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Ultrasonic bent waveguides approach for distributed temperature measurement

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ABSTRACT

This paper describes novel techniques for simultaneous measurement of temperatures at multiple locations using two configurations (a) a single transducer attached to multiple waveguides of different lengths (each with a single bend) and (b) single waveguide with multiple bends connected to single transducer. These techniques improve upon the earlier reported studies using straight waveguides, where the non-consideration of the effect of temperature gradients was found to be a major limitation. The range of temperature measurement is from room temperature to maximum utility temperature of the waveguide material. The time of flight difference of reflected ultrasonic longitudinal guided wave modes (L(0,1)) from the bend, which is the reference signal, and another signal from the end of the waveguide, is utilized to measure the local temperature of the surrounding media. Finite element simulations were employed to obtain the appropriate dimensions and other design features of the multiple bent waveguide. This work is of interest to several industrial applications involving melters and furnaces.

1. Introduction

In many heat treatment cycles, the measurement and recording of temperature at various points inside the furnace is mandatory as per manufacturing standards. Thermocouples and radiation pyrometers are the most common temperature sensors used by industries. The auditors of the ASME (ASME B31.3 and ASME B31.1 in ASME section VIII), for example, and customers demand that devices such as thermocouples should be placed at the required locations throughout the job and temperature uniformity should be proved during processes such as soaking. The parameters that are important for monitoring include, temperature profiles of the glass melts, plenum off-gases, molten glass conductivity, density, and viscosity (for example see Woskov et al. [1]).

However, these temperature diagnostic tools have accuracy problems due to sensor drift for long-term operation (as explained in [2]). Thermocouples in particular, are prone to reliability issues (at the hot junction) while being used in hostile elevated temperature environments. Hence, the replacement of distributed thermocouple based temperature measurements with a more robust and reliable temperature measurement approach is of much interest.

Several researchers have developed alternate sensors (contact and non-contact, see [3] for example) for online monitoring of temperature. In the work reported here, the authors aim to measure the temperatures at different depths of a laboratory furnace which simulates a melter environment using a novel ultrasonic waveguide approach.

While ultrasonic approaches in general allow one to probe inside the region of interest, bulk ultrasound based methods [4–6] require transducer ruggedization, as the operating temperatures impact them adversely. Lithium-Niobate and Bismuth Titanate crystals have been explored to make ultrasonic high temperature transducers [7,8] that can withstand the high temperatures with modest success. An alternate approach is the separation of the ultrasonic transducer from the hostile measurement zone using a waveguide that can be used to transfer the wave between the two locations, thereby enabling the use of conventional, efficient, low cost PZT transducers. Ultrasonic waveguide based measurement methods have been extensively used for developing sensors for level, density, temperature, viscosity and rheology measurement of the surrounding fluid among others [9–16].

The main drawback of the previous ultrasonic waveguide approaches reported in literature is that they are aimed at the measurement of temperature at a single region of interest. Moreover, due to continuously varying temperatures, measurement at a single region is also challenging, with straight waveguide approaches (see Section 2.2 for more details).

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The present article considers two different configurations for multi-location temperature measurements using a single transducer, namely: (a) multiple waveguides (each with a single bend) and (b) a single waveguide with multiple bends. These approaches address some of the key issues of the temperature gradients with the multiple straight waveguide method (as reported for example, in [17]). Thin wires with circular cross-section, similar to those used in thermocouples are chosen as the waveguide embodiments. The studies are carried out using the L(0,1) fundamental longitudinal ultrasonic guided wave mode of circular cylindrical wires. From the ultrasonic guided wave signals reflected from the bends, the time of flight (TOF) as well as the amplitude (A) measurements can be used for learning more about physical characteristics of the environment surrounding the waveguides. For this purpose, the material properties of the waveguide (density and elastic moduli) are assumed to be known as a function of temperature. If this is not available, an earlier reported technique [18–22] may be employed to determine these temperature dependent moduli.

The change in TOF due to a change in temperature, henceforth called δTOF, was used to monitor instantaneous temperatures around the bend (horizontal portion) region of the waveguide. A peak tracking algorithm [described in more detail elsewhere, 17,21–25] is used to continuously measure δTOF at different temperatures from each bend region of the waveguide. Each bend region of the multiple waveguide is considered to represent a uniform temperature distribution region of interest at multiple levels of furnace, due to the relatively short length of this region. Since the measured δTOF is an average value of local temperature changes over the bend (horizontal) region of the waveguides, the configuration of the waveguides must be carefully designed. This approach significantly reduces the cost of instrumentation involved, when compared to the more traditional approach of transducing each waveguide with separate pulsing and reception electronics. The performance of optimal configuration with multiple waveguides connected to a single transducer and a single waveguide with multiple bends was demonstrated in a high temperature furnace for operation up to 1100 °C.

2. Background

2.1. Ultrasonic waves in cylindrical waveguide

Guided waves [26] can be thought of as a superposition of partial plane waves that are reflected within waveguide boundaries. The propagation of ultrasonic waves in waveguides is characterized by the frequency, phase velocity, waveguide material properties and its dimensions. In a cylindrical waveguide, there are three families of modes: longitudinal (L), torsional (T) and flexural (F) that are propagating in the axial direction (z) of cylindrical coordinate system (r, θ and z). While, many wave modes can be excited in cylindrical waveguides, we concentrate on the fundamental longitudinal mode, L(0,1). This mode has smaller levels of dispersion over a wide range of frequencies and can be easily generated in wire-like waveguides made of high temperature thermocouple material Chromel.

Phase velocity and group velocity dispersion curves obtained using DISPERSE [27], for Chromel waveguide is shown in Fig. 1, for the frequencies and diameters of interest to this work. The elastic moduli and the density of the waveguide material obtained using an approach described previously [22] are shown in Table 1. Chromel was chosen for this work because of its high melting point, ductility, and affordable availability [23]. However the results are generic in nature (various thermocouple wire material properties can be found for example, in [28]). It is desirable that the waveguide must exhibit minimal dispersion in the chosen frequency range; this ensures that the pulse width of the signals is relatively narrow and improves the time of flight measurements. We see that different materials have specific frequency ranges where the wave behaviour is non-dispersive. Hence, an operational frequency of 200–500 kHz range was chosen, using the dispersion curves. Further, in order to maintain regions of low dispersion, appropriate diameter of the wire-like waveguide was chosen.

2.2. Waveguide sensors

Waveguide sensors measure changes to surrounding media based on velocity changes due to the variations in material properties (α, E, G and ρ) arising from changes to environmental conditions such as temperature. In the present work, the L(0,1) mode is transmitted and received through the waveguide sensors using a single commercial PZT based transducer for measurement of temperature gradients. The change in time of flight (δTOF) as compared to the room temperature, helps to measure the changes in the temperature of surrounding media.

Most previous work on waveguide sensors have considered straight waveguides. However there are various limitations to this approach, as can be illustrated with an example (see Fig. 1(a)). Assume that a certain region has temperature gradients along the lengths (L_1, L_2, L_3, …, L_n) and the corresponding temperatures in the vertical region of the waveguide are $T_1 < T_2 < T_3 < \ldots T_n$.

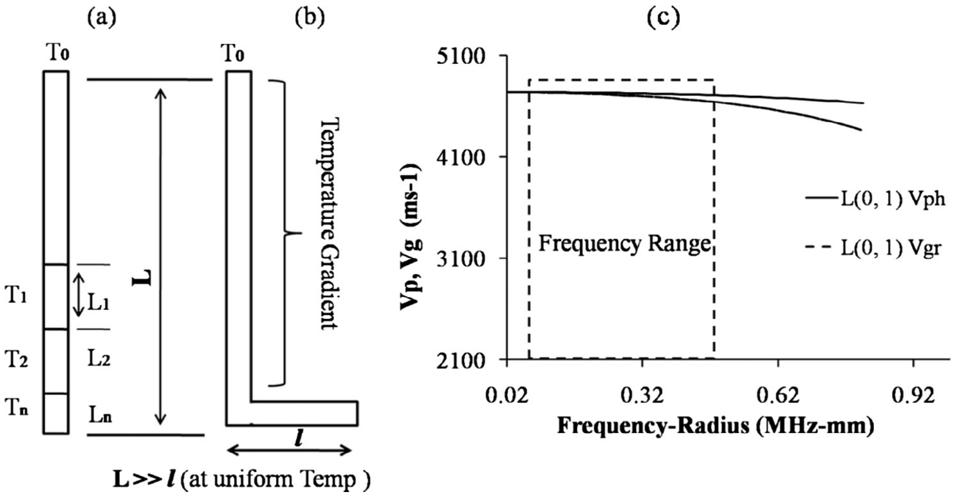

Fig. 1. Illustrations showing: (a) straight waveguide and (b) bent waveguide and (c) dispersion curves for L(0,1) modes of Chromel material as per Table 1.