

Research on Novel Remote Field Eddy Current Testing System for Axial Crack Detection with High Resolution

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ABSTRACT: Remote field eddy current was an effective non-destructive testing technology for tubular structure such as pipes and tubes. Firstly, experiment results using conventional sensor, the reason of poor sensitivity was analyzed and discussed by finite element simulation. Secondly, novel high resolution sensor with orthogonal magnetic field and self-differential mode pick-up coil was proposed. At last, proposed sensor was verified experimentally using various type defects, and conclusions were drawn as followed: detection ability and sensitivity of remote field eddy current testing system using proposed sensor improved significantly compared with using conventional sensor, especially for axial crack which is not easily to detect using conventional sensor, and sensitivity to various types defects remained almost the same.

KEYWORD: Remote Field Eddy Current; Sensors; Orthogonal Magnetic Field; Finite Element Simulation; Detection Sensitivity

1 INTRODUCTION

Remote field eddy current (RFEC) technique recently draws more and more attention in non-destructive testing of tubes and pipes for its promising advantages [1]. Fig1 shows conventional schematic diagram of RFEC, which is dependent on two different coupled paths when electromagnetic wave propagate in the pipe.

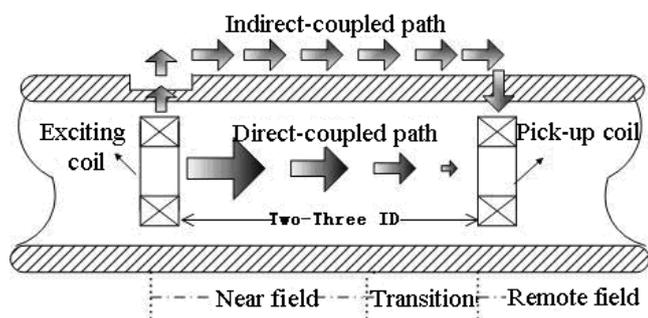


Fig1. Schematic diagram of remote field eddy current

However, further applications of remote field eddy current testing were restricted by disadvantages such as weak signal, poor sensitivity to axial crack. In this paper, we investigate novel sensor design to overcome these disadvantages [2].

2 SENSITIVITY ANALYSIS

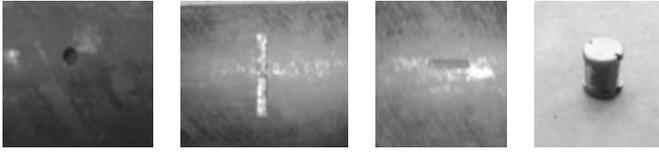
2.1 Axial crack detection ability of conventional RFEC sensor

Fig2 shows conventional remote field eddy current sensor usually adopts a coaxial solenoid coil excited by sinusoid to generate exciting field, and adopts another solenoid coil placed at about 2~3times pipes inner diameter to pick up field[3].

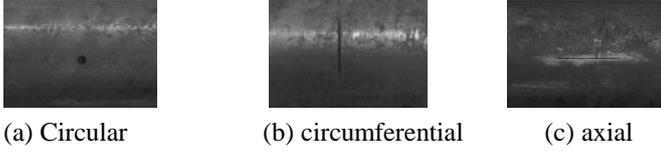


Fig2. Conventional sensor prototype of RFEC testing

To verify detection ability and sensitivity of conventional sensor, two classes defects are manufactured in a section of ferromagnetic tube with 70mm inner diameter, 82mm outer diameter and 6mm wall thickness. First class defects shown in Fig 5 include: circumferential and axial crack with 10mm length and 2mm width, circular defect with 6mm diameter; second class defect shown in Fig.4 include: circumferential and axial crack with 10mm length and 0.5mm width, circular defect with 3mm diameter. All defects are manufactured with depth of 3mm, equal to 50% tube wall thickness.



(a) Circular (b) circumferential (c) axial (d) pick-up coil
Fig3. Photography of first class defects and pick-up coil



(a) Circular (b) circumferential (c) axial
Fig4. Photography of second class defects

Fig 5 shows the experiment results of first class defects. All of defects can be detected and identified clearly, although sensitivity to axial crack is relative lower than circumferential crack and circular defect.

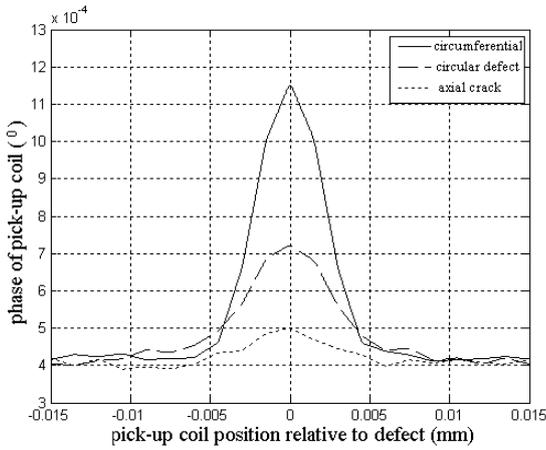


Fig 5. Experiment results for first class defects

However, with reduction of size of defect, all of defects detection ability decreases, especially for axial crack. Fig 6 shows experiment results of second class defects. Amplitude of axial cracks reduce too low to detect it.

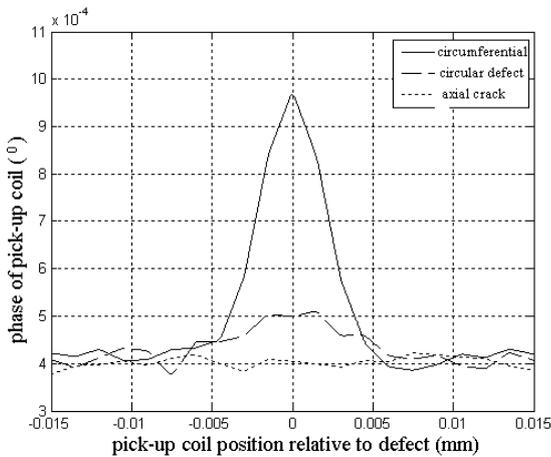


Fig 6. Experiment results for second class defects

2.2 Finite element simulation and analysis

Finite element method is proved to be an effective analysis method for eddy current NDT [4] [5] [6],

and is adopted to analyze the internal mechanism of poor sensitivity to axial crack rather than defects in other direction.

When excitation frequency is low, the displacement current can be neglected, and the basis governing Maxwell equation will be reduced to following equations:

$$\nabla \times \vec{H} = \vec{J} + \vec{J}_s \quad (1)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (2)$$

$$\nabla \cdot \vec{B} = 0 \quad (3)$$

Where \vec{J}_s is source current density, \vec{J} is eddy current density, \vec{B} and \vec{H} are magnetic flux density and magnetic field intensity, \vec{E} is electric field intensity.

Introducing magnetic potential vector \vec{A} , which is governed by $\vec{B} = \nabla \times \vec{A}$, the final governing equation is derived from equation (1) ~ (3):

$$\nabla \times \frac{1}{\mu} \nabla \times \vec{A} = -\sigma \frac{\partial \vec{A}}{\partial t} + \vec{J}_s \quad (4)$$

In harmonic excitation, whose angular frequency is ω , and considering coulomb gauge $\nabla \cdot \vec{A} = 0$, Equation(5) is rewritten as:

$$\left(\frac{1}{\mu}\right) \nabla^2 \vec{A} = -\vec{J}_s + j\omega\sigma \vec{A} \quad (5)$$

Then we obtain magnetic potential vector \vec{A} by using FEM to mesh and work out Equation (5), therefore magnetic flux density \vec{B} and other wanted quantity can be deduced from it.

Fig 7 shows axial component of magnetic flux density around circumferential crack, and Fig 8 shows axial component of magnetic flux density around axial crack. Distribution caused by circumferential cracks is five times high than axial. It is perhaps because conventional RFEC sensor using coaxial solenoid coil, which mainly generate axial magnetic and induct axial eddy current which is more sensitive to circumferential cracks

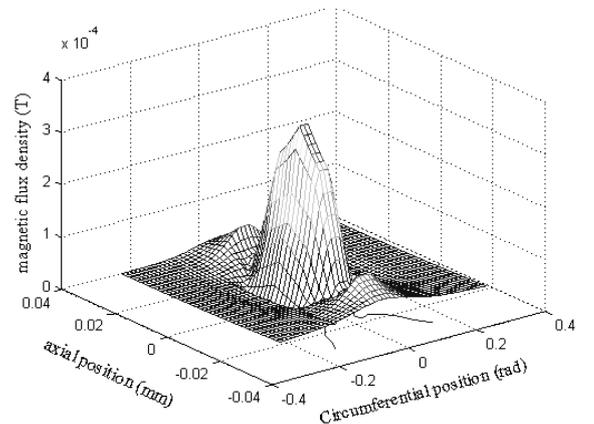


Fig 7. Axial component of magnetic flux density around circumferential crack

3 NOVEL SENSOR AND EXPERIMENT SYSEM DESING

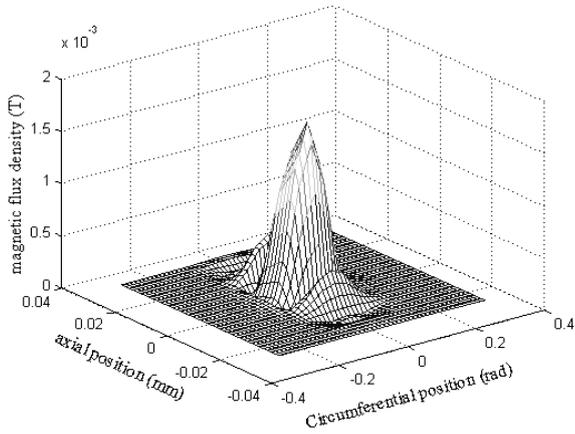


Fig 8. Axial component of magnetic flux density around axial crack

To further verify it, Fig 9 and Fig 10 shows circumferential component of magnetic flux density around axial and circumferential crack. Contrary to the previous case, Distribution caused by axial crack is four times high than circumferential crack.

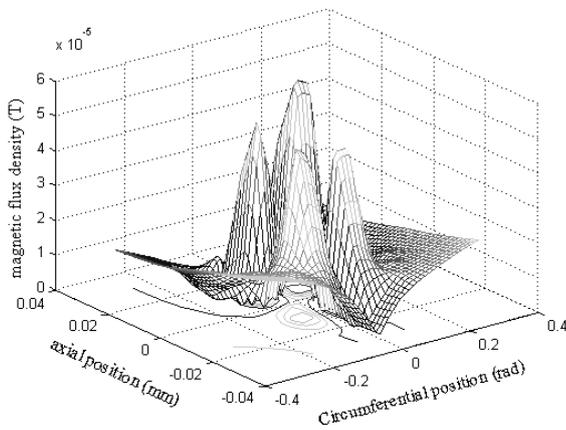


Fig9. Circumferential component of magnetic flux density around circumferential crack

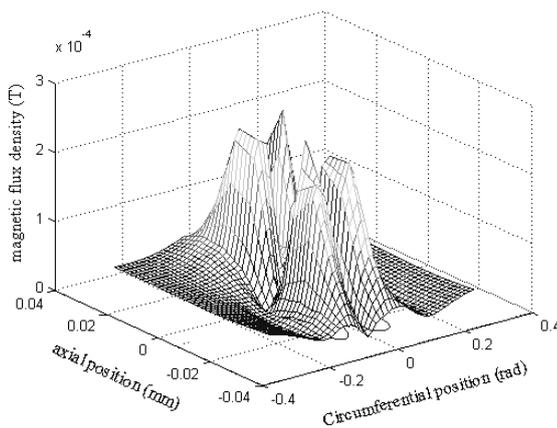


Fig10. Circumferential component of magnetic flux density around axial crack

From above analysis, conclusion can be drawn as followed: The most appropriate sensor configuration should be orthogonal magnetic field combined with axial and circumferential exciting, and specified pick-up coil should be adopted to detect it.

Fig 11 shows novel sensor with orthogonal magnetic field. The sensor consists of exciting coil using to generate orthogonal magnetic field, centering device using to reduce influence of sensor jitter or off-center, different type pick-up coils with adjustable base to detect field disturbance caused by defect, screw using to adjust the distance between the exciting coil and pick-up coil, and shielding facility using to reduce length of sensor.

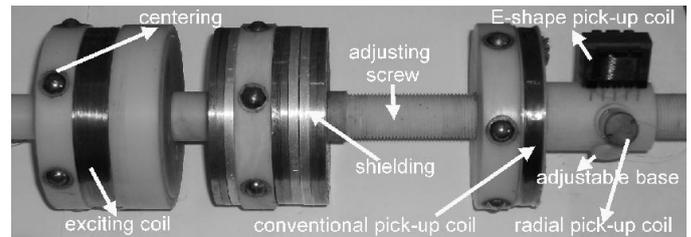


Fig 11 photography of new high resolution sensor

Fig 12 shows orthogonal magnetic field exciting coils and specified pick-up coil. Novel sensor adds a coaxial cylindrical conductor inner the conventional solenoid coil. When AC current was applied between its two ends, due to skin effect, it will be collected on its surface [7], and then spatial circumferential magnetic field will be generated, which will combine with the conventional axial magnetic field to generate orthogonal magnetic field. A new type differential mode pick-up coil with E-shape magnetic core is adopted, which is proposed firstly to detect cracks in aircraft multilayer structure, and is named as “self-differential” [8] [9].



Fig 12 photography of exciting and pick-up coil

Fig 13 shows the experiment system to test and verify the proposed sensor.

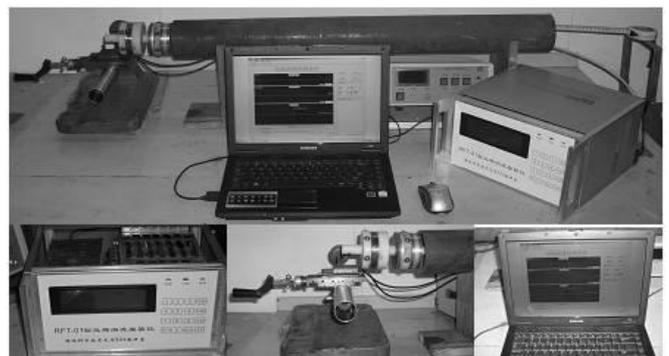


Fig 13 photography of experiment installation

4 EXPERIMENT RESULTS

Test specimen is same to above mentioned, and three types of defects are manufactured with different depth of 15%, 20%, 40%, 60% tube wall thickness, including circumferential and axial crack with 10mm length and 0.5mm width, circular defect with 3mm diameter.

Fig 14~Fig 16 show experiment results. All of defects can be detected; especially, the axial crack with depth of 20% wall thickness, which is very difficult to detect using conventional sensor, can be detected and identified clearly. At the same time, the proposed sensor has almost same sensitivity to cracks in different direction: 6.7° phase difference for axial crack, 6.2° phase difference for circumferential crack.

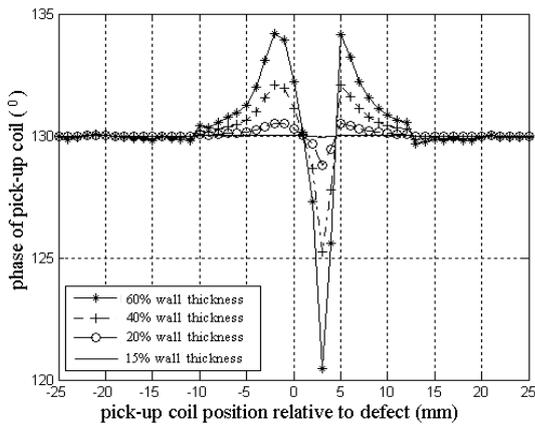


Fig 14 experiment result of axial cracks

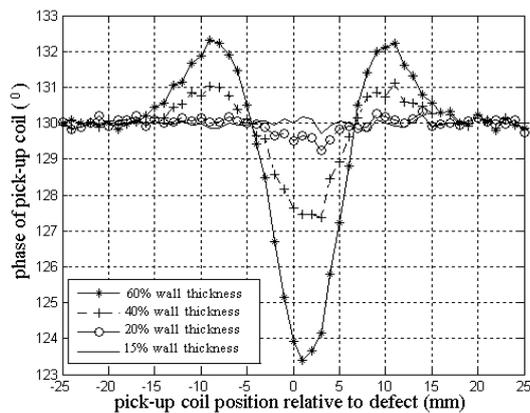


Fig 15 experiment result of axial cracks

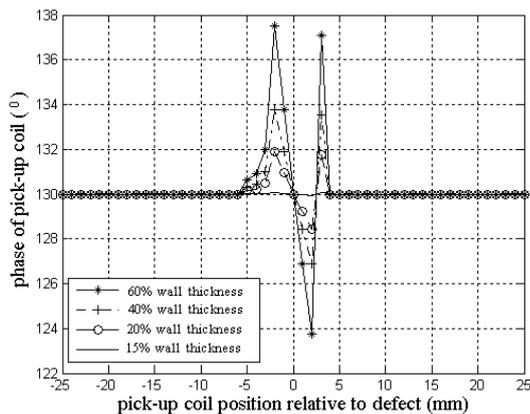


Fig 16 experiment result of circumferential cracks

5 CONCLUSIONS

A novel sensor based on orthogonal magnetic field for remote eddy current testing is proposed. After analysis of detection ability and sensitivity of conventional sensor, finite element method is used to simulate and declare the inner mechanism for poor sensitivity to axial crack. By adding a coaxial cylindrical conductor inner conventional solenoid coil, which is considered as the most appropriate configuration to generate orthogonal magnetic field for tubular structures, proposed sensor and experiment system is designed and realized. Experiment results show that proposed sensor has high resolution especially to axial crack which is difficult to detect by conventional sensor, and similar sensitivity to various type of defects.

6 ACKNOWLEDGEMENT

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