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Determination of temperature sequence length in pulse phase thermography

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HIGHLIGHTS

- The influence of temperature sequence length on the phase difference is analyzed.
- An optimal temperature sequence length can figure out the maximal phase difference.
- The method for determining the optimal temperature sequence length is obtained.
- A simplified equation for calculating phase is derived.
- The detect efficiency is improved along with the best ability to distinguish defects.

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ABSTRACT

In pulse phase thermography (PPT), the temperature sequence length affects the efficiency of phase calculation and the ability to distinguish defects. To improve the efficiency and ability of detection, the influence of the temperature sequence length on the phase difference was analyzed. This was carried out using finite element simulations under the conditions of different substrate thicknesses, defect depths, defect diameters, heat power densities and material properties. The simulation results show that each defect at a different depth has a corresponding optimal temperature length t_{opt}, which can provide the maximal phase difference and the best ability to distinguish defects in materials of certain properties. t_{opt} varies with the material properties, the defect depth and diameter, and the substrate thickness. The numerical t_{opt} formula was fitted through simulation results, and the experiment was carried out on aluminum alloy specimens with flat-bottomed holes as artificial defects. Through the experimental results, the relationship between phase difference and temperature sequence length is shown similar to that in simulation. When t_{opt} is calculated using the fitting formula, we can approximately obtain the maximal phase difference and the best defect phase image. t_{opt} can be determined by its change rule and the numerical formula, which can provide better defect distinguishing ability, avoid redundant temperature sequence, and improve the detection efficiency.

1. Introduction

As a new nondestructive testing method, infrared thermal wave testing, which has been widely developed and used throughout the world, has the advantages of fast detection speed, large observation area, better visual results and non-contact properties [1,2]. It can be divided into active method and passive method [3]. The former includes pulse and ultrasonic thermography, as well as others. Pulse thermography (PT) is the earliest, the most proficient and the most widely-used method. It involves using a short-duration high-intensity flash of light to heat the surface of a test piece, and to test it by the nonuniformity of the surface temperature difference when the heat flux conducts into the defected material [4,5]. Pulse phase thermography (PPT), as an improved method of PT, combines techniques such as infrared detection and signal processing, and it has the advantages of easy usage and speeds as fast as those of PT, robustness, and simple signal analysis. It can resolve the nonuniformity of surface temperature and emissivity and improve tests result to a certain extent [6–8].

In PPT, phase information is extracted by processing the temperature sequence of every pixel in the entire thermal image of the detected location, which is sensitive to calculation and time. Because of differences in substrate thickness and defect depth, the temperature sequence lengths that must be processed are

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usually different. If we do not know the proper sequence length, we could sample more or fewer frames than are needed. This can lead to the use of more calculation time than is needed, produce lower-quality detection results, and adversely affect detection efficiency. This paper will research the causes of temperature sequence length at the maximal phase difference and examine the relationships among them. With the proper relationships in place, the optimal temperature sequence can be calculated quickly, which can improve the detection efficiency of PPT.

2. Theory of PPT

In PPT, an infrared camera records the temperature variation of each point on the material surface within a certain time after a high power flash is applied, and each point has a temperature–time sequence. In theory, the sequence contains various frequency response characteristics of heat flux. Therefore, it can be expressed as

$$T(t) = \sum_{i=0}^{\infty} A_i \sin(2\pi f_i t + \varphi_i) \quad (1)$$

where T is the temperature function, f_i is the ith order harmonic frequency, φ_i is the corresponding magnitude and t is the time. If the

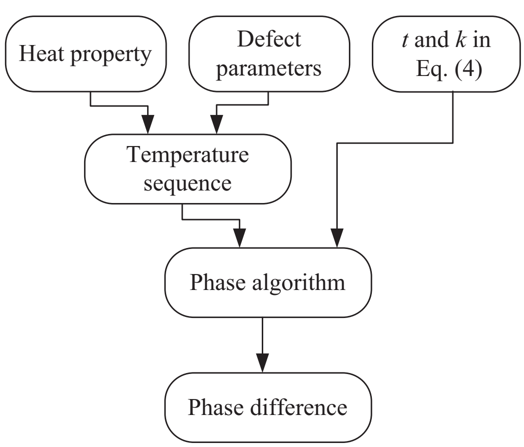

Fig. 1. Factors influencing the phase difference.

camera frame rate is s and the sampling length is N, then processing the temperature sequence by Fourier transform means taking the time length of N samples as the period of the fundamental frequency. Thus, the fundamental frequency is

$$f_1 = \frac{s}{N} \quad (2)$$

According to the Nyquist–Shannon Sampling Theorem, the infrared camera with a frame rate of s can sample the heat flux below a frequency of $s/2$. Therefore, the maximum harmonic order is $s/2f_1 = N/2$. Eq. (1) can be discretized as

$$T(n) = \sum_{k=1}^{N/2} A_k \sin(2\pi k f_k n/s + \varphi_k) \quad (3)$$

There are certain ways to extract the phase from the temperature sequence. The "4-bucket technique," fast Fourier transform (FFT), and correlation algorithm were used in Refs. [5–14]. Although it requires fewer operations, the 4-bucket technique is suitable to extracting the phase only from the sine signal or from the signal with a constant bias. In addition, the signal period must be known in advance. Because the 4-bucket technique only reads four equally spaced samples, its ability to suppress noise is very weak. The correlation algorithm extracts the message from the weak signal using the principle that noise signals and reference signals are not correlated. Usually, the reference signals are the sine and cosine signals. Here, the correlation algorithm has the same essence as the discrete Fourier transform (DFT) [10]. As a quick algorithm of DFT, FFT can play an effective role in analyzing the amplitude and phase of every harmonic frequency, and is widely used in PPT.

Decompose and calculate Eq. (3) using the theory of Fourier transform, and φ_k can be expressed as

$$\varphi_k = \tan^{-1}\left(\frac{\sum_{n=1}^{ts} T(n)\cos\left(\frac{2\pi kn}{ts}\right)}{\sum_{n=1}^{ts} T(n)\sin\left(\frac{2\pi kn}{ts}\right)}\right) \quad (4)$$

where t is the temperature sequence length expressed by time, and s is the camera's frame rate. If there are defects in material to be detected, the phase at a normal location is different than that at a defect location. The location and the parameter can be determined by the difference in φ_k calculated using Eq. (4).

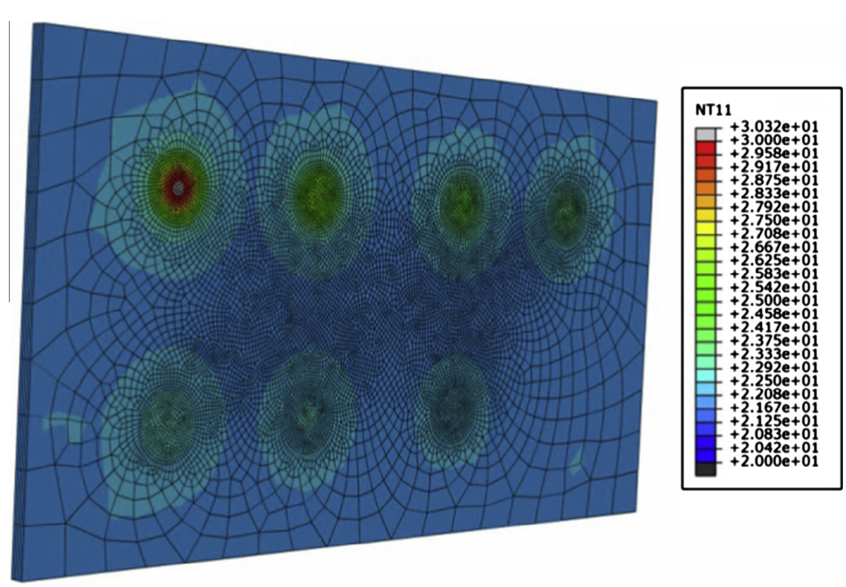

Fig. 2. Mesh model and temperature nephogram.