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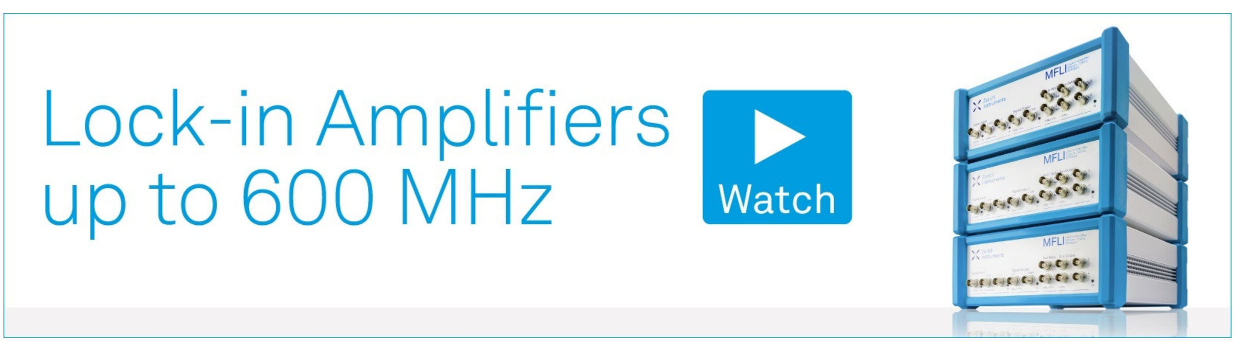

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Distributed Temperature Sensing Using a SPIRAL Configuration Ultrasonic Waveguide

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Abstract. Distributed temperature sensing has important applications in the long term monitoring of critical enclosures such as containment vessels, flue gas stacks, furnaces, underground storage tanks and buildings for fire risk. This paper presents novel techniques for such measurements, using wire in a spiral configuration and having special embodiments such a notch for obtaining wave reflections from desired locations. Transduction is performed using commercially available Piezo-electric crystal that is bonded to one end of the waveguide. Lower order axisymmetric guided ultrasonic modes were employed. Time of fight (TOF) differences between predefined reflectors located on the waveguides are used to infer temperature profile in a chamber with different temperatures. The L(0,1) wave mode (pulse echo approach) was generated/received in a spiral waveguide at different temperatures for this work. The ultrasonic measurements were compared with commercially available thermocouples.

INTRODUCTION

The development of an ultrasonic temperature sensor is motivated by many temperature profile measurement requirements in industries where temperature control is critical (for example, nuclear plants, steel power plants and glass melting plants). In a high temperature environment, particularly where there is limited access, it is essential to continuously monitor temperature at multiple locations using reliable methods. Thermocouples, resistive temperature devices (RTD) and radiation pyrometers are common temperature sensors used in industries. However most currently available tools present practical limitations. Pyrometers require a line-of-sight that is not feasible in enclosed industrial high temperature processes. Radiation pyrometers and Thermocouples suffer due to sensor drift during long term operation, as reported elsewhere for example, by Bentley [1] and Tooley [2]. The footprint of a thermocouple (involving two wires and often ceramic coatings/beads), flexibility of these wires and its ability to measure temperature only in one location, etc., are all considered as limiting factors for industrial applications where temperatures at different locations must be monitored. Additionally, the failure of the junction in a thermocouple is of concern, particularly for high temperature operations. The ultrasonic waveguide technique has the potential to address some of these limitations. Recently, efforts on the measurement of physical properties surrounding fluids (such as molten glass, mould powder slags, etc.) using this approach have been extensively reported [3-8]. It has also been shown that using an ultrasonic waveguide that is surrounded by a fluid with known properties (such as air), the elastic moduli of the waveguide at different temperatures can be measured. [9-12].

Waveguide based ultrasonic sensing of temperature have also been reported in the literature recently. Periyannan and Balasubramaniam [4] have reported an ultrasonic waveguide system for temperature measurements at multiple levels in a Joule melter using L(0,1) guided wave mode using a bank of straight waveguides. Tsai et al. [13] proposed an ultrasonic system for air temperature measurement using changes in the speed of sound calculated from phase shift records. Most of the previous approaches described measurements in a single zone of interest. Using these approaches, it would be necessary to have multiple sensors for multi-point distributed measurements. However, it may be feasible to have multiple reflectors along a single waveguide and hence reduce the footprint as well as the instrumentation needs. This approach has some similarities to earlier reports in the literature on distributed fiber optic temperature sensors using Fiber Bragg Grating reflectors [14-15]. In the fiber optic sensors, a broad band light source is used along with wavelength division multiplexing (WDM) technique that is well known. In our approach, the ultrasonic reflected signal and the time of flight differences are used to measurement of local temperatures.

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Multiple "notch" embodiments, acting as reflectors, that are positioned along the length of the waveguide shall be used to measure temperature in multiple zones using a single ultrasonic waveguide. The configuration of the waveguide can be straight or can take shapes such as helical, spiral, etc., depending on the type of application. The authors have reported earlier on similar approach using a straight and a helical waveguide configuration for distributed sensing of temperatures [3, 16-19]. In this paper, the authors aim to develop a spiral waveguide with notch-type sensors to measure the temperature inside the furnace. To our knowledge there are no earlier studies reported in the literature on the characteristics and applications of elastic waves in such spiral waveguides. Our results show much promise for application of spiral waveguide sensors for distributed temperature sensing.

WAVEGUIDE TEMPERATURE SENSORS

Waveguide temperature sensors measure changes in the time of flight of an ultrasonic wave mode due to the changes in the material properties of the waveguide (l_s. α, E, G and ρ) as a function of temperature. Here, l_s is the gage length of the sensor, α is the coefficient of thermal expansion, E and G are the elastic moduli and ρ is the mass density. In order to localize the measurement, embodiments such as notches and bends among many others, can be introduced in the waveguide that allow the signals to be reflected from these embodiments. Periodically spaced notches in the waveguide are used to reflect signals from these locations. The measurement of the relative time of flight (TOF) between these reflections (notches) can be monitored and used to obtain the temperature between the two reflectors. Here, each pair of reflections can be considered as one sensor to determine the temperature of the surrounding medium; the physical distance between these reflectors is the gage length.

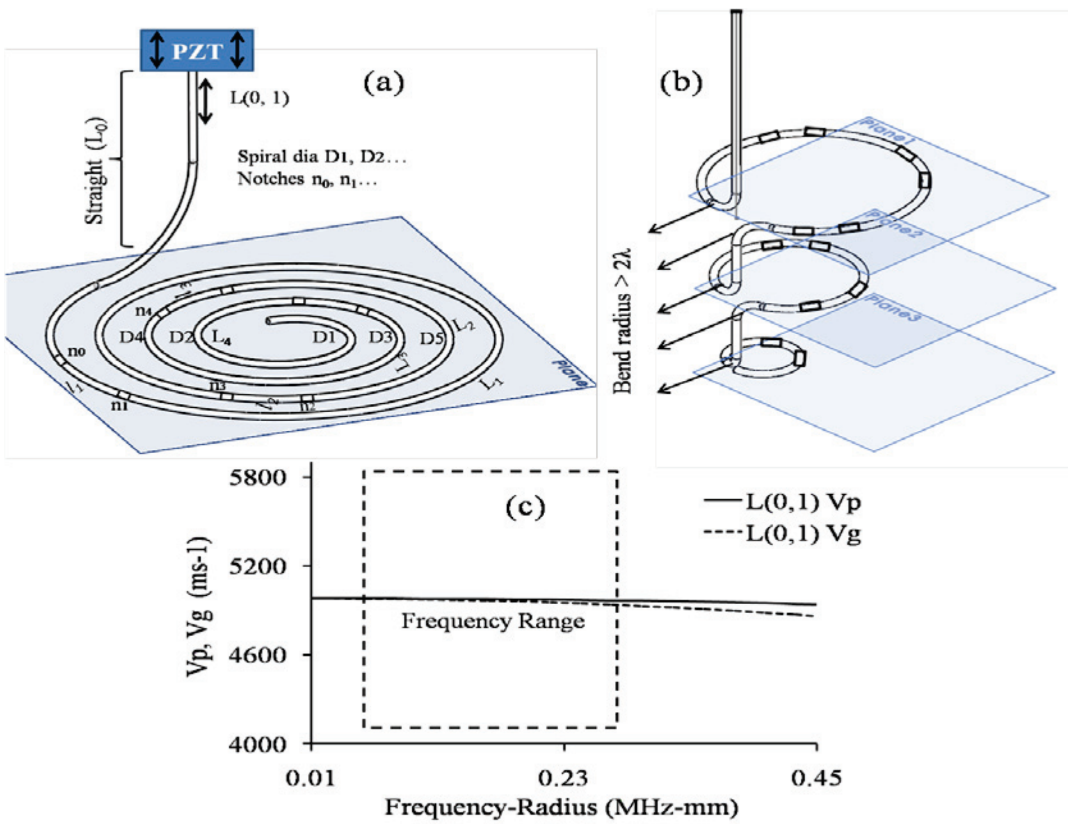

FIGURE 1. Illustration of temperature measurement concept in (a) spiral and (b) conical like spring waveguides respectively, (c) dispersion plot for a straight Chromel wire

In Figure 1(a), the spiral waveguide is illustrated in three possible spiral configurations: A) In a spiral waveguide, using more number of mean diameters by adjusting the radial pitch between the two successive mean diameters of spiral. The measurement can be made at surface (2D) region of interest in Figure 1(a). B) A spiral waveguide can be easily pulled in axial (conical like spring waveguide), and subsequently each sensor can be re-positioned at different depths of planes as shown in Figure 1(b) or it can be made as straight waveguide. The compressed position in Figure 1(a) allows for temperature measurements in one plane that are relatively closely spaced, compared to the waveguides shown in Figure 1(b). The spiral waveguide can be easily re-configured, based on the measurement region of interest. In this paper, notch type of embodiments (approximately 0.5 mm deep and 3 mm long) were machined along the length of the 1.18 mm diameter waveguide to provide reflected signals from each sensor embodiment. The total length of spiral waveguide was measured using Equation (1-2) for this work.

$$\text{Total length of wire } (L) = (L_0+L_1+L_2...+L_n) + (l_1+l_2+...+l_s) \quad (1)$$

$$(L) = \sum L_n + \sum l_s \qquad (n = 0, 1, 2,..) \quad (1a)$$

$$\text{Total length of sensors } (l) = \sum l_s = l_1+l_2+... \quad (s = 1, 2,..) \quad (2)$$

where,

$L_n = L_1, L_2, L_3\ldots$ are wire lengths between each pair of notches (1-2), (3-4), (5-6)... respectively
$l_s = l_1, l_2, l_3...$ are lengths of each sensor between two notches (0-1), (2-3), (4-5)... respectively
L_0 = length of the starting (before notch-n_0) portion of waveguide
$l_s < L_n$, for waveguides in Figure 1(a-b)

ULTRASONIC WAVES IN SPIRAL WIRE WAVEGUIDE

The guided waves can be thought of as a superposition of partial plane wave modes that constructively interfere within waveguide (rods, tubes, pipes etc.) boundaries. Three families of wave modes are considered: longitudinal (L), torsional (T) and flexural (F) that propagate in the axial direction (z) of the cylindrical coordinate system (r, θ and z) [20]. The ultrasonic guided wave propagation in a structure is dependent on the frequency, phase velocity, group velocity and attenuation. The material properties density (ρ = 8650 Kg/m3), Young's modulus (E = 215GPa) and Poisson ratio (μ = 0.3) of Chromel were experimentally obtained at room temperature using previously reported approaches [11-12] for dispersion analysis. The phase velocity and group velocity dispersion curves for the fundamental axisymmetric L(0,1) mode of a straight wire waveguide in order to limit the level of dispersion [21] as shown in Figure 1(c). The frequency range chosen is based on the non-dispersive region of interest in the straight waveguide. The dispersion effects observed are due to (a) the geometry of the waveguide, (b) the frequency of operation, and (c) the curvature effects [16], and must be considered while designing the spiral waveguide sensor.

In this paper, the fundamental longitudinal L(0,1) mode of the wire waveguide constituting the spiral shall be considered. An operational frequency range of 200 - 500 kHz was chosen for the experiments in this paper, in order to remain in the relatively non-dispersive region for L(0,1) wave mode as well as to keep the pulse duration of the signals to a reasonable level in order to identify the individual reflections. In order to ensure low dispersion, an appropriate thickness of the wire and suitable mean diameters ($D_m > 2\lambda$) of spiral due to curvature effect were considered for selection of waveguide using our earlier approaches [16, 19]. Studies of waves in helical waveguides were reported in literature [22-23] with applications in civil structures. The elastic wave dispersion effects were modeled for cylindrical and helix geometries using a finite element approach in a non-orthonormal coordinate system. It has been shown in such previous work that by increasing the helix radius, the helix effect on wave propagation and the dispersion caused by curvature can be significantly reduced. The dispersion effects due to the curvature of a helical structure (Chromel wire) were studied at different mean diameters [16, 19]. Also, the curvature effects at the bend regions of the waveguide has been recently reported [24].

PRINCIPLE OF EXPERIMENT AND MEASUREMENT

Figure 2(a) shows the spiral waveguide used in the experiment to measure temperature in a high temperature test furnace. A similar experimental setup, procedure, apparatus and transducer holder were described in the literature [3, 16-18]. Multiple notches were machined along the length of the Chromel spiral waveguide as shown in Figure 1(a) and 2(a). The notches were positioned in order to avoid the overlapping of reflected signals from each notch as shown in Figure 2(c). The location of the sensors can be repositioned by varying the mean diameter of the spiral.

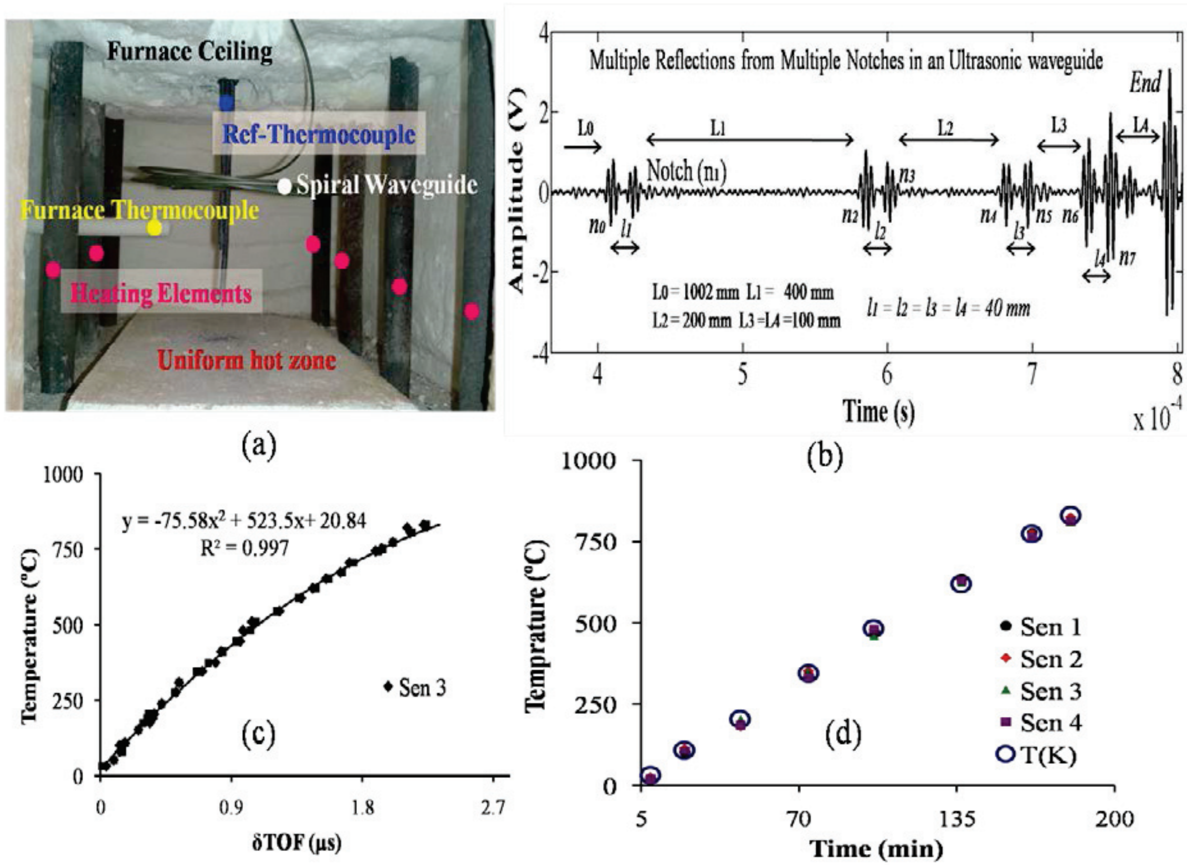

FIGURE 2. (a) Experimental setup of spiral waveguide system with melter, (b) Reflected signals are received from the four pair of notches (c). δTOF vs. Temperature for the calibration curve of spiral waveguide sensor (d) Comparison of temperature measurement using ultrasonic waveguide method (solid) with thermocouple T(K) (hollow).

The shear wave transducer was acoustically coupled [12] to one end of the waveguide as shown in Figures 1(a) and 2(a). An 8 bit, 100 MHz sampling rate analog to digital converter (NI USB-5133) was used to acquire and archive the A-scan signals from the ultrasonic pulser-receiver to a Personal Computer. Multiple reflected signals from multiple pair notches were continuously monitored using the signal peak-tracking technique method that has been used elsewhere [3, 16-18]. Subsequently, the δTOF between each pair of notches (one sensor) were measured using Equation (3). The TOF's and the δTOF's of multiple sensors in the spiral waveguide were recorded at different temperatures inside the furnace.

Instantaneous time of flight difference (δTOF) of a waveguide is defined as shown below.

$$(\delta TOF_{n+1})_i = [TOF_{(n+1)i} - TOF_{ni}] - [TOF_{(n+1)} - TOF_n] \quad (3)$$

where,

TOF_{ni} **,** TOF_n Instantaneous (i) TOF at various temperature and (ii) TOF at room temperature

$(\delta TOF_{n+1})_i$ Instantaneous change in TOF between the reflections from each sensor location n, in µs.

Each sensor's δTOF is measured in between the pair of notches ((0, 1), (2, 3), (4, 5), (6, 7)) locations n at T_i

$$U(T) = -75.6(\delta TOF)^2 + 523.5(\delta TOF)+20.8 \quad (4)$$

RESULTS AND DISCUSSION

A spiral waveguide with four pair of notches and a furnace were used in this work as shown in Figures 2(a). The L(0,1) mode was generated/received in the spiral waveguide using the shear wave transducer procedure [12] and was oriented parallel (0º) to the axis of the waveguide. The instruments reported earlier were used to obtain the A-scan (Figure 2(b)) from the spiral waveguide with notches. The spiral waveguide was kept in the uniform hot region of the furnace as shown in Figure 2(a). Temperature was uniformly increased inside the furnace for about three hours to calibrate the waveguide sensor. A K-type thermocouple was co-located near the spiral waveguides and the corresponding temperature was monitored. The calibration was based on the time of flight difference (δTOF) at locations in-between the pair of notches (one sensor) using peak-tracking method. The δTOF of each sensor was measured at instantaneous temperature using Equation (3). Spiral waveguide sensor number 3 was initially calibrated using with thermocouple output as shown in Figure 2(c). Equation (4) was found from the calibration plot using the 2nd order polynomial expression. Calibration of sensor number 3 was found to be adequate for the other sensors on the same waveguide. Each sensor δTOF measurements were then related to the local temperature measurement using Equation (4). The thermocouple output was compared with the waveguide sensors output at different time instances as shown in Figure 2(d).

CONCLUSION

An ultrasonic spiral waveguide temperature sensor provides a more robust, small footprint and a cost effective solution for measurement of temperatures over an area when compared to junction based thermocouples. This technique uses pairs of notches in a waveguide and each pair of notches was considered as one sensor. The spiral waveguide sensors using guided L(0,1) modes that can be generated and received by using a shear or longitudinal transducer was demonstrated. The spiral waveguide sensor was calibrated based on the time of flight changes (δTOF) from L(0,1) mode by uniformly varying the temperature inside the furnace. The calibration curve was curve was obtained for each sensor. Temperatures were measured using ultrasonic technique and compared with thermocouple readout. In this work, only four pairs of notches were used in the spiral waveguide. It is possible to increase the number of sensors in an appropriate waveguide material.

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