NDT&E International 70 (2015) 1–8

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Determination of the modulation frequency for thermographic non-destructive testing

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ARTICLE INFO

Article history:
Received 28 March 2014
Received in revised form
27 November 2014
Accepted 2 December 2014
Available online 11 December 2014

Keywords:
Inverse heat conduction
Infrared thermography
Excitation frequency
Experimental validation

ABSTRACT

We propose polynomial solutions of the inverse heat conduction problem to design thermographic non-destructive tests for detecting defects in composite and multi-layer materials. Inverse heat conduction in a multi-layer material slab with periodic temperature excitation is considered, and analytical quadrupole representation is used to derive a lumped parameters formulation. Predictions of the proposed polynomial representations are experimentally validated by detecting machined defects on thermally excited panels. For modulation frequencies outside the predicted detection range, defects appear on thermal images as blurry and unstructured; conversely, for modulation frequencies within the predicted range, defects are correctly represented on thermal images.

1. Introduction

Nondestructive testing techniques based on infrared thermography find application in several fields such as structural and civil engineering [1,2], with application to restoration and maintenance of historical structures [3,4]; material and aerospace engineering [5–7]; and evaluation of safety and reliability (quality control) in manufacturing [8]. Detecting the characteristics of a possible defect in a reasonably short time can be crucial for processes cost effectiveness and minimization of human life threats in working environments [9].

Inspection and damage detection are particularly challenging for composite and multi-layer materials [10,11]. Any defect in multi-layer materials or composites, such as ply separation, air bubbles and delamination, can lead to the modification of mechanical properties [12], which can affect reliability and safety. Among several available techniques for defect detection, infrared thermography is often adopted for its simplicity and relatively short diagnosis time [13–16]. Specifically, infrared thermography is an inspection method in nondestructive testing to detect a defect on the surface and the subsurface of a material body [17]. Active infrared thermography [6,18–20] refers to a class of detection techniques in which an infrared camera captures images of the surface of a material body rendering the temperature distribution corresponding to a periodic boundary excitation, and identifies possible anomalies by detecting patterns associated with reflected thermal spatial transients. Detection techniques depend on several parameters such as thermal conductivity, heat capacity, and defect depth as internal factors and convection heat transfer, variation on surface emissivity, and ambient radiation reflectivity as external factors [17]. Modeling of thermal wave inspection techniques has been extensively addressed, with works that include analytical treatments [21–27], numerical modeling based on finite element [28–32] and software simulation tools [33], and the use of neural networks [34,35]. Effective experimental design requires the predetermination of the radial frequency of the boundary excitation that corresponds to a certain temperature amplitude, since this parameter is correlated with the size and characteristics of the flaws [36].

In this paper we present an efficient method to determine the frequencies of boundary excitation to detect defects with non-destructive testing of composite and multi-layer materials. The predetermination of the frequency of excitation is crucial in the design of non-destructive tests [37] as it dictates the detectability of a defect at a certain depth in the material specimen. Inverse heat conduction in a multi-layer material slab with periodic temperature excitation is considered. We use the analytical quadrupole representation to derive a lumped parameters formulation of the problem that allows for an input–output representation in terms of a transfer function in the Laplace domain. The generally transcendental transfer function is approximated by a power series, which allows for a polynomial implicit approximated solution of the inverse problem. With respect to existing literature focused on analytical and numerical methods to detect defects in composite multi-layer materials, the polynomial series representation for the transfer function allows to obtain simple formulas for the predetermination of the frequency of excitation in thermal wave inspection techniques. Predictions of the proposed closed

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http://dx.doi.org/10.1016/j.ndteint.2014.12.001
0963-8695/

forms are experimentally tested with a simple apparatus comprised of a plate with machined defects. Experimental results show that when exciting the system with frequencies outside the range predicted by the proposed formulas, defects in thermal images appear blurry and unstructured as opposed to the ones obtained by thermally exciting the system with frequency in the detection range predicted by the formulas. Therefore the proposed formulas based on truncated polynomial expansions are an effective tool for designing infrared thermography defect detection tests, specifically for establishing the range of excitation frequencies for detection.

The rest of the paper is organized as follows. In Section 2 we briefly present the initial-boundary values problem governing the heat conduction in a multi-layer slab with periodic boundary excitation, and obtain an input to output representation based on thermal quadrupoles. In Section 3 we present a polynomial series approximate solution that allows for simple explicit representations of the frequency of excitation in terms of the amplitude of the excitation in the material. This allows us to quickly predict the range of the frequency of excitation corresponding to detectability of defects with infrared imaging. Predictions of the proposed models are experimentally tested and results presented in Section 4. Summary and conclusions are drawn in Section 5.

2. Heat conduction in a multi-layer slab

We consider a multi-layer slab-like domain, see Fig. 1, which is a three dimensional continuum with two sides very large with respect to thickness so that the effect of the edges can be neglected. It is therefore appropriate to introduce a reduced one-dimensional approximation along the spatial coordinate x in the interval $[0,l]$ of the initial boundary values problem governing the heat conduction. Moreover, we assume that the lateral surface has no heat loss and that there is no internal heat source. The one-dimensional initial-boundary value heat conduction problem is formulated as [38]

$$\frac{\partial T_i}{\partial t} = \alpha_i \frac{\partial^2 T_i}{\partial x^2} \tag{1a}$$

$$T_1(0,t) = T_\infty + U \ \sin(\omega t) \tag{1b}$$

$$T_i(a_i,t) = T_{i+1}(a_i,t) \tag{1c}$$

$$k_i \frac{\partial T_i(a_i,t)}{\partial x} = k_{i+1} \frac{\partial T_{i+1}(a_i,t)}{\partial x} \tag{1d}$$

$$k_n \frac{\partial T_n}{\partial x}(l,t) = -\mu(T_n(l,t) - T_\infty) \tag{1e}$$

$$T_i(x,0) = T_\infty \tag{1f}$$

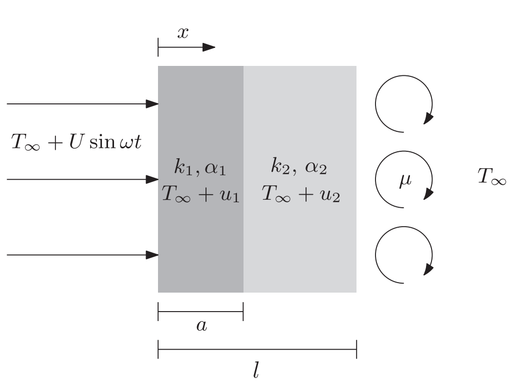

Fig. 1. Two layer model with sinusoidal excitation on one side and convection on the other side.

where T_i is the temperatures in the ith layer at point (x,t) with space x and time t being both real numbers, $a_1, a_2, \ldots, a_{n-1}$ are the coordinates of the material interfaces in the slab that are assumed to be parallel to the sides at $x=0$ and $x=l$, and constants α_i and k_i represent respectively the thermal diffusivity and the thermal conductivity of the materials. We consider $a_1 = 0$ and $a_n = l$. The slab is assumed to be initially the ambient temperature, T_∞, consistently with the initial condition (1f). At time zero a persistent oscillating perturbation of amplitude U and radian frequency ω is added at $x=0$, as formalized by the boundary condition (1b). Eq. (1e) is a convective boundary condition with thermal coefficient of μ describing the experimental condition that we want to reproduce.

According to (1b), the boundary condition is an oscillation around the ambient temperature T_∞. By introducing the temperature difference $u_i(x,t) = T_i(x,t) - T_\infty$ we obtain the following set of equations:

$$\frac{\partial u_i}{\partial t} = \alpha_i \frac{\partial^2 u_i}{\partial x^2}, \quad i = 1, \ldots, n \tag{2a}$$

$$u_1(0,t) = U \sin(\omega t) \tag{2b}$$

$$u_i(a_i,t) = u_{i+1}(a_i,t) \tag{2c}$$

$$k_i \frac{\partial u_i(a_i,t)}{\partial x} = k_{i+1} \frac{\partial u_{i+1}(a_i,t)}{\partial x}, \quad i = 2, \ldots, n-1 \tag{2d}$$

$$k_n \frac{\partial u_n}{\partial x}(l,t) = -\mu u_n(l,t) \tag{2e}$$

$$u_i(x,0) = 0 \tag{2f}$$

For any ambient temperature T_∞, the resulting temperature can be calculated as $T_\infty + u_i$.

By introducing the non-dimensional variables, $x^* = x/l$, $t^* = t\omega$, $u^* = u/U$, we rewrite the initial-boundary value problem (2) in non-dimensional form

$$\frac{\partial u_i^*}{\partial t^*} = \frac{1}{\beta_i} \frac{\partial^2 u_i^*}{\partial x^{*2}}, \quad i = 1, \ldots, n \tag{3a}$$

$$u_1^*(0,t) = \sin \ t^* \tag{3b}$$

$$u_i^*(a_i,t) = u_{i+1}^*(a_i,t) \tag{3c}$$

$$\varrho_i \frac{\partial u_i^*(a_i,t)}{\partial x^*} = \varrho_{i+1} \frac{\partial u_{i+1}^*(a_i,t)}{\partial x^*}, \quad i = 2, \ldots, n-1 \tag{3d}$$

$$\varrho_n \frac{\partial u_n^*}{\partial x^*}(1,t) + \sigma u_n^*(1,t) = 0 \tag{3e}$$

$$u_i^*(x,0) = 0 \tag{3f}$$

where the nondimensional coefficients are defined by

$$\varrho_i = \frac{k_i}{k_1}, \quad \beta_i = \frac{\omega l^2}{\alpha_i}, \quad \sigma = \frac{\mu l}{k_1} \tag{4}$$

with $\varrho_1 = 1$. Therefore the system of equations (3) depends on $n + (n-1) + 1 = 2n$ nondimensional parameters. Unless otherwise stated, in the remaining part of the paper we will drop the superscript star and refer to non-dimensional variables by using the same symbol as the corresponding dimensional ones.

2.1. Transfer function representation via thermal quadrupoles

A thermal quadrupole is a two-port network that can be used to obtain a lumped parameters representation of the system [39]. The temperature and heat flux are respectively the across and the through network variables. The structure of the one dimensional initial-boundary value problem allows for the input to output