Detection of defects of different types in lead by laser ultrasonic SAFT

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Abstract. Lead is widely used in the installation of high voltage cable accessories. Defects in lead tend to cause serious electrical accidents. However, there is no means to detect the sealing quality yet. In this paper, laser ultrasonic synthetic aperture focusing technology (SAFT) technology is applied to the detection of lead sample defects. The SAFT algorithm is used to locate and image the various types of defects in lead samples. The results show that SAFT laser ultrasonic is suitable for detecting sub-millimeter small defects in the lead. This technology has some application prospect in the detection of high-voltage cable sealing lead layer quality.

1. Introduction
Lead has good ductility, corrosion resistance and sealing. And lead tin alloy can be easily obtained. It is widely used in high-voltage cable accessories sealing. However, there may be minor defects in lead products, which may affect the subsequent use of the product. In recent years, many of the cable failures because of the seal quality defects of sealing lead layer. Figure 1 shows an example of lead sealing failures.

Figure 1. Failed lead sealing layer.

Therefore, it is important to check them to ensure reliability. Traditional ultrasonic testing relies on a coupling agent and requires direct contact between the probe and the sample. Therefore, it is not suitable for detecting lead products with complex shape or for long-distance inspection. In this case, laser ultrasonic, a long-range, non-contact detection technique, could be considered.

However, when the defect size is sub-millimeter magnitude or smaller, the signal-to-noise ratio (SNR) of ultrasonic echo signal is low. Traditional laser ultrasonic technology is difficult to locate the defect. Synthetic aperture focusing technology (SAFT) as a common signal processing method in ultrasonic
imaging, can increase the SNR, and obtain a higher resolution image of the defects at low signal amplitude. By combining laser ultrasonic technology with SAFT, it can improve detection accuracy and imaging contrast.

In 1997, Lorraine et al. applied SAFT technology to the laser ultrasonic, improving the ability of laser ultrasonic technology to detect small defects, and enabling imaging of material surface and internal defects [1]. Since then, Blouin [2] and Lévesque [3] have used SAFT technology to improve the spatial resolution and SNR of laser ultrasonic non-destructive testing, and to detect millimeter-magnitude defects on the surface of aluminum blocks. Lévesque et al. [4-5] have been working on SAFT laser ultrasonic technology, and has proposed two algorithms, time and frequency domains, to detect defects in the millimeter magnitude of the weld, as well as defects in the aluminum material. Selim et al. [6] combined laser ultrasonic technology with traditional sensor detection technology, using SAFT technology to detect defects with vertical size millimeter magnitude. Li Junyan et al. [7] proposed the SAFT imaging method with separating the excitation point from the detection point.

Various types of defect arise in lead, such as: holes, inclusions, cracks, unmelted and so on. Ultrasonic has different propagation characteristics after interaction with different types of defects. Laser ultrasonic sensitivity to different morphological defects, and images quality of different types defects reconstructed with SAFT algorithms, vary under the same scanning method. Besides, laser ultrasonic has a specific propagation direction, the different direction of defects under the same scanning method may affect the image quality. Therefore, this paper focuses on the SAFT to detect different types of defects inside the lead block. The SAFT algorithm was optimized based on the directionality of laser ultrasonic propagation. The result has important references for the defects detection of the cable accessories lead-sealing layer.

2. SAFT principles
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. The basic idea is to improve the resolution of a pulse-echo inspection data set. This method uses ultrasonic transducers to scan samples along fixed trajectories and focus on pulsed echo signals by time-lapse overlay (DAS) method, thus simulating large aperture arrays with a single small aperture ultrasonic transducer.

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 2. 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.

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

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

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

\[
t_A = \frac{d_1 + d_2}{v}
\]

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:

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

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.
3. Imaging of different types defects with laser ultrasonic SAFT technology

Compared with traditional ultrasonic, laser ultrasonic has the characteristics of multimode and broadband. And the body waves excited by laser have a certain direction. Therefore, when SAFT imaging technology is applied to laser ultrasonic, these features should be considered. We optimize the algorithm based on these features of laser ultrasonic. For the multimode and broadband characteristics of laser ultrasonic, we use band-through filtering in our algorithms to improve the signal SNR. For the directional characteristics of laser ultrasonic propagation, we use the coefficient-weighted method to strengthen the area of laser ultrasonic propagation while weakening other regions. Figure 3(a) shows the results of imaging directly using the ultrasonic SAFT algorithm. The figure shows serious interference formed on the upper surface of the sample due to the influence of surface wave and thermal expansion. In this case, we can use windows filtering at the time domain signals of laser ultrasound, and then the influence area of surface wave and thermal expansion can be removed. Figure 3(b) is the result of our improved SAFT algorithm. Figure 3(b) shows better results and enables SAFT algorithm imaging of smaller defects.

Since Laser ultrasonic SAFT technology detect the defects with reflection waves, the sensitivity to defects with the same shape but different directions is different. Thus the geometric characteristics and direction of defects must be considered.

3.1. Imaging defects with different geometric features

According to the geometric characteristics, the defects can be roughly divided into volume defects and area defects. Volume defects are mainly characterized by internal holes, bubbles, inclusions, and so on, which can be simplified to circular defects. The area defects are mainly characterized by cracks, unmelted, mezzanines, faults, and so on, which can be simplified to elliptical defects. The corresponding circular and elliptical defects after the two typical types of defects are simplified here.

For the homogenous lead samples, the three-dimensional (3D) model can be simplified to a two-dimensional (2D) model in the case of excitation light as a line source. The penetration depth of the metal lead to the laser with a wavelength of 1064nm is about ten nanometers, and the reflection rate is 0.84. Then the thermal action of the laser can be regarded as a boundary condition, equivalent to the
surface there is a certain spatial distribution and changes over time of the thermal flow. The simulation model used in this paper can be found in reference [8].

Four high 3mm defective lead samples were used in this paper. Two of which have a circular through hole defect, 0.2mm and 0.1mm in diameter, buried depth of 2.3mm. The other two samples have an oval through hole defect. The long axis is 0.6mm, the short shaft is 0.2mm and 0.1mm, depth of 2.3mm.

The excitation area and the detection area are located on the upper surface of the sample. The excitation step is 1.00mm, for a total of 5 excitation points, and the detection step length is 0.05mm for a total of 101 detection points. Each time after the ultrasonic wave is excited at an excitation point, a set of echo signals is detected in the detection area, the signal is processed by SAFT algorithm, and five sets of inversion data are superimposed.

Figure 4 shows inversion images of circular defects and elliptical defects with SAFT technology. The dotted black line in the figure indicates the position where the actual defect is located, and the red area indicates the location of the defect derived from SAFT algorithm. Figure 4(a) and (c) show the inversion of circular defect. The upper and lower surfaces of the defect can be obtained from the inversion figures. Figure 4(b) is an elliptical defect inversion with minor axis of 0.2mm and major axis of 0.6mm, the upper surface of the defect can be observed in the figure. Figure 4(d) is an elliptical inversion elliptical defect with minor axis of 0.1mm and major axis of 0.6mm, which shows the entire ellipse.

When the defect longitudinal dimension is 0.2mm, as shown in Figure 4(a), (b), some of the ultrasonic wave will diffraction and scatter at the bottom of the defect after encountering the circular defect. The ellipse defect has the same longitudinal dimensions as the circular defect. However, the lateral dimensions of the ellipse and the radius of curvature on the upper surface are larger than the circular defects, resulting in more diffuse energy scattering or reflection on the upper surface of the ellipse and less winding to the lower surface. Thus, only the upper surface of the ellipse can be observed at this time.

Similarly, when the defect portrait size is 0.1mm, as shown in Figure 4(c), (d). The oval horizontal dimension is 6 times the vertical size. The upper surface of the ellipse here can be seen as a plane, and the ultrasonic can be approximated as a specular reflection when it reaches the defect. Then when the defect is ellipse, the magnitude of the image is much larger than the circular defect.

The results show that laser ultrasonic SAFT technology is more sensitive to area defects such as cracks, unmelted and faults, which reflect more ultrasonic energy under the same vertical dimensions. We have discussed the condition of the defect long shaft and the upper surface level of the sample. In
fact, there are many non-horizontal defects in the detection. The direction of the defect affects the direction of the reflected wave. When the detection point is on the upper surface of the sample, the limited detection area affects the energy of the detected reflected ultrasonic wave, thus affecting the imaging effect. Therefore, we need to discuss the effect of area defect orientation on imaging effect.

3.2. Imaging defects with different direction features
In addition to geometric features, the direction of defects also has an important impact. Because laser ultrasonic SAFT technology imaging defects use the echo signals detected on the sample surface. These echo signals are scattered or reflected by the defect. For non-circular defects, it is not only the size of the defect that affects the characteristics of the echo signal, but also the direction of the defect.

Defects of similar shape but different orientation are actually present in lead products. When the long axis of the narrow ellipse defect is parallel to the sample surface, the laser ultrasonic will approximate the specular reflection on the surface of the defect. When the ellipse's long axis is at different angles than the horizontal direction, the laser ultrasonic reflection direction will be different, thus affecting the imaging effect. The following will discuss the effect of the direction of elliptic defects on the imaging results, providing a theoretical basis for the detection of laser ultrasonic SAFT technology for mezzanine, fault, crack and other defects.

In order to study the effect of defect orientation on imaging effect, four samples with different inclination elliptical defects are imaged here. The size of the lead sample and the excitation-detection method of laser ultrasonic are consistent with Figure 4. The long axis of the four elliptic defects is 0.6mm, the short shaft is 0.1mm, the depth of 2.3mm, the inclination of the long axis is 0, 30, 60 and 90 degrees respectively. The results are shown in Figure 5. The black dotted line in the figure represents the actual defect location. The red area indicates the defect location obtained by inversion.

![Figure 5. SAFT images of ellipse defects with different dip angles. (a) dip angle=0°; (b) dip angle=30°; (c) dip angle=60°; (d) dip angle=90°.](image)

Figure 5 (a) and (b) are the inversion result at the inclination of the long axis at 0 and 30 degrees respectively. The red area in the figure is high in magnitude, strong in contrast, and the image is basically consistent with the actual defect. Figure 5(c) is an inversion result with an inclination of 60 degrees. Because the ultrasonic excitation and detection are on the upper surface of the sample, the smaller the ellipse inclination, the more reflected energy will reach the upper surface, the better imaging effect. When the inclination increases to 60 degrees, the ultrasonic wave encounters a defect and reflects less energy to the upper surface detection area, and the result of the inversion is shown in Figure 5(c). As the inclination increases further to 90 degrees, only a small portion of the ultrasonic scatters at the top of the ellipse, and a portion of ultrasonic scatters along both sides of the ellipse to the bottom. And most of the sound waves will reflect to the lower surface at the left and right boundary of the ellipse, which is why only the bottom of the ellipse can be observed in Figure 5(d).

In order to better illustrate the propagation of the ultrasonic when it encounters an elliptical defect that the long axis is perpendicular to surface of the sample, we discuss further with sound field diagram.
The sound field excited by the laser at the upper surface (-2mm, 0mm) of the model shown in Figure 5 (d), with the ultrasonic sound fields at different times in Figure 6 (a), (b) and (c). It is obvious that after the reflection of the cross-wave on the left side of the defect, the reflected wave will propagate to the bottom surface of the sample.

![Figure 6. Sound fields of Figure 5(d) at different times.](image)

For defects perpendicular to the excitation-detection area of the sample surface, choosing probe points at opposite side of excitation points can obtain better result, if actual conditions permit. Figure 7 shows the results of SAFT inversion using the probe points at opposite side of excitation points. The lower surface detection area has the same horizontal coordinates as the upper surface, with a step of 0.05mm, and a total of 101 detection points. The black dotted line in Figure 7 indicates where the actual defect is located, and the red area indicates the location of the defect as derived from inversion.

Compared with Figure 5(d), the defect is basically the same as the actual defect size, and there is no background noise and the contrast is strong. Since ultrasonic waves are detected on the lower surface, completely unaffected by surface waves, the defect contrast in Figure 7 is very high. The position is slightly offset in the depth direction compared to the actual, because the ultrasonic waves first meets the upper end of the defect, with most of the energy reflecting or scattering at the upper end and the lower side reflecting or scattering relatively little energy. This results in a relatively small amount of inversion and low contrast at the lower end of the inversion.

![Figure 7. SAFT image of Figure 5(d) with signals obtained from bottom surface.](image)
4. Conclusions
In this paper, the ability of laser ultrasonic SAFT technology to detect defects with different geometric features and inclination in lead is studied. The results show that laser ultrasonic SAFT technology has higher accuracy and contrast for defect detection with large horizontal dimensions and small horizontal inclination. As the defect inclination increases, the reflected amplitude of the upper surface detection decreases, at which point it may be considered to use the method of center detection to detect echoes on the undersurface surface of the sample. This detection technology is more sensitive to the area defects such as cracks, unmelted and faults. It has also been found that the direction of area defects also affects detection capability. When the detection and excitation areas are on the same side, laser ultrasonic SAFT technology is more sensitive to defects with parallel or tilt slightly between the long axis and the sample surface. Considering the actual situation, defects perpendicular to the surface of lead tin alloy products will also have an impact on subsequent use. High accuracy and contrast imaging results can be obtained by detection the ultrasonic signal at the opposite side of excitation area.

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