Experimental Investigation of Influence on Non-destructive Testing by Form of Eddy Current Sensor Probe

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Abstract. Eddy current testing is a kind of non-destructive testing (NDT) method based on the principle of electromagnetic induction. The probe is the key of eddy current non-destructive inspection and its design or combination of form will influence detectability. A complete set of eddy current testing system is designed for standard testing copper and defect copper. Under the same lift-off distance and the same high frequency excitation signal, designed three types of probe, which are single probe single coil, single probe double coil and double probe double coil, are used to carry out NDT experiment. Experimental results show that sensitivity and resolution of detection system are obvious difference among the different form of eddy current sensor probe. Probe shape and coil winding are improved according to the experimental results. Corresponding improved probe is adopted to carry out NDT experiment at the same condition. Experimental results show that detectability is enhanced significantly.

Keywords: Eddy current testing, Probe, Non-destructive testing (NDT), Sensitivity

1 Introduction

Eddy current testing based on the principle of electromagnetic induction is a kind of NDT method for testing metal semi-finished and metal components. It has been more and more widely used for its no need touch, high-speed of testing, easy automation, suitable for online testing and high detection sensitivity of surface defect. For example, YANG[1]et al, considered identification of corrosion fringe in pulsed eddy current non-destructive testing, He[2] et al, considered pulsed eddy current technique for defect detection in aircraft riveted structures.

However, the form of sensor probe has a great influence on the detection performance. In recent years, it is a research focus of many scholars how to improve the sensitivity of eddy current probes. But the discussion only is in the influence of one aspect, rather than the system. For example, Ren[3] et al, proposed to increase the

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probe diameter or adapt big pie-type probe to improve the detection sensitivity, but it will reduce detection sensitivity of small defects. Kim[4] et al, considered a dual-electromagnetic sensor system for weld seam tracking of I-butt joints. Li[5] et al, analyzed detection principle and influence factors of eddy current. Yu[6] et al, designed a novel pulsed eddy current testing probe based on 3D magnetic field measurement. Gao[7] et al, studied on structure optimization of eddy current probe, and obtained three influence factors on eddy current sensitivity: exciting coil of eddy current is stronger than slot width ,and slot width is stronger than detection coil of eddy current.

In this paper, we summarize the previous discussion, full unscramble measurement principle of eddy current. The procedure is: to design a placed device of eddy current testing; to use different forms of probe to carry out comparative test to the standard copper and defect copper. The specific objectives are: to get the relations between probe form and sensitivity of NDT; to put forward recommendations for improvement of the probe.

2 Testing Principle and Methods of Eddy Current

Eddy current testing is a kind of NDT method based on the principle of electromagnetic induction, which is applied to conductive materials. Testing principle is the following: the signal generator provides high frequency alternating current to the probe in the detection coil, detection coil produces an alternating magnetic field, and the specimen produces eddy current. Eddy current is affected by the properties of the specimen, and in turn it changes impedance (voltage) of coil, then oscilloscope output impedance (voltage) of coil. Testing process includes picked up signal, signal amplification, signal processing, eliminated interference signal, and display and record test results.

There are two kinds of detection methods. One is a double-coil high frequency reflection, whose schematic diagram is shown in Fig. 1.it has a high detection sensitivity of surface defect, but it is lower defect sensitivity with deeper below the surface; The other is double-coil low frequency transmission, whose schematic diagram is shown in Fig. 2.

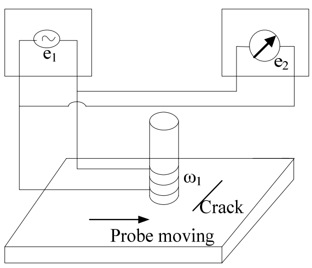

Fig. 1. Schematic diagram of low frequency reflection

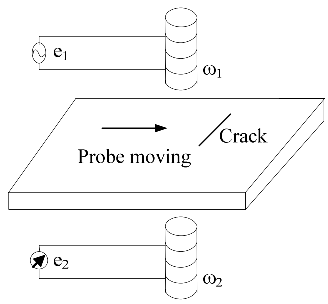

Fig. 2. Schematic diagram of high frequency transmission

Two methods have the same testing process. Signal generator produced alternating current flows through the coil, when the probe moves to the specimen, the eddy current will decrease. Impedance of the coil is displayed and recorded by the meter. Using auxiliary equipment to do comparative analysis of results from Standard specimens and defect specimens can obtain NDT results.

3 Theoretical Basis for Experimental Study

The workpiece signal of detected is from impedance of the detection coil or the induced voltage changes of secondary coil in eddy current testing.

We use long straight solenoid of cylindrical conductor as the object of research, suppose the radius of cylindrical conductor as *a* less than the solenoid inner radius *b*, and suppose turns of per unit length as n. In the cylindrical conductor ($0 < r < b$), the magnetic field strength is $\dot{H}_z(r)$, magnetic field strength is equal to the excitation magnetic field H_0 in the gap ($a < r < b$).Using the concept of Foster effective permeability can obtain the magnetic flux through the coil cross-section[3].

$$\dot{\Phi} = \mu_0 \mu_r \mu_{eff} H_0 \pi a^2 + \mu_0 H_0 \pi (b^2 - a^2). \qquad (1)$$

Coil phasor of induced electromotive force(EMF) per unit length is written as

$$\dot{\varepsilon} = -j\omega n \dot{\Phi} = -j\omega n \mu_0 \mu_r \mu_{eff} H_0 \pi a^2 - j\omega n \mu_0 H_0 \pi (b^2 - a^2). \qquad (2)$$

Coil no-load induced EMF per unit length is

$$\dot{\varepsilon}_0 = -j\varpi n \dot{\Phi} = -j\varpi n \mu_0 H_0 \pi b^2. \qquad (3)$$

Thus, coil of normalized induced EMF per unit length is

$$\frac{\dot{\varepsilon}}{\varepsilon_0} = 1 - \eta + \eta\mu_r \mu_{eff}. \qquad (4)$$

where $\eta = \frac{a^2}{b^2}$ — the coil filling factor. Considering relationship between the impedance per unit length and the induced voltage are $Z = \frac{\dot{U}}{\dot{I}}$, normalized impedance is

$$\frac{Z}{Z_0} = 1 - \eta + \eta\mu_r \mu_{eff}. \qquad (5)$$

From eqs (4) and (5), we can obtain the same expression by normalized induced EMF of the solenoid detection coil and normalized impedance, which can instead each other in calculating sensitivity. Moreover, if the detection coil and the excitation coils have the same flux and turns *N*, the induced EMF of detection coil is

$$\dot{U} = \dot{U}_0 (1 - \eta + \eta\mu_r \mu_{eff}) = 2\pi f N \mu_0 H_0 \frac{\pi d^2}{4} (1 - \eta + \eta\mu_r \mu_{eff}). \qquad (6)$$

where the induced EMF of detection coil is relation to excitation frequency *f*, detection coil diameter *d*, detection coil turns *N*, excitation magnetic field for H_0, fill factor η ,the effective permeability μ_{eff} .

4 Eddy Current Testing Scheme

According the principle of eddy current testing, the scheme is shown in Fig. 3.

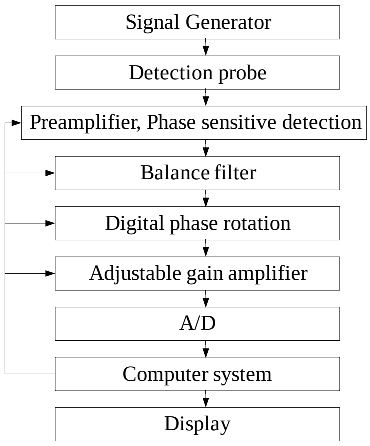

Fig. 3. Eddy current testing scheme

Signal Generator issues high frequency alternating signal to the detection probe, taking into account impedance of the exciting coil and detection coil may not be equal. We use a balanced circuit to eliminate the voltage difference between the two coils in pre-test.

In the detection, the detection coil to detect defective parts will produce a slight and imbalance signal. After amplification, phase sensitive detection, filter, and removed the interference signal will turn into the DC signal which contains phase and amplitude characteristics of impedance (voltage) of coil, at last displayed and recorded by display device.

According to records of the results, we draw the normalized sensitivity curves with the lift-off change, put forward recommendations for improvement of probe the form and carry out improvement by analyzing the curves. At the same time, we draw the normalized sensitivity curves with the lift-off change, and draw final test conclusions.

5 NDT Experimental Study

5.1 Test Preparation

In accordance with the testing program, preparing experimental apparatus, the main instruments include a high frequency signal generator, an oscilloscope , a standard copper , a defect copper whose depth of defect size is 2mm, and length of defect size is 12mm, multiple probes which have a single probe self-inductance coil (1000 turns), a single probe mutual inductance coil (500 turns each), two double probe transmission coils (500 turns).To make the coil diameter of probe is 8mm and 10mm, thickness is 4mm and 6mm.

5.2 Test Procedure

Test procedure is to build test equipment in accordance with testing program. We regulate output frequency of high-frequency signal generator as 4KHz, adjust lift-off distance of excitation coil and detection coil respectively as 0mm, 1mm, 2mm, 3mm, 4mm, 5mm. Using different forms probe test standard copper and defect copper, output voltage peak – peak value by oscilloscope, we draw the normalized sensitivity curves of the different probe forms with the lift-off change, Abscissa for the lift-off distance and ordinate for the normalized signal amplitude of specimens. Curves are the results of different probe forms including single probe self-inductance, single probe mutual inductance, double probe transmission, double probe reflection, double probe in series and in parallel. Output voltage peak-peak value of can be obtained form the display device.

5.3 Influence of Detection Sensitivity by Different Probe Forms

Fig. 4 and 5 are the normalized sensitivity curves with the lift-off change to initial test standard copper and defect copper. Curve 1 is the result of oscilloscope by directly connecting to signal generator, curve 2 is the detective result of the single probe, curve 3 is the result of the double probe in series, curve 4 is the no-load result of the double-probe, curve 5 is the result of double probe reflection, curve 6 is the detective result of the double probe transmission.

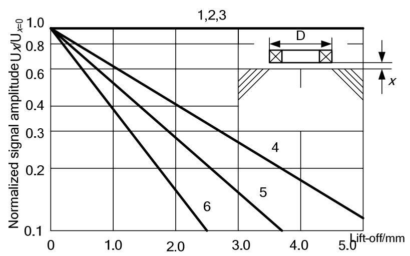

Fig. 4. Standard copper sensitivity curves with the lift-off

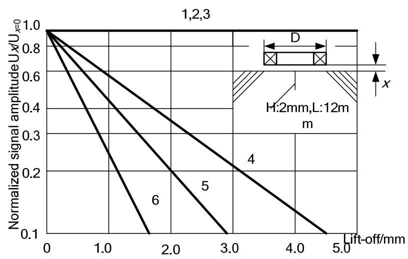

Fig. 5. Defect copper sensitivity curves with the lift-off

5.4 Influence of Impedance (Voltage) by Probe Diameter

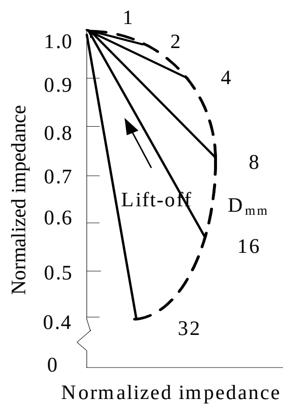

Fig. 6. Influence of impedance by probe diameter

Under the 4KHz high-frequency alternating signal generator, we change the probe diameter. Fig. 6 shows the influence of probe diameter, with the probe diameter increasing, the impedance moves down along the curves, as the coil diameter increases, the detection sensitivity decreases.

5.5 Improved Probe Test

Analyzing initial test results can obtain that probe size, coil thickness and coil turns closely related test results. Improved probe is the following : arranged the copper wire of probe as far as possible orderly, enhanced the magnetic flux density of the surface, increased the probe turns by 100 turns, changed the probe diameter for 8mm and thickness for 4mm. Using the improved appropriate probe include single probe self-inductance, single probe mutual inductance , double probe transmission, double-probe reflection , double-probe in series and in parallel to carry out NDT and experimental analysis, and draw sensitivity curves of Fig. 7 and 8.

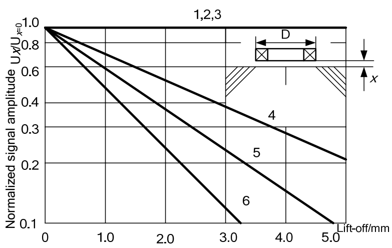

Fig. 7. Standard copper sensitivity curves of improved probe with the lift-off

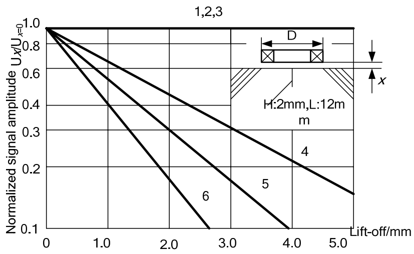

Fig. 8. Defect copper sensitivity curves of improved probe with the lift-off

5.6 Results and Discussion

We contrast sensitivity curve of before and after Probe improved.

1) Sensitivity curve 1 to 3 almost has no change under small lift-off distance. Curve 1 is the result of oscilloscope by directly connecting to signal generator, curve 2 is the detective result of the single probe, curve 1 and curve 2 almost coincide, it shows little effect on the output changes by single probe self-inductance. Curve 3 is the result of the double probe in series, curve 1 and curve 3 almost coincide, it shows the probe in series with different the number of turns, if equal of turns add, the results have no change.

2) Sensitivity curve 4 to 6 changes significantly, sensitivity of double-probe transmission no specimen is higher than the existing specimen, minimum sensitivity is double-probe reflection.

3) Detective sensitivity of standard copper is higher than defect copper. With lift-off distance increasing, sensitivity decreases rapidly, for example, Fig. 5 shows the defect signal amplitude down to the 1/ 4 of the surface when curve 6 lift-off for the 1mm,.

4) Comparing Fig. 4 and Fig. 7, Fig. 5 and Fig. 8, the sensitivity of improved probe is significantly higher than before improvement.

5) Probe diameter significant has influence on the detection sensitivity, with the coil diameter increasing, the detection sensitivity decreases. As diameter of the probe coil increases, the magnetic flux density of workpiece increases, the eddy current value increases, then the equivalent resistance decreases.

6 Conclusion

Eddy current NDT is high sensitivity for detecting defects of conductor surface and near surface, by comparison of the test, the following are concluding summaries:

1) The different probe forms have a significant influence on the ability of eddy current testing. Detectability of double probe transmission is greater than detectability of double probe reflection, detectability of double-probe is greater than detectability of single probe. The coil in series, detectability will be no change if equal of turns add.

2) Probe diameter has influence on the detection sensitivity, with the coil diameter increasing, the detection sensitivity decreases significantly. To increase detection sensitivity, the probe coil diameter must be equal to or less than the length of defects.

3) Probe placed has a great influence on the detection sensitivity, with lift-off distance increasing, detection sensitivity decreases rapidly.

4) Excitation coil has more influence than detection coils on detection sensitivity, increased excitation coils turns can help to improve the detection sensitivity, but increased detection coils turns will decrease the detection sensitivity.

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