Research on the Influence of Noise to Laser Ultrasound SAFT for Lead Defect Detection

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Abstract. Synthetic Aperture Focusing (SAFT) is one of the methods to improve the spatial resolution in the traditional acoustics field. Its basic principle is to combine a series of small-aperture sensors to replace a large-aperture sensor in order to improve the detection lateral resolution. However, the practical detection results will be affected by noise. In this paper, the time-domain B-scan signal is obtained by establishing a physical model of a lead sample containing defects and computing with finite element method. Then, the influence of noise with different signal-to-noise ratio(SNR) on SAFT imaging results is studied. The results show that SAFT algorithm has better anti-noise performance, and can still obtain good results even when the SNR is low.

1. Introduction

When the ultrasonic are used to detect the defects in the material, the horizontal resolution is affected by the width of the ultrasonic beam. For a transducer with aperture of $D$ and wavelength of $\lambda$, the half-power beam angle is proportional to the wavelength of $\lambda$ and inversely proportional to aperture $D$. Therefore, in order to improve the lateral resolution, a large aperture transducer was used to reduce the half-power beam angle of the ultrasonic wave. However, the aperture of the transducer cannot be too large for the complex shape samples, which limits the horizontal resolution improved [1]. In this case, the laser ultrasonic technology can be considered, and combined with SAFT algorithm.

Laser ultrasound technology is an interdisciplinary discipline that combines ultrasound with laser technology, which enables long-range, non-contact non-destructive testing of complex, smaller samples. Synthetic aperture focusing technology (SAFT) is one of the ways to improve detection resolution in the traditional acoustic field. The basic principle is to combine a series of single small aperture sensors instead of a large aperture sensor in order to improve the detection of lateral resolution.

SAFT technology was first used in radar. Flaherty and Burckhardt [2] et al. expanded the technology to ultrasonic detection in the 1970s to improve ultrasonic resolution. The effects of different parameters on the time domain SAFT imaging are studied by Johnson et al. [3]. The side lobe was successfully inhibited with multiplying different weighting coefficients on different echo signals with by Burch et al. [4]. Lockwood et al. [5] proposed a SAFT imaging method for sparse cycle array probes, which can reduce the generation of side lobes and achieve high frame rate imaging by using different sensor spacing for emission and reception. Karaman et al. [6] proposed an ultrasonic sub-aperture treatment based on synthetic aperture and beam space interpolation. Lorraine et al. [7] have...
for the first time combined SAFT with laser ultrasonic.

In conventional laser ultrasonic, the optical detection methods, such as optical deflection and interference, usually requires smooth sample surface. Whereas in fact, the material to be inspected in industry is often difficult to meet this condition. Therefore, the actual laser ultrasonic signal always contains a variety of noise, which affects the results of using laser ultrasonic SAFT defect detection method. Lead has good ductility, corrosion resistance and sealing. It is easy to make excellent performance alloy with other metals. It is widely used in high-voltage cable accessories sealing. However, there may be minor defects in lead products and affect the subsequent use of the product. In order to study the effect of laser ultrasonic signal-noise ratio(SNR) on the defect detection results of laser ultrasonic SAFT in lead samples, this paper first establishes lead samples containing defects, and obtains the time-domain B-scanning signal with finite element method. Then the effect of signals for different SNR on SAFT imaging results was studied. It provides reference for laser ultrasonic SAFT applications in lead layer packaging of power cable accessories.

2. Methods

2.1 Numerical Simulation Model

In order to study the effects of noise on laser SAFT imaging, the physical process was simulated with COMSOL multiphysics software. In the calculation process, the two modules of thermal transmission and solid mechanics are used to simulate thermal expansion after laser incident the sample surface. Local thermal expansion in turn stimulates ultrasonic waves in the sample, which spread through the sample. The model used in the numerical calculations is shown in Figure 1. Table 1 lists the lead material properties.

| Parameter                   | Value            |
|-----------------------------|------------------|
| Density/(kg/m³)             | 11645.61         |
| Young's modulus /MPa        | 3.22×10⁴         |
| Poisson's ratio             | 0.39             |
| Thermal expansion coefficient/K⁻¹ | 2.4×10⁵         |
| Lamé instant λ(N·m²)        | 4.11×10¹⁰        |
| Lamé instant μ(N·m²)        | 1.16×10¹⁰        |

The model is 7mm wide and 2.6mm high. The abscissa value of the left boundary is -3.5mm, and the right boundary is 3.5mm. The ordinate value of upper-side boundary is 0mm and the lower border is 2.6mm. The left, right, and lower interfaces are treated with low-reflection interfaces, so the entire model can be treated as half an infinite space.

The point of laser ultrasonic excitation is centered on the surface of the model (0, 0). The position of defect center is (0, -1.44). The defect circle radius is 0.1mm. The vertical wave velocity is 1676m/s, and the surface wave is 808m/s.
Figure 1. Physical models

Figure 2 shows the B-scan image obtained by using the reflected wave in Figure 1. The horizontal axis is the location of the detection point, and the vertical axis is time. In the Figure 2, SP represents the grazing longitudinal wave. R represents the direct surface wave. rR-1 represents the surface wave reflected by the left boundary of the sample. rR-2 represents the surface wave reflected by the right boundary of the sample. In addition to the ultrasonic waves of the above modes, two curves C1 and C2 can be seen. The C1 curve is the S-wave signal scattered back to the detection point after arriving at the defect from the excitation point. The C2 curve is the mode conversion signal after the body wave meets the defect.

2.2 Laser Ultrasonic SAFT Method

SAFT is used to improve detection resolution in the field of traditional acoustics. SAFT derived from synthetic aperture radar technology (SAR), was introduced into the field of ultrasonic imaging in the 1970s[2]. The basic idea is to use the pulse echo mechanism. This method uses ultrasonic transducers to scan samples along fixed trajectories and focus on pulsed echo signals by time-lapse overlay method, thus simulating large aperture arrays with a single small aperture ultrasonic transducer[8].

In this paper, laser ultrasonic and SAFT technology with a number of "single point excitation, multi-point detection" was approach to detect the defects in the lead. As shown in Figure 3. The green dots represent the detection points, and the red dot represents the excitation points. m is the number of probe points. n is the number of excitation points. For each probe point, a series of ultrasonic signals are obtained by moving the excitation point position, until the all the probe points were achieved. Suppose point A is any point within the sample, and the A-point coordinates are \((x_A, y_A)\). Excitation point coordinates are \((x_e, 0)\), \((e=1,2,3,\ldots, n)\). Detection point coordinates are \((x_d, 0)\), \((d=1,2,3,\ldots, m)\). \(d_1\) and \(d_2\) are the distance between excitation point \((x_e, 0)\) and detection point A.

\[
d_1 = \sqrt{(x_A - x_e)^2 + y_A^2} \tag{1}
\]

\[
d_2 = \sqrt{(x_A - x_d)^2 + y_A^2} \tag{2}
\]

\(v\) is the sound velocity. \(t_A\) is the transmission time of laser ultrasonic from point A to the excitation point:

\[
t_A = (d_1 + d_2)/v \tag{3}
\]

Assume there is a defect at point A, then there will be a reflection peak caused by defect at the \(t_A\) moment of the signal \(S(x_e, x_d, t)\). If there is no defect at point A, there will be no reflection peak caused by A at the \(t_A\) moment. Then the expression of the reconstruction of the inside point A of the sample is:

\[
P(A) = \sum_{e=1}^{m} (\sum_{d=1}^{n} S[x_e, x_d, t_A]) \tag{4}
\]

The same processing of all pixels in the sample gives an inversion of the entire region. Because
SAFT technology superpositions the resulting signal $N$ times, the SNR can be increased to $\sqrt{N}$ time.

![Figure 3. Schematic of laser ultrasonic SAFT method](image)

3. Results and Discussion

3.1 Defect Imaging with Noise Free Ultrasonic Signal by Laser Ultrasonic SAFT Method

The results obtained by the SAFT algorithm is shown in Figure 4 with noise free ultrasonic signal. As shown in the Figure 4, the defect has a strong reflection signal in the center of the graph. It indicates that the SAFT algorithm has the ability to detect the defects in lead samples with noise free.

However, in practice, the laser ultrasonic signals always contain noise of different intensity. Therefore, it is of great significance to study the influence of noise on the reconstruction results of SAFT.

![Figure 4. Results obtained using SAFT algorithm without noise](image)

3.2. Influence of Different SNR on Defect Imaging Results by Laser Ultrasonic SAFT Method

Based on simulation, the white noise was added to the laser ultrasonic signal. Then the defect is imaged by SAFT algorithm to verify the effect of noise with SAFT algorithm. The laser ultrasonic signal after adding noise satisfies the SNR: $\text{SNR}=10; \text{SNR}=2; \text{SNR}=0.17$. Then, smooth filtering is used to reduce noise and analyze the effect of noise on SAFT reconstruction results.

When SNR is 10, the result is shown in Figure 5. In Figure 5(a), the red line is the original signal, the black line is the signal that adds noise (SNR = 10), and the green line is the result of filtering. Figure 5(b) shows the results reconstructed by SAFT algorithm.
Figure 5. The result of using SAFT when SNR is 10. (a) The red line is the original signal, the black line is the signal that adds noise (SNR ≤ 10), and the green line is the result of filtering. (b) Defect imaging by laser ultrasonic SAFT method.

Comparing Figure 5(b) with Figure 4, it can be found that the defect is imaging well when SNR is 10 although the overall brightness of the defect image disfigured. The result shows that the imaging effect of laser ultrasonic SAFT will not be significantly affected at such SNR.

In Figure 6(a), the black line is the signal that adds noise satisfy SNR = 2. By comparing Figure 5(a) with Figure 6(a), the laser ultrasonic signal of Figure 6(a) shows stronger noise interference. Figure 6(b) shows the results reconstructed by SAFT algorithm when laser ultrasonic signal SNR is 2.

Figure 6. The result of using SAFT when SNR is 2. (a) The red line is the original signal, the black line is the signal that adds noise (SNR = 2), and the green line is the result of filtering. (b) Defect imaging by laser ultrasonic SAFT method.

Comparing Figure 6(b) with Figure 4, it shows that the defect is imaging well still. However, the size of the defect imaging is bigger than the result in Figure 5(b). The results show that the noise intensity of ultrasonic signal reduces the defect resolution of laser ultrasonic SAFT method.

In Figure 7(a), the green line is the original signal, the black line is the signal that adds noise satisfy SNR = 0.17, and the red line is the result of filtering. In Figure 7(a), the laser ultrasonic signal shows more stronger noise interference, and the red line filtered has more fluctuation than the original signal. Figure 6(b) shows the results reconstructed by SAFT algorithm when laser ultrasonic signal SNR is 0.17. It can be seen from Figure 7(b) that although the defect can be reconstructed by using the SAFT algorithm, the reconstruction results are relatively significantly affected by the noise at this SNR, and obvious false signal can be observed in the figure. The results show that laser SAFT method has good anti-noise ability, but when the SNR is very bad, it may bring false signal.
4. Conclusion
SAFT is one of the ways to improve the detection resolution in the traditional acoustic field. A series of single small aperture sensors can be combined to replace a large aperture sensor to improve the detection transverse resolution. However, SAFT cannot avoid the influence of noise in laser ultrasonic testing. In this paper, the simulation model of lead sample containing defects is established, and the laser ultrasonic signal is obtained by using the finite element method. Then, the influence of noise on the reconstruction algorithm of SAFT is studied by adding noise with different SNR. The results show that the SAFT algorithm has better anti-noise ability after simple noise reduction. But in the case of bad noise, it may bring false signal. The results provide a reference for the practical application of laser ultrasonic SAFT technology.

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6. References
[1] Junyan L., Zhonghua S., Xiaowu N., Ling Y., and Chenyin N, Chinese Journal of Lasers, 2018, 45(9): 0904003
[2] Flaherty J.J., U.S. Patent: 3,548,642, 1970-12-22
[3] Johnson, J., Review of Progress in QNDE, 1982, 1:735-752
[4] Burch S.F., and Burton J.T., Ultrasonics, 1984, 22(6): 270-274
[5] Lockwood, G.R., and Foster, F.S., ULTRASONICS SYMPOSIUM, 1991, 2(1):1237-1244
[6] Karaman, M., and O’Donnell, M., IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control, 1998, 45 (1): 126-135
[7] Hutchins, D.A., Dewhurst, R.J., and Palmer, S.B., Acoustical Society of America Journal, 1998, 70(5): 1362-1369
[8] Guan, X., He, J., and Rasselkorde, E.M., 2015, 56: 487-496