Laser ultrasonic testing for inspection of curved surface samples based on synthetic aperture focusing

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Abstract. Synthetic Aperture Focusing (SAFT) is one of the methods to improve the spatial resolution in laser ultrasound. However, the research on laser ultrasonic SAFT technology is mainly focused on block or plate samples. In order to study the detection capability of laser ultrasonic SAFT technology on the samples with curved surface, a finite element simulation model of curved surface samples with sub millimeters internal defects is established. And then the laser ultrasound field is obtained through numerical simulation. At last the SAFT algorithm was performed to image the defects in the samples. The results show that laser ultrasonic SAFT technology can image curved surface samples with sub millimeters internal defects. The results provide a reference for the practical application of laser ultrasonic SAFT technology.

1. Introduction

Laser ultrasonic technology can achieve a complex shape, smaller size of samples long-distance, non-contact and non-destructive testing. Since its birth, it has been widely concerned by scholars and lots of research has been carried out. As early as 1963, White[1] and Askayan[2] proposed laser ultrasound in solids and liquids, respectively. In 1979, Lebetter and others[3] discovered that there are several patterns of ultrasonic waves excited by lasers in materials, and shear wave, longitudinal wave and surface wave were observed. Subsequently, Dewhurst [4] and Hutchins [5] accomplished the quantitative measurement of ultrasonic wave, and the theoretical foundation for the excitation of elastic waves under thermoelastic conditions was established.

With the development of laser ultrasonic technology, the detection of micro defects in materials has become an important content. Synthetic aperture focusing (SAFT) is one of the ways to improve the detection resolution in the traditional acoustic field. Its basic principle is to combine a series of single small aperture sensors instead of a large aperture sensor to achieve the purpose of improving the lateral resolution of detection. This technology was first used in radar field. Flaherty [6] and Burckhardt et al. [7] extended this technology to ultrasonic detection field in 1970s to improve ultrasonic resolution. In 1997, Lorraine et al. [8] first applied SAFT technology to the field of laser ultrasound, which improved the performance of laser ultrasonic technology in detecting small defects. The detection ability of the subsurface area can be equivalent to that of ultrasound using a focused piezoelectric sensor. Since then, Blouin [9] and Levesque [10] have used SAFT technology to improve...
the spatial resolution and signal-to-noise ratio (SNR) of laser ultrasonic technology, and detect millimeter scale defects on the surface of aluminum blocks.

At present, the research on laser ultrasonic SAFT technology is mainly focused on block or plate samples. However, in the actual industrial components, most of them are not plate-shaped or block shaped, but rather complex curved surfaces. Such as cylindrical pipe or connector with arc chamfering, 3D printing works, lead sealing layer of cable, etc. In view of this kind of situation, laser ultrasonic physical model is established in this paper. Through simulation, the laser ultrasonic SAFT imaging technology for defects in lead samples with curved surface was studied, so as to verify the applicability of laser ultrasound SAFT technology in the detection of curved surface samples.

2. Methods

2.1. Numerical simulation model

In order to study the detection capability of laser ultrasonic SAFT technology for inspection curved surface samples, two models with different types of surfaces were built as shown in Figure 1. The height of the samples is 3mm. The width is 6mm wide. 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 position of defect center is (0, 2.3). The defect circle radius is 0.2mm. The red line indicates the excitation area of the laser ultrasound. The green line indicates the detection area.

![Figure 1. Schematic diagram for defect samples with curved surface.](image)

To excite ultrasound under the thermoelastic mechanism, only the thermal conduction of laser energy and material simply is considered. Then the thermal conduction equation can be described as

$$\rho c \frac{\partial T(x,y,t)}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T(x,y,t)}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T(x,y,t)}{\partial y} \right)$$ (1)

$T(x, y, t)$ represents the temperature distribution change at time $t$. $\rho$ is the density, $c$ is thermal capacity. $k$ is the thermal conductivity coefficient.

In the laser irradiation area, the thermal flow boundary condition is

$$-k \frac{\partial T(x,y,t)}{\partial y} \bigg|_{y=0} = I_0 A(T) f(x) g(t)$$ (2)

$I_0$ is the peak power density of the incident laser. $A(T)$ is the absorption rate of the material. $f(x)$ is a pulsed laser spatial distribution function. $g(t)$ is the laser time distribution function. They can be described as
\[ f(x) = \exp\left(-\frac{x^2}{r_0^2}\right) \]  \hspace{1cm} (3)

\[ g(t) = \frac{t}{t_0} \exp\left(-\frac{t}{t_0}\right) \]  \hspace{1cm} (4)

Where \( r \) is the laser spot radius and \( t \) is the laser pulse rise time. The initial condition of the temperature field is

\[ T(x, y, t) \bigg|_{t=0} = 293.15K \]  \hspace{1cm} (5)

By the thermoelastic mechanism, laser ultrasound can be excited nondestructively on the sample with a pulse laser. Ultrasonic propagation in thermal elastomers satisfies the Navier-Stokes equation.

\[ (\lambda + 2\mu) \nabla \cdot \mathbf{U}(x, y, t) = \mu \nabla \times \nabla \times \mathbf{U}(x, y, t) + \rho \frac{\partial^2 \mathbf{U}(x, y, t)}{\partial t^2} + \alpha (3\lambda + 2\mu) \nabla T(x, y, t) \]  \hspace{1cm} (6)

\( \mathbf{U}(x, y, t) \) represents the transient displacement of the media internal point. \( \lambda \) and \( \mu \) are the Lamé constant of the material, which can be calculated by Yang's modulus and Poisson ratio. \( \alpha \) is thermal expansion coefficients. Free boundary conditions are met on the upper and lower surfaces of the sample.

The ultrasonic displacement field in the sample can be obtained by solving the equations (1) and (6) with initial and boundary conditions.

![Figure 2. Failed lead seal layer](image)

Lead has good ductility, corrosion resistance and sealing. 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. However, there is no suitable detection method for cable lead sealing layer. And the surface of the lead sealing layer is curved surface. Laser ultrasonic SAFT has potential applications in this field. Therefore, in this paper, lead material is selected to study the detection ability of ultrasonic SAFT for curved surface samples. Figure 2 shows an example of the lead seal failures due to the seal quality. Table 1 lists the lead material properties.

| Parameter                  | Value          |
|----------------------------|----------------|
| Density/(kg/m\(^3\))       | 11645.61       |
| Young's modulus /MPa       | 3.22×10\(^4\)  |
Poisson's ratio 0.39
Thermal expansion coefficient/K⁻¹ 2.4×10⁻⁵
Lamé instant λ/(N·m⁻²) 4.11×10¹⁰
Lamé instant μ/(N·m⁻²) 1.16×10¹⁰

2.2. Laser ultrasonic SAFT method
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 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, ..., n). Detection point coordinates are (x_d, 0), (d = 1, 2, 3, ..., m). d₁ and d₂ are the distance between excitation point (x_e, 0) and detection point A.

\[ d₁ = \sqrt{(x_A - x_e)^2 + y_A^2} \]  
\[ d₂ = \sqrt{(x_A - x_d)^2 + y_A^2} \]

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

\[ t_A = \frac{d₁ + d₂}{v} \]

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.

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

3. Results and discussion
It should be noted that the curved surface sample is different from the plane surface sample in the time delay superposition of the signal. For the sample with plane surface, the relative height between the excitation point and the detection point is not considered when calculating the arrival time of scattering echo. For the sample with curved surface, the relative height of excitation point and detection point at different positions should be considered in calculation.
In Figure 1, the step size of excitation points is 1.00mm, with a total of 5. The step size of detection points is 0.05mm, and there are 101 detection points in total. After the ultrasonic wave is excited at a certain excitation point, a group of echo signals are collected in the detection area, and the signals are processed by SAFT algorithm. Finally, five groups of inversion data are superimposed.

In Figure 4, the black circle dotted line indicates the location of the defect, and the red area is the defect obtained by inversion. The inversion result is in good agreement with the actual defect size. It shows that the laser ultrasonic SAFT technique can successfully reverse the sub millimeter defects in non-planar samples. Compared with the traditional contact transducer, laser as the excitation source has more flexible advantages, more suitable for the detection of complex surface samples.

4. Conclusion
Combining laser ultrasound with SAFT can not only give full play to the advantages of laser ultrasound, but also improve the detection accuracy. This method has a more flexible feature than traditional ultrasound and can be used to image high-quality internal defects in samples with complex surface appearances. In this paper, the detection capability of the laser ultrasonic SAFT technology is studied by establishing a physical model of laser ultrasound transmission for curved surface samples. The results show that laser ultrasonic SAFT technology can obtain the micro-defects inside the surface sample. The results provide a reference for the practical application of laser ultrasonic SAFT technology.

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