Enhancement characteristics of laser ultrasonic basin-type insulator based on carbon nanocomposites

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Abstract: Laser ultrasonic technology has been widely used in the field of NDT due to its advantages of non-contact and high resolution. The sensitivity of laser ultrasonic detection signal is not only related to laser excitation parameters, but also to the thermal absorption of the target. Therefore, once the measured target is determined, the sensitivity of laser ultrasonic detection based on thermoelastic effect is limited by the damage threshold of the measured target. In order to improve the sensitivity of the detection signal under the damage threshold, it is a good choice to add a layer of enhanced medium with high photoacoustic conversion efficiency on the surface of the laser target material. Based on this, a method based on CB(carbon black)-PDMS composite film was proposed to enhance the sensitivity of detection signal.

1. Introduction

Laser ultrasonic technology is mainly to irradiate the surface of the material with laser light, generate ultrasonic waves due to thermal expansion, and analyze material defects information by receiving ultrasonic waves[1,2]. At present, Laser ultrasonic technology is widely used in the field of non-destructive testing of materials due to the advantages of non-contact, remote working, wide ultrasonic frequency band and high spatial resolution. Laser ultrasonic technology is particularly suitable for the detection of harsh environments, such as acid, alkali, high temperature and pressure, corrosion, radiation and other harsh environments and has great potential in the detection of GIS basin-type insulators.

At present, the research on the defect detection of basin-type insulators mainly focuses on the ultra-high frequency method, local ultrasonic detection and pulse current method. These three methods are based on the electromagnetic waves, acoustic waves generated by the defects and the current generated by the partial discharge[3,4]. The ultra-high frequency method is mainly used for on-site monitoring, and can detect 5% of the discharge phenomenon. However, the defect location capability of this method is not accurate enough; the pulse current method can quantitatively detect discharge. This method is mainly used in laboratory settings due to its sensitivity to interfering signals; X-ray digital imaging technology can be used to detect large crack gaps on the insulator, but the sensitivity to small cracks is not high. Therefore, laser ultrasonic technology, as an improved local ultrasonic detection method, has more advantages, which makes the detection effect of basin-type insulators better.
There are mainly two mechanisms to detect defects of basin-type insulators by laser ultrasonic technology, namely thermoelastic mechanism and ablative mechanism\cite{5,6,7}. The ablative mechanism will damage the insulator material, but the detection signal sensitivity generated by the thermoelastic mechanism is low. Therefore, an enhanced medium with high photoacoustic conversion efficiency is needed to improve the detection signal strength. Efficient photoacoustic transducers require materials with high light absorption, high thermal conductivity, low heat capacity, and high coefficient of expansion, such as for gold nanoparticles-polydimethylsiloxane (AuNPs-PDMS). In recent years, the application of carbon nanotubes (CNT) and PDMS composite materials as laser ultrasonic emitters has achieved good results. In this paper, CB-PDMS composite film was proposed to improve the intensity of laser ultrasonic detection signal.

2. Laser ultrasonic theory and simulation modeling

In order to study the laser ultrasonic enhancement characteristics of CB-PDMS composite films, the simulation model shown in Figure 1 was established.

Fig.1. Schematic diagram of laser excited ultrasonic model based on CNT-PDMS composite film

As can be seen from Figure 1, the composite film is mainly composed of carbon absorbing nanomaterials and polymer PDMS. In the temperature field, the light-absorbing nanomaterial in the composite film absorbs the pulsed laser energy and immediately transfers the heat generated to the surrounding polymer PDMS. In the linear non-viscous domain, the heat diffusion equation is expressed\cite{8} as:

\[ \rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T) + H_i(r,t) \]  \hspace{1cm} (1)

Where, \( \kappa \) is Thermal conductivity, \( \rho \) is the density, \( C_p \) is the specific heat, \( C_p = \kappa_i / \rho \alpha_i \), \( \alpha \) is the thermal diffusivity, \( T \) is the temperature in the material, \( H_i(r,t) \) is heat source function. The subscripts \( i \) represents the different media in Figure 1 (\( i=1 \): water media, \( i=2 \): composite membranes, \( i=3 \): different substrates). When the duration width of pulsed laser is much smaller than the thermal diffusion time in composite materials, the thermal diffusion in photoacoustic transformation can be ignored. Therefore, the approximate thermal diffusion equation is obtained as follows:

\[ \rho_i C_{pi} \frac{\partial^2 T_i}{\partial t^2} = \frac{\partial}{\partial t} H_i(r,t) \]  \hspace{1cm} (2)

In the sound field, the thermoacoustic coupling equation in the medium can be expressed as:

\[ \left[ \nabla^2 - \frac{1}{c_i^2} \frac{\partial^2}{\partial t^2} \right] P_i(r,t) = -\rho_i \beta_{pi} \frac{\partial^2 T_i}{\partial t^2} \]  \hspace{1cm} (3)

Where, \( P \) is the sound pressure, \( \beta_i \) is the volume thermal expansion coefficient, \( c \) is the sound velocity in the medium.
According to formula (2) and Formula (3), the acoustic wave equation in the composite material can be written:

\[
\left(\nabla^2 - \frac{1}{c_i^2} \frac{\partial^2}{\partial t^2}\right) P_i(r,t) = -\frac{\beta \partial_r}{C_{pi}} \frac{\partial}{\partial t} H_i(r,t) \tag{4}
\]

In Equation (4), the temperature field is no longer involved, and the relationship between sound pressure and heat source is directly expressed.

In order to study the thermoelastic effect of laser ultrasonic in solid materials, the electromagnetic-solid mechanics-acoustic coupling module is adopted. When solid mechanics module is coupled with acoustic module, the thermal displacement output of thermal stress module is taken as the input of acoustic module. Quadrilateral mesh is adopted and the maximum size of the material is 20 µm. In order to increase the number of cells in the heat source region, the method of edge thinning mesh is adopted. The simulation time is set to 3 µs, which is enough to meet the transmission time of sound field within the material.

3. Simulation and result analysis

The laser energy density \(I_0\) is set to \(1 \times 10^{11}\) W/m², the half width of the laser \(W\) is 100 µs, and the laser rise time is set to 10 ns. The excitation point of the laser is located at the center of the upper surface of the 2-dimensional model. When CB-PDMS composite film is not included, the sound pressure waveform at 3 mm away from the laser excitation is shown in Figure 2, and the peak value of the highest sound pressure is about 62.5 kPa.

When CB-PDMS composite film with a thickness of 30 µm was applied on the surface of the sample, the simulated sound pressure signal waveform was shown in Figure 3 at the same laser excitation parameters and detection position. It can be seen from Figure 3 that the maximum sound pressure received is close to 3 MPa. Compared with the film without CB-PDMS, the sound pressure amplitude increased by nearly 50 times.

![Fig.2. Sound pressure signal without CB-PDMS film 3mm away from the laser excitation position](image-url)
4. Conclusion

In this paper, a two-dimensional multi physical field coupling simulation model is established based on laser ultrasonic basin insulator detection. In order to improve the sensitivity of laser ultrasonic detection of ultrasonic signal, the method based on CB-PDMS composite film reinforced medium was proposed. The simulation results show that when CB-PDMS composite film with thickness of 30μm is added on the surface of insulator material, the amplitude of sound pressure signal is significantly enhanced, and the maximum sound pressure value is increased nearly 50 times.

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