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Research Paper

Reconstruction of internal temperature distributions in heat materials by ultrasonic measurements

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HIGHLIGHTS

- A new method for reconstructing internal temperature distribution in a heat material is presented.
- Heat conduction problems of transient state boundaries are solved by quasi-steady approximation.
- Parameter analyses show that the new method has good robustness and estimated accuracy.

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ABSTRACT

An improved method for reconstructing internal transit temperature distribution in a heat material is presented in this paper. This method combines the advantages of the ultrasonic measurement and inverse analysis. Firstly, a numerical model of sensing interior temperature field is obtained based on temperature dependence of the velocity of ultrasonic wave (acoustic velocity) propagating through heated materials. Then, an inverse analysis by the sensitivity method for estimating equivalent thermal boundary conditions are developed to determine the non-uniform temperature fields. Experiments are referred to validate the feasibility and reliability of the presented method, whose robustness and accuracy is also analyzed through a comprehensive parameter analysis. Numerical results reveal that internal temperature gradient and its variation estimated by the developed method agree well with the measured values using thermocouples installed in the steel. Besides, this method can be helpful for solving the problems of transient state boundary using the quasi-steady approximation. It demonstrates that the method presented in this work is a promising means for high-accurately determining internal transient temperature distributions in heat materials by ultrasonic pulse-echo measurements.

1. Introduction

Measuring internal transient temperature distributions in heated materials has increasingly played a fundamental and significant role in various fields of science and engineering. For example, the development of a temperature sensor would be an important step in improving productivity and quality of metals processing, due to temperature dependence of materials properties [1]. Although a conventional thermocouple technique is widely used and cover a wide temperature range, it is not always acceptable because of its limitation of installation and destructive detection mode. In addition, the infrared or other optical technique, which are well known as noncontact or non-destructive measurement, may also not be appropriate for monitoring a transient variation of internal temperature because they only give surface temperatures of heated materials [1–3]. It is noted that surface and internal temperatures are often closely related to each other and sometimes independent of each other. Therefore, it is strongly required to realize an effective technique for in-situ or in-process measurements of such internal temperature distribution.

Ultrasound is an attractive modality for measuring internal temperature distributions in heated structures because of its capability to probe the interior of materials and its high sensitivity to temperature [4]. The principle of temperature measurement by ultrasound is based on temperature dependence of the speed at which sound travels through a material (acoustic velocity). There are some promising advantages in ultrasonic measurements, such as nondestructive, noncontact (by electro-magnetic or laser ultrasonic technique) and real time evaluation. Besides, it is non-ionizing, convenient, inexpensive and faster time response in comparison with the thermocouple technique [4,5]. Currently, ultra-

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sonic thermometry has been mainly used in gases or liquids, but there is little application in solids [6]. The reason may be that acoustic velocities propagating through solids are faster than those in gases or liquids. Thus, the signal acquisition and processing would be more difficult relatively.

Ultrasonic thermometry may be useful for internal transient temperature estimation if a temperature-dependent ultrasonic parameter can be identified, measured and calibrated. Fortunately, with recent advances in signal processing, it is both technically feasible and economically attractive to non-intrusively measure internal temperature using ultrasonic echo data [7–9]. In previous work, Norton and his team [6] gave two ultrasonic techniques for reconstructing internal temperature in metals and other materials: time-of-flight tomography and dimensional resonance profiling. Using a pulse-echo technique, Ihara and Tomomatsu developed an inverse analysis method coupled with a finite difference calculation to determine one-dimensional temperature distribution in the heated plate [10]. The least-squares method, which is capable of considering the refraction effect, is employed by Lu et al. to reconstruct two-dimensional temperature distribution [11]. Obviously, a large number of investigations in temperature field reconstruction are available in open literatures [12–15]. However, the reconstruction of internal temperature gradient and its variation during heating is an inverse problem in nature. Some problems such as a restriction on the thermal boundary condition and time-consuming in the inverse analysis should be solved to further improve the precision and efficiency of temperature field reconstruction [10].

In this work, an improved inverse method that overcomes the problems mentioned above has been developed to reconstruct internal temperature distribution in solid structures. Based on acoustic pulse-echo measurements, the proposed method consists of two parts: an inverse analysis is used to estimate the equivalent heat boundary conditions using the sensitivity method, and then internal temperature fields are achieved through the calculation of heat conduction problem. The results of an experiment and the previous study are given to validate the feasibility and reliability of the presented method. To demonstrate the robustness and practicability of this method, a comprehensive analysis is conducted to investigate the influences of several factors, such as uncertainty of material properties, number of measurement points and measurement error.

2. Principle of ultrasonic thermometry

2.1. Theoretical model

It is known that the speed of ultrasonic wave (acoustic velocity) propagating through a medium changes with temperature of the medium. The most studied form of ultrasonic thermometry is the pulse echo method [3]. Assuming a single side of the structure of a rectangular parallelepiped-shape is uniformly heated, one-dimensional temperature distribution in interior of this structure is shown in Fig. 1. By sending an ultrasonic pulse through a medium of known length, the propagation time of ultrasonic wave t_{delay} between the initial pulse and the reflection of the pulse from the opposite end of the medium can be given by

$$t_{delay} = 2\int_0^L \frac{1}{V(T)}dx \tag{1}$$

where x is the direction of the temperature distribution of the heated structure, L is the single propagation distance and $V(T)$ is the acoustic velocity which is a function of temperature T. Obviously, the following equation can be obtained if the temperature field is uniform

$$t_{delay} = \frac{2L}{V(T)} \tag{2}$$

In general, the acoustic velocity $V(T)$, which depends on material properties and may have an approximately linear relationship with temperature for a certain temperature range [4], can be expressed as

$$V(T) = aT + b \tag{3}$$

where a and b are calibrated by experiments. Fig. 2 shows the relationships between the velocity of ultrasonic wave and temperature of the steel [4].

Clearly, if the temperature field of a medium is uniform, the temperature can be easily achieved according to the Eqs. (2) and (3) when the propagation time of ultrasonic wave t_{delay} is measured. However, it may be complicated if the temperature field is transient and non-uniform.

The internal temperature distribution in a heated material $T(x, t)$, which can be given as a function of location x and the elapsed time after heated t, is unknown and difficultly solved because of little knowledge about boundary conditions. By introducing ultrasonic thermometry and measuring the time delay of echoes, temperature $T(x, t)$ may be derived. In this paper, an improved inverse analysis is proposed to estimate appropriate equivalent thermal boundary condition. Then, the internal temperature distribution is determined through solving the direct problem of heat conduction.

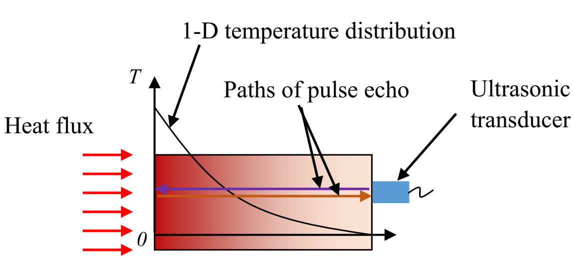

Fig. 1. 1-D model of ultrasonic thermometry.

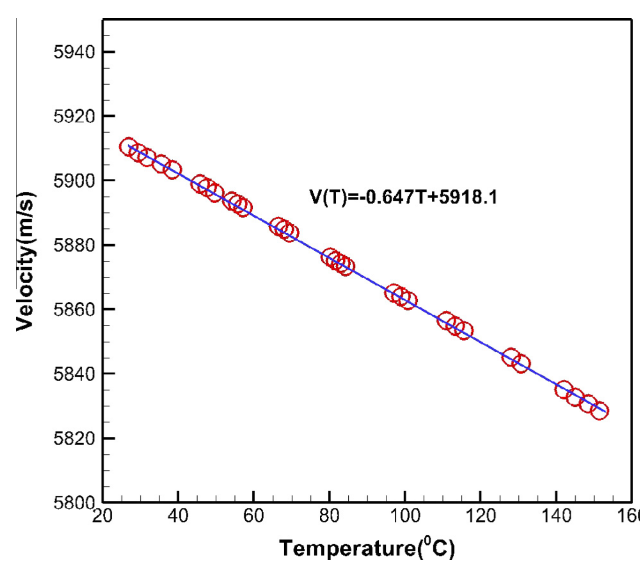

Fig. 2. The relationship between ultrasonic wave velocity and temperature in steel.