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Dynamic thermal tomography based on continuous wavelet transform for debonding detection of the high silicon oxygen phenolic resin cladding layer

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ABSTRACT

Photothermal diffusion-wave imaging and thermal tomography are promising techniques for the analysis of debonding detection of the solid-propellant missile engine. In this paper, the dynamic thermal tomography based on continuous wavelet transform (CWT-DTT) was introduced to detect the defect and reconstruct the 3D (three-dimensional) visualization of the high silicon oxygen phenolic resin cladding layer. The basic principle of CWT-DTT and the tomography processing were described. Moreover, 3D thermal wave model stimulated by pulse signal was developed. The relationship between the SNR of the feature image and the scale factor of CWT was analyzed. The tomography experiment of cladding layers with simulated flat bottomed holes (FBHs) defects by CWT-DTT was carried out. The experimental results demonstrated that the measuring depth of all FBHs has a good agreement with the actual depth. Therefore, the research on CWT-DTT is of significant importance to quantitative evaluation the quality of the high silicon oxygen phenolic resin cladding layer.

1. Introduction

As an important part of the solid-propellant missile engine, the quality assurance of cladding layer is very important [1]. The main component of cladding layer is the high silicon oxygen phenolic resin. The high silicon oxygen phenolic resin has the merit of thermos ability and corrosion resistance, which lead to the wide application in the cladding layer manufacturing material field of aircraft, aerospace, and military industries. However, due to the manufacturing process, storage and service condition, and ambient temperature changes, solid-propellant missile engine often has debonding defects happened between the cladding layer and the engine case, which affect the reliability of the missile engine seriously. The debonding defects of cladding layer non-destructive testing and evaluation (NDT&E) techniques such as visual analysis, X-ray detection, ultrasonic detection and laser holographic detection method have the problems such as strong subjectivity, low detection efficiency and complex implementation conditions. Therefore, finding an efficient, easy implementation and high sensitivity detection method has important meaning [2,3].

Photothermal detection technique has aroused widespread concern since the middle of the nineteenth century [4–7]. Recently, three-dimensional (3D) tomography based on photothermal technique has become the research hotspot in this field [8–10]. Therefore, 3D tomography of solid-propellant missile engine cladding layer by photothermal technique can be used as a quantitative detection approach. With the deep study of photothermal 3D tomography, many different kinds of photothermal tomography technique have been emerged.

The main thermal tomography methods include dynamic thermal tomography (DTT) [11], photothermal optical coherence tomography [12], truncated correlation photothermal coherence tomography [13,14] and 3D thermal tomography based on parameters inversion [15], and dynamic thermal tomography is the most widely used recently. Vavilov and Maldague [16,17] proposed dynamic thermal tomography (DTT) which based on the pulse excitation thermal image sequence, and this method has been applied in the 3D tomography of carbon fiber reinforced polymer (CFRP) and aluminum plate. This method can achieve 3D visualization of specimen, but the signal to noise ratio (SNR) is very poor. In order to improve SNR, Maldague [18] presented pulsed phase algorithm to extract characteristic images form

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thermal image sequence, and DDT based on pulsed phase algorithm enhanced the SNR. Melnyk et al. [19] applied the projection dynamic thermal tomography method to test objects with irregular internal structure. The experimental results illustrated this method allowed detecting internal defects with size several times smaller than their depth of occurrence. Pavar et al. [20] used 3D normalization method to overcome the problem of uneven heating and absorption. The results illustrated the validity of 3D normalization, and it is a promising tool in the inspection of composite aerospace parts with relaxed requirements to choosing a reference area while performing DTT, and consequently increasing the number of topographically resolved layers. Truncated correlation photothermal coherence tomography (TC-PCT) was a photothermal detection method which was first proposed by Mandelis et al. [13]. This method combines thermal wave imaging pulse excitation and linear frequency modulated radar detection. The TC-PCT was used to achieve the tomography of different material (bone, steel, and skin). Experimental results showed that this method had larger detection depth of bone. However, this method need more time to process 3D visualization. Toivanen et al. [15] 3D thermal tomography with experimental measurement data. In their work, target volume is sequentially heated at different source locations and temperature evolutions are measured at several measurement locations on the surface of the volume. Based on these measurements, the thermal conductivity, volumetric heat capacity and surface heat transfer coefficient of the volume are estimated as spatially distributed parameters using the framework of Bayesian inversion. This method is based on the inversion of parameters.

In summary, DTT is the most convenient way to achieve 3D visualization. Now, the main investigate content of DTT focuses on how to improve the quality of tomography. In this present study, an enhanced thermal tomography named dynamic thermal tomography based on continuous wavelet transform (CWT-DTT) was introduced to enable the three-dimensional visualization of the high silicon oxygen phenolic resin cladding layer. First of all, the principle of CWT-DTT was presented in Section 2. Then the experimental setup of CWT-DTT and experimental materials were introduced in Section 3. Finally, the relationship between the SNR of the feature image and the scale was analyzed, and CWT-DTT enabled the three-dimensional visualization of cladding layer in Section 4.

2. The principle of CWT-DTT

The main problem in enabling three-dimensional (3D) tomography is to find a parameter which has a relationship with the depth of the defects. The thermal transfer process stimulated by pulse heating should be analyzed firstly. According to the principle of pulsed thermal imaging, the geometric model of three-dimensional thermal transfer is shown in Fig. 1.

In Fig. 1, $Q(x, y, 0)\delta(t)$ is the pulsed excitation heat source ($\delta(t)$ is Dirac function,), and h is the convection coefficient, respectively. Assuming that the lateral surface of the specimen is adiabatic, the thermal transfer processing in the specimen can be given by,

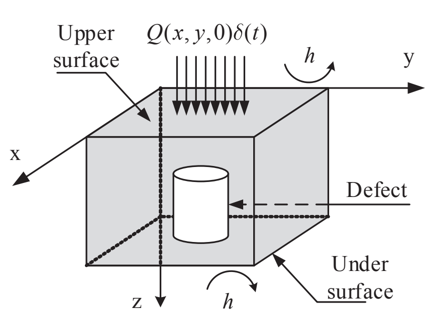

Fig. 1. The geometric model of three-dimensional thermal transfer.

$$k\frac{\partial^2 T(x, y, z, t)}{\partial x^2} + k\frac{\partial^2 T(x, y, z, t)}{\partial y^2} + k\frac{\partial^2 T(x, y, z, t)}{\partial z^2} = \rho c\frac{\partial T(z, t)}{\partial t} \tag{1}$$

Here, ρ is the density of the specimen, c is the specific heat capacity, and k is the thermal conductivity, respectively. The initial condition and boundary conditions are given by,

$$T(x, y, z, t)|_{t=0} = T(x, y, z, 0) = T_{am} \tag{2a}$$

$$k\frac{\partial T(x, y, z, t)}{\partial z}\bigg|_{z=0} = Q(x, y, 0)\delta(t) + h[T_{am} - T(x, y, 0, t)] \tag{2b}$$

$$-k\frac{\partial T(x, y, z, t)}{\partial z}\bigg|_{z=Z} = h[T_{am} - T(x, y, Z, t)] \tag{2c}$$

$$-k\frac{\partial T(x, y, z, t)}{\partial x}\bigg|_{x=0} = -k\frac{\partial T(x, y, z, t)}{\partial x}\bigg|_{x=X} = 0 \tag{2d}$$

$$-k\frac{\partial T(x, y, z, t)}{\partial y}\bigg|_{y=0} = -k\frac{\partial T(x, y, z, t)}{\partial y}\bigg|_{y=Y} = 0 \tag{2e}$$

here T_{am} is the ambient temperature. X, Y, Z are the border of x, y, z.

It is very difficult to obtain the temperature field distribution $T(x,y,z,t)$ by the analytical method. Finite element method (FEM) is a numerical method for solving the approximate solution of partial differential equations. Therefore, FEM was used to obtain $T(x,y,z,t)$ by FEM software COMSOL 5.2 in this paper.

As is well known that the Fourier transform is a classical method in the field of signal processing [21,22]. It can achieve the signal conversion from the time domain to the frequency domain. However, the non-stationary signal losses the time information after the Fourier transform, which affects the characteristic extraction seriously. The short-time Fourier transform can analyze the time-frequency information, however this method still exists many deficiencies about window selecting [23]. In order to solve these problems, the continuous wavelet transform is used to simultaneously analyze the information of the thermal wave signal in the time domain and the frequency domain [24].

The continuous wavelet transform process can be represented as [25],

$$WT_x(a, b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} x(t)\psi*\left(\frac{t-b}{a}\right)dt \tag{3}$$

where $x(t)$ is the signal, $\Psi(t)$ is the mother wavelet, $a$is the scale factor, and b is the translation factor.

Assume that the mother function bandwidth is f_{b}, the center frequency is f_{c}, and its quality factor, Q, is defined as,

$$Q = \frac{\frac{f_{\mathrm{b}}}{a}}{\frac{f_{\mathrm{c}}}{a}} = \frac{f_{\mathrm{b}}}{f_{\mathrm{c}}} \tag{4}$$

The value of Q is a constant, therefore, with the increase of a, both f_{b} and f_{c} were reduced and the frequency is focused on the low frequency region. When a reduced, f_{b} and f_{c} were increased and the frequency is focused on the high frequency region. At this time, the frequency is subdivided. Therefore, the continuous wavelet transform can analyze the time-frequency information, meanwhile, it can also solve the window selecting problem of short-time Fourier transform. The continuous wavelet transform can automatically adjust the window to achieve a comprehensive analysis of the signal. It is used to extract the features of the thermal-wave signal. The selected eigenvalue is the maximum modulus of the wavelet coefficients of each pixel's temperature signal. The definition of the eigenvalue $b_m(i, j)$ is given by,

$$C(a, b) = \int_{-\infty}^{+\infty} x(t)\Psi(a, b)dt \tag{5a}$$