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Evaluation of the flaw depth using high- T_c SQUID

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Abstract

Using high- T_c SQUID, we investigated quantitative nondestructive evaluation for flaws in conducting samples. The spatial derivative of the defect field was found to provide valuable information about the position and the depth of the flaw. By analyzing the spatial derivative of the defect field, the quantitative flaw evaluation was demonstrated. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: SQUID; Nondestructive evaluation; Flaw depth; Defect field

1. Introduction

In last decade, many researchers have made efforts to develop the SQUID-based nondestructive evaluation (NDE), which is a powerful tool for detecting deep flaws [1,2]. Among many remarkable works [3–9], the method utilizing the sheet inducer was report to be useful for performing the phase-sensitive flaw detection with SQUIDS. The uniform excitation generated by the sheet inducer is advantageous for analyzing the eddy-current problem, but the spatial resolution is limited to the SQUID-to-sample distance because of the uniform excitation field. In contrast, the method using the differential coil exciter has achieved a better spatial resolution [4–9]. But it is a challenge to use the differential coil exciter for the quantitative flaw evaluation because the anti-symmetric excitation field introduces a complex

eddy-current problem. To avoid solving the complex eddy-current problem, we investigated the empirical relation between the defect field, which is the magnetic field due to the eddy current around a flaw, and the depth of the flaw in this work. The differential defect field was proposed to correlate the detected field with the depth and the position of flaws.

2. Experimental details

The electronics used for the SQUID NDE system was described elsewhere [8,9]. The SQUID used in the system was a commercialized dc SQUID fabricated by Conductus Inc. The SQUID was mounted at 18 mm above the center of the differential coil exciter, where the excitation field generated by the differential coil exciter was zero. The distance from the sample to the differential coil exciter was 2 mm. To operate the system in the unshielded environment, we utilized a small μ -metal cylinder to shield the SQUID. In this way [6,9], the dynamic range of the SQUID NDE

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system was enhanced. For the optimal signal-to-noise ratio, the impedance of the coil exciter was designed to be equal to that of the excitation source to achieve the highest excitation field.

3. Results and discussion

The vertical component of the excitation field generated by the differential coil exciter was calculated according to the Biot–Savart law as shown in Fig. 1. The excitation current in the coil was 1 A, and the diameter of the coil exciter is $D = 28$ mm. The symbol d shown in Fig. 1 represents the vertical distance measured from the plane of the coil to the SQUID, or to the sample beneath the coil. The excitation field, B_z , is found to be anti-symmetric with the zero amplitude at $x = 0$ for various d s. Since the SQUID was mounted right above the center, $x = 0$, of the coil, the magnetic field sensed by the SQUID is zero. Besides, when d is much smaller than D , the maximum excitation field occurs at the centers of the left and right branches of the differential coil exciter. For $d > 16$ mm, the locations for the maximum excitation field move apart. For $d \gg D$, the

locations for the maximum excitation field move further apart, and the differential coil exciter behaves like a magnetic quadrupole.

When the differential coil exciter scans over a crack-like flaw with the symmetric axis on the plane of the coil parallel to the line of the crack, the in-phase and the quadrature-phase defect fields are also anti-symmetric across the position of the flaw if the height and the width of the crack was much smaller than the diameter of the excitation coil [7–9]. However, the anti-symmetric defect fields are usually accompanied with an offset field, which may be caused by the tilting of the differential coil exciter, or the asymmetry metallic objects near the SQUID. Once there is an offset field, the phase of the defect field varies. It was reported that the unwanted offset can be removed by using the additional compensation [7,9], but it is not practical to apply this technique when the position of the flaw is unknown. As the offset field usually varies slightly at various positions, it is reasonable to remove the offset field by differentiate the defect field with respect to the horizontal position. The spatial derivatives of the in-phase and quadrature-phase defect field above a buried flaw is shown in Fig. 2. Since the spatial derivative has a maximum

Fig. 1. Vertical component of the excitation field beneath the 28 mm differential coil exciter. The excitation current in the coil is 1 A. The excitation field is negligible for $|x| > D$.

Fig. 2. In-phase and quadrature-phase differential defect field over a slot buried in an aluminum slab. The excitation frequency is 400 Hz. The depth of the flaw is 2.2 mm.

Fig. 3. Phase of the differential defect field over the slot buried at 0.7–8.2 mm deep in an aluminum slab. The excitation frequency is 400 Hz.

or a minimum at the point of inflection of the defect field, the position of the flaw is indicated by the peak or valley of the in-phase and the quadrature-phase “differential defect field” as shown in Fig. 2. The phase of the differential defect field for various flaw depths is shown in Fig. 3. It was found that the phase of the differential defect field is quite uniform near the position of the flaw. In addition, the phase at the position of the flaw changes uniformly as the flaw depth increases. This behavior is quite similar to the depth dependence of the phase for the defect field, which is a linear function of the flaw depth [9]. In fact, it can be proved that phase of the differential defect field approximates to that of the defect field near the position of the flaw. If $x = 0$ was chosen as the position of the flaw, the phase of the defect field at the position x can be written as

$$\phi(x) = \tan^{-1}[B_{90^\circ}(x)/B_{0^\circ}(x)], \quad (1)$$

in which $B_{0^\circ}(x)$ and $B_{90^\circ}(x)$ are the in-phase and the quadrature-phase defect fields respectively, and $\phi(x)$ is the phase of the defect field. Using the Taylor's expansion, $B_{0^\circ}(x)$ and $B_{90^\circ}(x)$ can be approximated in the vicinity of $x = 0$,

$$B(x) = B(0) + \left(\frac{dB}{dx}\right)\bigg|_{x=0}x + \frac{1}{2}\left(\frac{d^2B}{dx^2}\right)\bigg|_{x=0}x^2 + \dots, \quad (2)$$

in which $B(x)$ stands for $B_{0^\circ}(x)$ or $B_{90^\circ}(x)$. Because the defect field $B(x)$ is anti-symmetric, the first and the third terms on the right-hand side of Eq. (2) are zero. Thus,

$$\begin{aligned} \phi(x \rightarrow 0) &= \tan^{-1}[B_{90^\circ}/B_{0^\circ}]_{x=0} \\ &\approx \tan^{-1}[(dB_{90^\circ}/dx)/(B_{0^\circ}/dx)]_{x=0}. \end{aligned} \quad (3)$$

Hence, the phase of dB/dx is equal to the phase of $B(x)$ at the position of the flaw.

Although the phase of the differential defect field is close to the phase of the defect field at the position of the flaw, the spatial variation of the phase is more radical for differential defect field. As it was shown in Fig. 3, the phase of the differential defect field changes rapidly when $x \approx \pm D/4$. At these positions, the defect fields were about at maximum, and the differential defect fields were about zero as it was shown in Fig. 2. The rapid change in the phase of the differential defect field is beneficial for the evaluation of flaw because the position of the flaw could be easily identified with the U-shaped curves as it was shown in Fig. 3. In addition, the phase of the differential defect field at the bottom of the U-shaped curve corresponds to the depth of the flaw.

To demonstrate the flaw evaluation with the differential defect field, a sample with flaws at different depths was explored as shown in Fig. 4. The flaws were 50 mm long slots, which were 1.5 mm in thickness and 1 mm in width. They were buried 4 and 7.2 mm in depth respectively inside the conducting slab, which is 160 mm $\times$ 60 mm $\times$ 10 mm in dimension. With an excitation frequency of 400 Hz, the spatial variation of the defect field above the sample is shown in Fig. 4(a). The corresponding differential defect field is shown in Fig. 4(b), and the phase of the differential defect field is shown in Fig. 4(c). It was found that the positions of flaws were easily identified according to the local maximum or minimum of the differential defect field as shown in Fig. 4(b). In addition, the positions of the flaws were also identified by the U-shaped curve of the phase of the differential defect

Fig. 4. Spatial variation for the in-phase and the quadrature-phase components of (a) the defect field, (b) differential defect field over the sample with buried flaws. The spatial variation for the phase of the differential defect is shown in (c). The dimension of the sample is $60 \text{ mm} \times 160 \text{ mm} \times 10 \text{ mm}$, and the diameter of the differential coil exciter is $D = 28 \text{ mm}$. The excitation frequency is 400 Hz .

field. The phase of the differential defect field was found to change rapidly near the margins of the $D/2$ region, in which $D = 28 \text{ mm}$ was the diameter of the differential coil exciter. The values at the bottom of the U-shaped curves corresponds to the flaw depth since these value is equivalent to the phases of the defect field, which were linear functions of the flaw depth [9]. Hence, the depths of the flaws were evaluated from these values. According to the results shown in Fig. 4(c), the depths of the flaws were found to be 4.0 and 7.2 mm respectively, which were the same as the depths of the buried flaws. In addition, the horizontal distance between the flaws was found to be 5.5 cm according to the distance between the U-shaped curves. The evaluated distance was exactly the distance between the flaws.

The spatial resolution for distinguishing two buried flaws was limited to the diameter of the

Fig. 5. Phase of the differential defect for slots spaced by 0 mm , 10 mm , and 20 mm . The dimension of the sample is $60 \text{ mm} \times 160 \text{ mm} \times 10 \text{ mm}$, and the diameter of the differential coil exciter is $D = 11 \text{ mm}$. The excitation frequency is 400 Hz .

excitation coil when the phase of the differential defect field is used for flaw characterization. To investigate this point, the phase of dB/dx for two slots separated by a horizontal distance Δx was explored as shown in Fig. 5. The diameter of the coil exciter was 11 mm . When the horizontal position of the two slots overlapped, the phase of differential defect field exhibited an U-shaped curve at the position of these slots. In this case, the two slots were identified as one slot. We noted that the width of the U-shaped curve is wider than $D/2$ because the diameter of the coil is not much greater than depth of the flaw. As the horizontal distance between the slots increased to $\Delta x = 10 \text{ mm}$, the U-shaped curve moved to the position of the shallower slot. At the same time, a smaller U-shaped curve occurred at the position of the deeper slot. This implied that the defect field of the shallower slot dominated because of the greater signal magnitude. When the horizontal distance increased to $\Delta x = 20 \text{ mm}$, the U-shaped curve at the position of the deeper slot separated from that of the shallower slot. Hence, the minimum distance Δx for distinguishing the two slots is $\Delta x \approx D$ because the interference between the defect fields of the two slots become negligible for $\Delta x > D$. This is also suggested by the spatial distribution of the

excitation field, which is effective for $|x| < D$ as it was shown in Fig. 1.

4. Conclusion

In conclusion, the evaluation of flaw depth was investigated by using the differential coil exciter. The magnitude and the phase of the differential defect field were correlated directly to the defect field. For the crack-like flaw with the width and the height much less than D , the phase of the differential defect field is useful in indicating the flaw depth at least for the flaw depth smaller than D . Using the differential defect field instead of the defect field is beneficial because the unwanted offset field is removed in taking the spatial derivative.

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