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Robust Ultrasonic Waveguide based Distributed Temperature Sensing

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Abstract

This is a novel technique for distributed temperature measurements, using single robust ultrasonic wire or strip-like waveguides, special embodiments in the form of Helical or Spiral configurations that can cover large area/volume in enclosed regions. Such distributed temperature sensing has low cost applications in the long term monitoring critical enclosures such as containment vessels, flue gas stacks, furnaces, underground storage tanks, buildings for fire, etc. The range of temperatures that can be measured are from very low to elevated temperatures. The transduction is performed using Piezo-electric crystals that are bonded to one end of the waveguide which acts as both transmitter and receivers. The wires will have periodic reflector embodiments (bends, gratings, etc.) that allow reflections of an input ultrasonic wave, in a pulse echo mode, back to the crystal. Using the time of fight (TOF) variations at the multiple predefined reflector locations, the measured temperatures are mapped with multiple thermocouples. Using either the L(0,1) or the T(0,1)modes, or simultaneously, measurements other than temperature may also be included. This paper will describe the demonstration of this technology using a 0.5MHz longitudinal piezo-crystal for transmitting and receiving the L (0, 1) mode through the special form of waveguide at various temperatures zones.

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Keywords: Ultrasonic guided waves; grating, waveguides; distributed sensing; temperature; physical properties.

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1. Introduction

The laboratory based development of this sensor is motivated by a requirement for temperature profile

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measurement in glass melting plants, steel melting plants, nuclear power plants, atmospheric air temperatures etc. In order to control the melting process, it is required to monitor the temperatures at multiple levels inside the melt zone, with multiple sensors. Earlier similar efforts have been reported, where the time of flight (TOF) and amplitude (A) from the reflected ultrasonic signal received at one end of a waveguide were used for measuring the temperature and properties of *molten glass* material in which the other end was immersed by various authors (Shah et al. (1996), Balasubramaniam et al. (1999), Balasubramaniam et al. (2001), Shah et al. (2001) and Prasad et al. (2008)). Pandey et al. (2011) demonstrated that, using the ultrasonic guided flexural mode F (1, 1) in a long buffer rod, it is feasible to measure, at the high temperatures, properties of mould powder slags such as viscosity, break temperature, liquids temperature during the *steel forming process*. Jen et al. (1996) developed an ultrasonic sensors for on-line monitoring of *castings and moulding* at elevated temperatures. Periyannan and Balasubramaniam (2015) has reported a multiple waveguide system for the temperature measurements at multi levels in the *nuclear vitrification melter* using (L(0, 1) mode) Chromel wires. In Nuclear vitrification melters; thermocouple banks inside thermo-wells are currently used to guarantee the production of a high quality stabilized product that must meet stringent regulatory waste disposal requirements. Optimization of the vitrification process, through improved process control, could significantly reduce costs and improve the reliability associated with this effort studied by Ojovan et al. (2011). Also, thermocouple and radiation pyrometers are common temperature sensors used in glass and steel melting industries. However these diagnostic tools have accuracy problems due to sensor drift for long term operation, for example Bentley (1990). Huang et al. (2003) and Tsai et al. (2005) reported a temperature measurement *sensor for air* using an ultrasonic device. The waveguide is surrounded by a fluid, with known properties (such as air), then the material properties of the waveguide can be obtained at different temperatures as reported by Periyannan and Balasubramaniam (2014, 2015). Most of the authors have performed studies using single waveguide approaches for temperature measurements instead of the thermocouple. The ultrasonic waveguide sensors have several advantages over the conventional thermocouples. This includes the inherent property of higher reliability, since there is no junction that can fail. Due to this high potential, the authors aim to measure the temperatures at different depths of hot region using multiple sensors performed in a single waveguide system. These multiple sensor waveguide system was used in the special embodiment of helical form as shown in Fig. 1(b). In this work a high temperature (35º C to 1450° C) laboratory furnace was used.

2. Methods

2.1. Ultrasonic Waves in Rod Waveguide

The guided waves (see for ex: Rose (1999)) 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 variables: frequency, phase velocity, and attenuation. 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 rods, we concentrate on the fundamental longitudinal mode, L (0, 1). This mode has smaller levels of dispersion over a wide range of frequencies as shown by Pavlakovic et al. (1997) and can be easily generated in the wires (Periyannan and Balasubramaniam. 2015) made of high temperature (Chromel) materials.

2.2. Working Principle of Waveguide Sensors

The working principle waveguide sensor depends on the fact that a velocity (Sound speed) change in a material is related to its temperature. Velocity changes are due to the variations of material properties (α, E, G &ρ) at different temperatures. Here, the pulse echo L(0, 1) mode was transmitted and received by longitudinal transducer (Panametrics-0.5MHz) on the waveguide sensors for the temperature measurements. After that, the waveguide sensors were calibrated using the change in time of flight (δtof) that is directly proportional to the change in coefficient of thermal expansion of material at different temperatures.

3. Results and Discussion

3.1. Multiple Sensor Approach in a Single Waveguide

Fig. 1(b). describes multiple sensors are made in a single waveguide for temperature measurement at multilevel of a high temperature furnace. A similar experimental setup, procedure, apparatus and transducer holder as given in Periyannan and Balasubramaniam (2015) have been followed in this work. Here, using multiple sensor (gratings) with single helical waveguide instead of the multiple waveguides as shown in Fig. 1(a, b). A helical waveguide (Chromel wire) with notches was considered similar to multiple sensors. From Periyannan and Balasubramaniam (2015) the multiple waveguide system of each waveguide was positioned at different levels of furnace as shown in Fig. 1(a). In a helical waveguide system; multiple sensors (each notch) were positioned with respect to the number of active coils, mean dia of coil, pitch and free length of the coil. These notches were made on a waveguide in order to avoid the overlapping of signals from each notch as shown in Fig. 1(b). Hence, the position of the sensors (radial as well as depth) are easily adjusted at a helical waveguide system. Thus the waveguide configuration and the sensor locations can be in 1D, 2D or 3D domain. Adjusting the position between the two sensors were very limited in multiple waveguide system than helical waveguide method. Those methods (helical, multiple straight waveguides) were used same thickness of Chromel wires.

3.2. Principle of Measurement

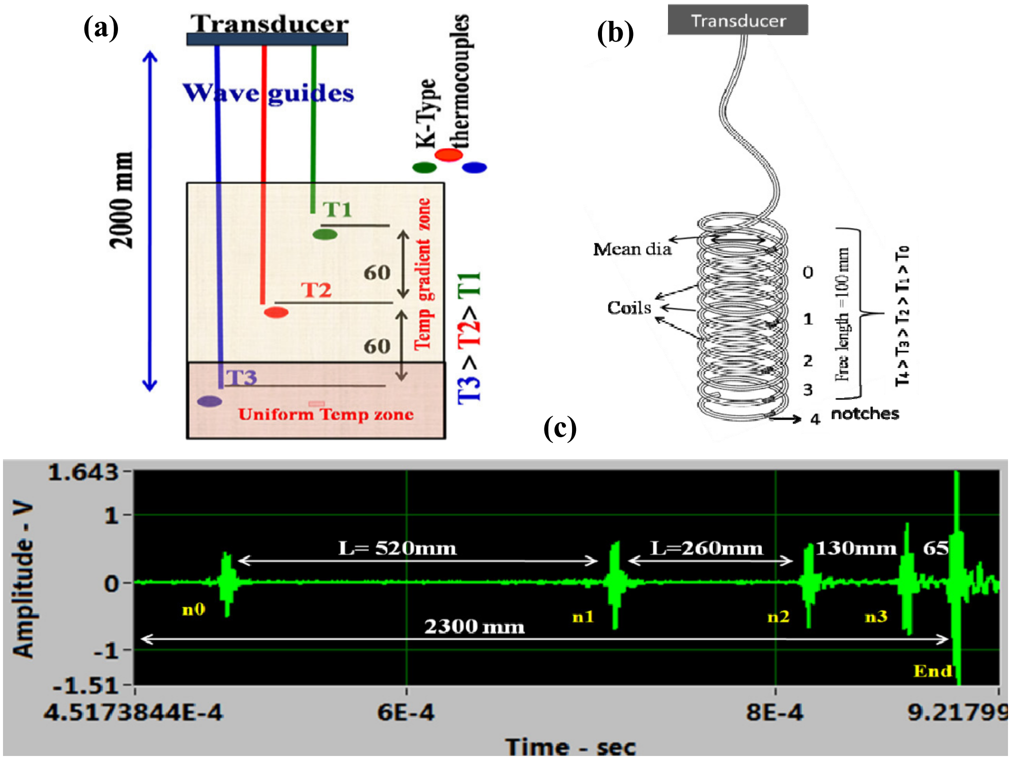

Fig. 1. (a) Multiple level temperature measurement using multiple waveguides Periyannan and Balasubramaniam (2015); (b) Multiple notches (sensors) in a helical waveguide; (c) A- scan signal for the helical waveguide sensors and the dimensions are marked.

The ultrasonic pulse-echo mode was used and the piezoelectric crystal based broad band ultrasound transducer was acoustically coupled to the one end of waveguide as shown in Fig. 1(b). The other end of that waveguide was made in the special embodiment (helical shape) for this work. The analog to digital convertor (for more details Periyannan and Balasubramaniam (2015)) was used to acquire the data from the pulser-receiver. Multiple signals from multiple notches at single waveguide have to be monitored. After that a signal peak-tracking technique (Periyannan and Balasubramaniam (2015)) was employed to lock the time of flight measurement to specific signals of interest even though the signals are shifting in time during the heating process. Subsequently the δTOF between each pair of notches (one sensor) were measured using Eq. (1). The temperature was measured using calibrated reference-TC (K-thermocouple) that were co-located with the waveguide notches for the initial calibration of the multiple sensors from a waveguide.

$$(\delta tof_{n+1})_i = [((TOF)_{(n+1)i} - TOF_{ni}) - ((TOF)_{(n+1)} - TOF_n)] \qquad (1)$$

where,

TOF_{ni}, TOF_n → Instantaneous TOF at various temperatures and TOF at room temperature from each notch

$(\delta TOF_{n+1})_i$ → Instantaneous change in TOF from each sensor

n = 0,1,2,3... Number of notches in a waveguide

For each sensor, δTOF was measured by Eq. (1) from a helical waveguide at various temperatures using co-located thermocouple as shown in Fig. 2(a). Then fine co-relations could be observed from thermocouple data as well as the multiple sensors outputs of a waveguide. Finally, the helical waveguide system was used for temperature measurements at temperature gradient region (multilevel) of furnace. Next the heating cycle experiment was conducted for approximately 4 hrs of heating rate and simultaneously the δtof's data was collected from all sensors at a rate of every 60 s. The δTOF values were measured from each sensor in a waveguide and the corresponding temperatures of sensors were calculated using empherical equations from Fig. 2(a). The temperatures were also obtained using co-located K-type thermocouples and plotted along with the ultrasonic measurements. Fig. 2(b) shows a plot of different time instances (only a few time instances are provided in this plot) and the temperatures at 4 levels (10mm, 30mm, 50mm, and 70mm) are obtained by adjusting the free length of coil. It can be observed that the comparison between the ultrasonic waveguide measurements and the thermocouple outputs are well comparable with a maximum average error of 1°C to 3°C.

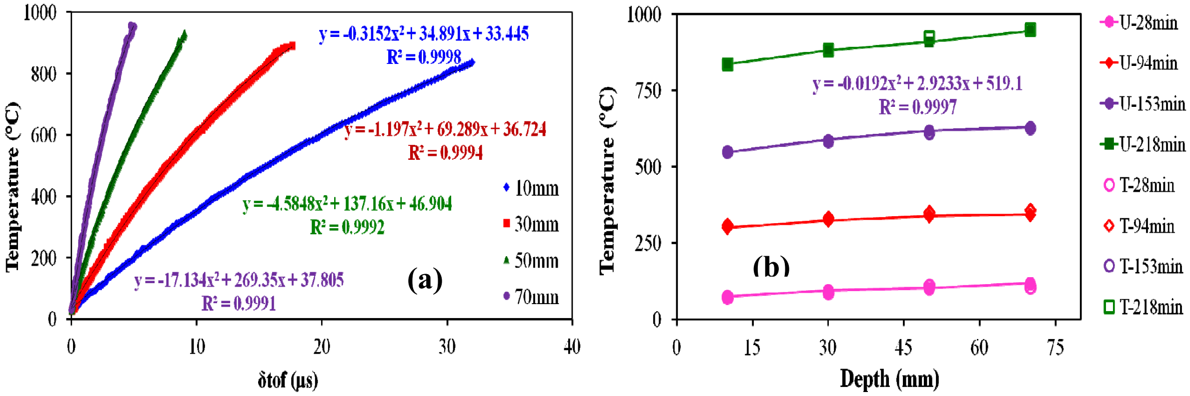

Fig.2. (a) The δTOF vs. Temperature obtained from multiple sensor of helical waveguide; (b) The ultrasonic temperature measurements vs different depths at different time instances during a heating cycle inside a furnace. Here, U represents ultrasonic measurements and T represents corresponding thermocouple readings.

4. Conclusion

The ultrasonic distributed temperature sensor as described here provides a more robust and cost effective solution for measurement of temperature gradients, in applications involving elevated temperature processes, when compared to junction based thermocouples. This novel technique reported here uses a multiple gratings (sensors) in a single helical waveguide, functioning as ultrasonic waveguide sensor, and employs the guided L (0, 1) mode that can be reliably generated and received by using a conventional longitudinal transducer. The technique relates the δTOF parameter to multi sensors of helical waveguide temperatures. This technique was demonstrated to measure the temperatures at multiple levels inside a furnace. Grating spacing can be easily varied from the helical waveguide. This allowed for the demonstration of the real-time monitoring of the temperatures at multi-level inside a hot chamber in the laboratory. Further the ultrasonic sensors output has been verified with thermocouple data. Hence, only 1 set of ultrasonic electronics and 1 transducer to make measurements at multi levels within the region of interest.

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