. 8. The voltage variations of three probes caused by the crack width variation.

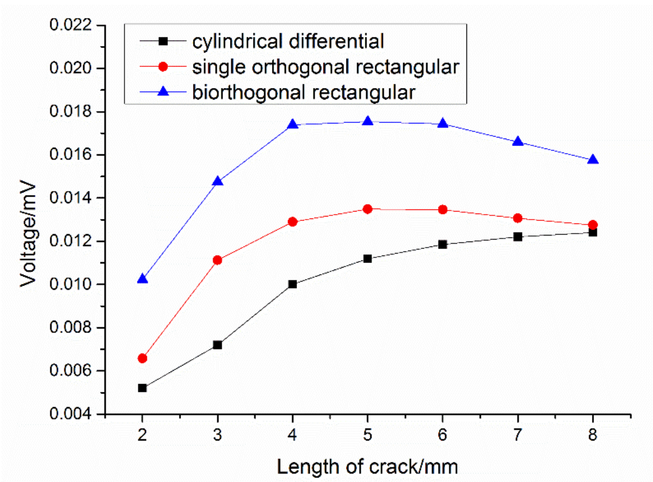


Fig. 9. The voltage variations of three probes caused by the crack length variation.

5.3. Crack length variation

Simulation was carried out using a model with a pre-set crack. The values of the depth and width of crack were 0.5 mm and 0.2 mm. The values of crack length considered in the simulation were 2mm, 3 mm, 4 mm, 5 mm, 6 mm, 7 mm, 8 mm. Solving the FE model, the magnetic induction intensity distributions and the eddy current distributions under the probes were obtained. The real and imaginary voltages of the detection coil were also obtained from the FEA calculation. The output voltages of models with different crack lengths under cylindrical differential probe, single orthogonal rectangular probe and biorthogonal rectangular probe reflect the impedance of the coils. Then the effect of coil shape on the detection performance of crack length is obtained, as shown in Fig. 9.

Figure 9 shows that the output voltages of the probes are in approximately parabolic growth with the increase of crack length. Among cylindrical differential probe, single orthogonal rectangular probe, biorthogonal rectangular probe, cylindrical differential probe has smallest voltage gradient values and lowest detection sensitivity, and the biorthogonal rectangular probe has largest voltage gradient values with the increase of crack length. The biorthogonal rectangular probe is a kind of probe with highest detection sensitivity.

6. Conclusion

The results of the present investigation can be summarized as follows:

- Compared with the cylindrical coil, the rectangular coils have a better inhibition effect on the Lift-off effect.
- The detection sensitivity of coil in three dimensions of the crack is different; the coils have a better detection sensitivity of depth variation than length and width variation. Compared with the single orthogonal rectangular coil, the biorthogonal rectangular coil has a more significant change of output signal and improved detection sensitivity.
- The shape of coil has a direct influence on the sensitivity of the crack detection. The rectangular coils have higher detection sensitivity than the cylindrical differential coil. Compared with the single orthogonal rectangular coil, the output signal variation of the biorthogonal rectangular coil is more obvious and the detection sensitivity is higher.

Acknowledgements

This study was performed as a part of a 973 program named “Basic research on the design and manufacture of large load bearing parts of high pressure hydrogen system”, supported by Ministry of Science and Technology, China. The item number is 2015CB057602.

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