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Numerical Simulation of the Reliability of In-Situ Eddy Current Testing Considering the Influence of Penetration Depth

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Abstract. In order to study the reliability of in-situ eddy current testing, the factors affecting the in-situ eddy current detection and the signal response values are firstly determined. Then the numerical simulation model of eddy current detection is established by COMSOL, and the different values of the device and the tested structural are substituted into the simulation model to obtain the signal response value. Finally, the probability of detection (POD) curve is obtained by numerical simulation method based on function model. In this paper, based on the numerical simulation method of probability density function, the numerical simulation of eddy current testing reliability is formed. Through the in-situ eddy current testing reliability numerical simulation case, the detection probability of cracks in the structure is quantitatively affected by the penetration depth.

1. Introductions

The purpose of non-destructive testing is mainly to determine whether there is a crack in the object to be tested. Properties such as physical parameters of cracks are analyzed when cracks are present in the structure.[1][2] In practical detection applications, eddy current testing determines the state of the test piece being tested by detecting changes in the impedance of the detecting coil. At the same time, eddy current detection is affected by many factors, such as the parameters of the detection equipment, the size of the object to be inspected and the cracks in the structure. In order to describe the detection of limit cracks by inspection equipment, detection probabilities are currently generally used to characterize the uncertainty of detecting small cracks. [3][4]

2. The theory of Eddy current testing

Eddy current detection technology is a non-destructive testing technology based on the principle of electromagnetic induction. When the exciting coil is connected with the alternating exciting current, the induced current is generated inside the conductor. This induced current is called eddy current [5]. In the impedance analysis method, when the excitation coil is placed above the metal conductor to be tested, the model formed by the interaction is equivalent to the relationship between the primary coil and the secondary coil. The probe excitation coil is used as the primary coil, and the eddy current loop in the conductor to be tested is used as the secondary coil. The model of the excitation coil is in the form of a series connection of a resistor and an inductor with an alternating excitation. The model of the detected conductor is in the form of a closed resistor in series with the inductor [6]. The complex impedance of the primary coil is expressed as:

$$Z=R+jX \tag{1}$$

Where R, X- the resistance and inductive reactance of the primary coil;

3. Research content

In this paper, by analyzing the basic principle of eddy current testing and impedance analysis, the test equipment parameters and the tested structural parameters are determined and substituted into the COMSOL numerical simulation model firstly. Then the quantitative effects of crack size and penetration depth on in-situ eddy current testing were studied respectively, and the corresponding crack detection probability (POD) curve was obtained. The two-parameter Weibull function was used to fit the POD curve. Finally, the crack size and penetration depth were obtained. The factors are combined to obtain the crack detection probability (POD) function under the influence of multiple factors. It can inversely calculate the minimum detectable size under a certain detection probability, which provides ideas for numerical simulation of in-situ eddy current testing reliability.

4. Establishment of simulation model for in-situ eddy current testing

Because the stress on the hole edge of the aircraft structure is concentrated and easy to be destroyed, the numerical simulation of the reliability of the in-situ eddy current test is carried out by using the common hole edge crack on the aircraft structure as the research object. The numerical simulation model of eddy current testing is established by using COMSOL simulation software. The parameters of the detection device and the detected structure is set, as shown in Table 1.

Table 1. Input parameter table for simulation model

Parameters	Values
Material of the detectded structure	Aluminum Alloy
Material of the coil	Copper
Inner diameter of the coil	Φ3mm
Outer diameter of the coil	Φ6mm
Frequency of probe	200kHz

By substituting the input parameters into the simulation model, a magnetic induction distribution map of the crack (0.39 mm*0.13 mm) can be obtained, as shown in Figure 1.

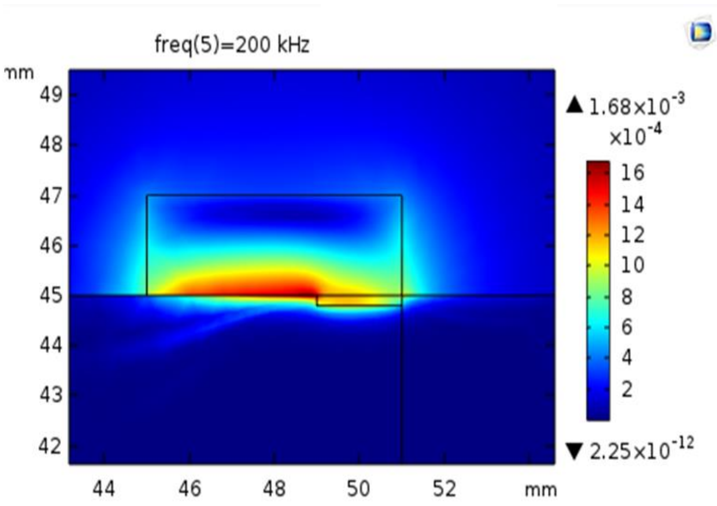

Figure 1. The distribution map of magnetic induction.

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After measuring the impedance value R_i with the probe of COMSOL, the impedance value R=(1.5680+13.037i) when the penetration depth d=0 mm, and the crack size a=(0.39*0.13) mm is obtained.

5. Research on numerical simulation of eddy current testing reliability

5.1. Numerical simulation of reliability considering the influence of penetration depth

As the penetration depth between the detecting device and the detected structure is greater, the electromagnetic field generated by the device coil has a weaker influence on the induced magnetic field formed by detected the structure. It means the greater the penetration depth, the smaller the impedance value, thereby affecting the probability of the crack detection.

Taking the hole edge crack as 0.39mm*0.13mm as an example, when there is no crack at the edge of the hole, the impedance value measured by the simulation is the threshold value R_0=0.3336Ω. When in-situ eddy current testing is performed on the edge crack, the penetration depth should be randomized. It is assumed that the penetration depth between the detection device and the structure under inspection obeys the normal distribution N~(10.5,0.1), and the penetration depth data subject to the normal distribution is substituted into the eddy current detection numerical simulation to obtain the probability density of the corresponding impedance value. By integrating the probability density, the detection probability value of the hole edge crack at the penetration depth d=10.5 mm is obtained, as shown in Figure 2.

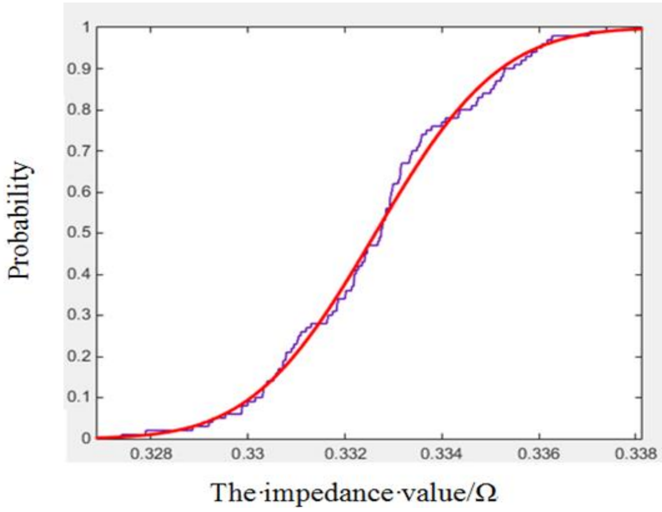

Figure 2. The probability curve of Crack detection when d=10.5mm.

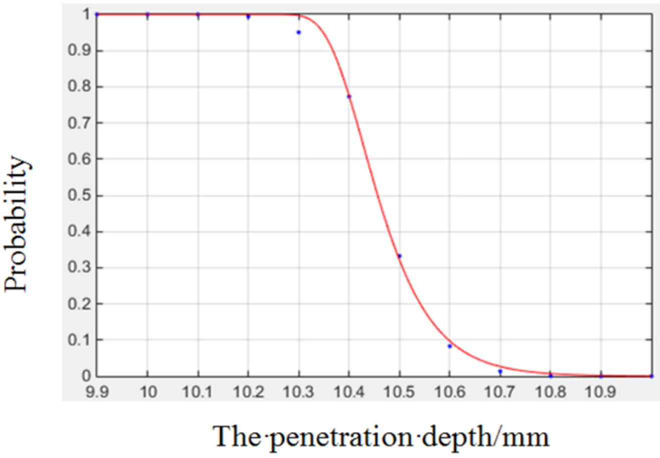

Figure 3. The curve of probability varying with penetration depth.

When the penetration depth d=10.5 mm, the crack detection probability P_h=0.33. The crack detection probability values at different penetration depths can be obtained by repeating the above process, as shown in Table 2.

Table 2. The detection probability of cracks at different penetration depths.

Penetration depths/mm	9.9	10.0	10.1	10.2	10.3	10.4
The detection probability	1	0.9999	0.9998	0.9941	0.9504	0.7730
Penetration depths /mm	10.5	10.6	10.7	10.8	10.9	11
The detection probability	0.3322	0.0829	0.0138	0.0005	1E-05	0

Using the two-parameter Weibull function to fit the detection probability values at different penetration depths, the curve of crack detection probability with penetration depth can be obtained, as shown in Figure 3.

Then the probability of crack detection with the change of penetration depth is expressed as:

$$P = 1 - \exp\left[-\left(\frac{d}{10.43}\right)\right]^{-140.8} \tag{2}$$

5.2. Function of POD curve and determination of minimum crack

Since the research content is under in-situ conditions, it is affected by many factors when performing in-situ eddy current testing. Therefore, the probability of in-situ eddy current detection under the influence of crack size and penetration depth should be studied next. In the in-situ eddy current testing of the hole edge crack, firstly, the numerical simulation of multiple cracks at the same penetration depth and one crack at multiple penetration depths was carried out by using COMSOL. The impedance values are obtained by the simulation. Then the same process as 5.1 can be used to find the detection probability of different cracks at different penetration depths. Then use the two-parameter Weibull function to fit the POD curve (as shown in Figure 4) and the corresponding POD function (as shown in Table 3).

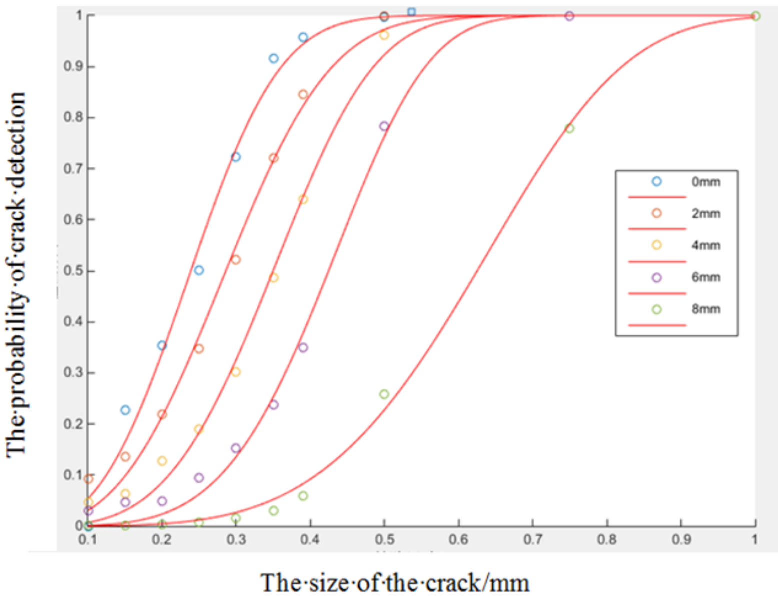

Figure 4. The POD curve of crack detection probability.

Table 3. Summary of POD functions and Detectable minimum size.

Penetration depth/mm		0	2	4	6	8
Weibull function: $P = 1 - \exp\left[-\left(\frac{a}{\beta}\right)\right]^{-\alpha}$	α	**2.90**	**2.95**	**3.65**	**4.48**	**4.41**
	β	**0.27**	**0.32**	**0.39**	**0.46**	**0.68**
Detectable minimum size /mm		0.36	0.43	0.49	0.56	0.82

Therefore, The detection probability of different cracks at different penetration depths can be quantitatively calculated by the POD function in Table 3. Finally, the POD function obtained by the Weibull function fitting inversely calculates the minimum crack size detectable under a certain detection probability, as shown in Table 3. As can be seen from Table 3, the minimum detectable crack size gradually increases with the penetration depth increases and the minimum crack size can be quantitatively calculated.

6. Conclusions and Prospect

In order to quantify the influence of penetration depth on the reliability of in-situ eddy current testing, the crack detection probability (POD) under different conditions was obtained by numerical simulation of in-situ eddy current testing. The conclusions are summarized as follows:

1) By analyzing the basic principle of in-situ eddy current testing, the numerical model of in-situ eddy current detection was established by COMSOL. The impedance values at different crack sizes and penetration depths are obtained, and the probability density function of the impedance values is obtained. When the impedance value is greater than the threshold value, the crack can be detected, otherwise it cannot be detected. The probability of detecting the crack is obtained at the same time. The two-parameter Weibull function is used to fit the crack detection probability to obtain the detection probability (POD) function. The numerical simulation method of in-situ eddy current detection reliability is formed.

2) The probability of detection under different penetration depths is obtained by case calculation. The POD of different cracks can be calculated by the POD function, and the influence of penetration depth on the reliability of eddy current detection is quantitatively characterized.

3) The case shows that when the detection probability of the crack in the structure is 90%, the minimum size of the detectable crack increases from 0.36mm to 0.43mm as the penetration depth changes from 0mm to 2mm. The minimum size of the detected crack increases by 19.4%.

In addition to eddy current testing, there are various non-destructive testing techniques such as ultrasonic testing, radiation detection and magnetic particle testing. Therefore, various non-destructive testing reliability studies can be carried out for different defects in other structures.

Acknowledgements

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