Ultrasonic Waveguide Techniques for Distributed Temperature Sensing

Suresh PERIYANNAN, Prabhu RAJAGOPAL, Krishnan BALASUBRAMANIAM
Centre for Non Destructive Evaluation and Department of Mechanical Engineering
Indian Institute of Technology Madras, Chennai 600036, India

Contact e-mail: balas@iitm.ac.in, suresh.periyannan@yahoo.com

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 or strip-like ultrasonic waveguides in the form of straight, helical and geometrical configurations and having special embodiments such as notches or bends 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 flight (TOF) differences between predefined reflectors located on the waveguides are used to infer temperature profile in a chamber with temperature gradients. The ultrasonic measurements were compared with commercially available thermocouples.

Keywords: Ultrasonic guided waves, waveguide sensor, helical spring, distributed sensing, high temperature measurement

Introduction

The laboratory based development of this sensor is motivated by a requirement for temperature profile measurement in many industry applications; glass melting plants, steel melting plants, nuclear power plants, vitrifiers, 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. Ultrasonic waveguide based measurement methods have been extensively used for developing sensors for level, density, temperature, and rheology measurement of the surrounding fluid [1-14]. While using as a sensor, the material property of the waveguide (density and elastic moduli), as a function of temperature, were assumed to be known. Consequently, if the waveguide is surrounded by a fluid, with known properties (such as air), then the material properties of the waveguide can be obtained as a function of temperature as reported by Periyannan and Balasubramaniam [15, 16].

In a nuclear waste vitrification melter, a bank of thermocouples placed inside thermowells 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. [17]. Also,
Thermocouples 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 [18]. Huang et al. [19] and Tsai et al. [20] reported a temperature measurement sensor in air using an ultrasonic device.

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. Also, as described in this paper, many notches along the waveguide can ensure multiple temperature measurements using a single waveguide. Additionally, in this paper, a reconfigurable spring-like configuration is discussed. Here, the spring allows for the sensor locations to be adjusted by expanding or compressing the spring waveguide. Here, the authors aim to measure the temperatures at different depths in a hot region at multiple locations using a single waveguide system as shown in Fig. 1(a, b) over a range of temperatures (35°C to 1450°C) using a laboratory furnace setup.

2. Methods

2.1. Ultrasonic Waves in Rod Waveguide

The propagation of ultrasonic waves in waveguides is characterized by the variables, frequency- \( f \), phase velocity- \( V_{ph} \) and attenuation \( \alpha \). A guided wave can be thought of as a superposition of partial plane waves that are reflected within the waveguide boundaries by Rose [21]. In a cylindrical waveguide, there are three families of modes; longitudinal (L), torsional (T) and flexural (F) that are propagating along the axial direction (z) and the wave behavior can be expressed analytically in a cylindrical coordinate system (r, \( \theta \) and z) [21]. Our analysis concentrates on the fundamental axi-symmetric longitudinal and torsional modes i.e. \( L(0, 1) \) and \( T(0, 1) \) respectively. These two modes show low or no dispersion over particularly at low frequencies and can be easily generated in the rods.

The group velocity dispersion curves (obtained by DISPERSE [22]) for rods of different diameters made of high-temperature materials are shown in Fig. 2a. The material properties and dimensions of the high-temperature waveguides that are explored in this paper are provided by [11, 15] as in Table 1. It can be noted that different materials have specific frequency ranges where the wave is non-dispersive. It must be noted that it is desirable that in the chosen frequency range the waveguides must exhibit only a small degree of dispersion. Thus, the pulse width of the signals remains relatively narrow and consequently improves the time of flight measurements. The waveguide diameters were chosen based on the dispersion curve analysis and availability of such wires. Based on elasto-dynamic FEM model, using commercial software ABAQUS® simulation studies were performed on the wave propagation in the rods and tubes in order to obtain the predicted displacement response, also called as an A-scan, by monitoring a point near to the point of transduction of the guided wave, and is reported in more detail [15, 23].

2.2. Working Principle of Waveguide Sensors

The working principle waveguide sensor depends on the fact that a velocity change in a material is related to its temperature. Velocity changes due to change in temperature can be attributed to the variations of material properties (\( \alpha, E, G &\rho \)) as well as the coefficient of thermal expansion at different temperatures. Here, in our experiments, the \( L(0, 1) \) mode was transmitted and received by longitudinal transducer (Panametrics-V101) which was mounted on the waveguide.
3. Results and Discussion

3.1. Multiple Sensor Approach in a Single Waveguide

The Figs. 1(a, b) compares two approaches for multiple point measurements. In Fig. 1(a) multiple ultrasonic waveguides are employed while in Fig. 1(b) the same is accomplished using a single waveguide in a helical configuration. A multiple waveguide system where each waveguide was positioned at different levels of furnace as shown in Fig. 1(a) has been reported earlier [8]. In a helical waveguide system; multiple sensors (pair of notches) were designed by controlling the different helix parameters i.e. mean diameter of coil, pitch and free length of the coil. Hence, the position of the sensors (radial as well as depth) are easily adjusted at a helical waveguide system.

![Figure 1(a). Multiple level temperature measurement using multiple waveguides system [8]; (b) Multiple notches (sensors) in a helical waveguide and the dimensions are marked.](image)

3.2. Helical Waveguide Design Using Finite Element Modeling (FEM)

The waveguide of diameter (d) was chosen based on the dispersion curve analysis Fig. 2a made of Chromel. The wave propagation (FEM) simulations were performed for a pulse-echo mode measurement. The material (Chromel) properties, the FEM model details, etc. that were used in the simulations are listed in Table I. The A-scan signals were obtained by plotting the displacements at the receiver nodes as a function of time. The receiver nodes coincide with the transmitter nodes and the A-scan is the average of the displacements over these nodes. In these studies, temperature effects were not considered and used only to design the helix configuration. A normal (to the axis) input excitation was provided at one end of the helical waveguide as shown in Fig. 2b, in the form of a six (n = 6) cycle Hanning pulse displacement amplitude (A), using the relationship in Equation. (1).

\[
\text{Hanning pulse (A) = } [1 - \cos \left(\frac{2\pi ft}{n}\right)].\cos (2\pi ft) \tag{1}
\]

\[
\text{Wavelength (}\lambda\text{) = } \frac{\text{Longitudinal velocity of waveguide (V_L)}}{\text{Input frequency (f)}} \tag{2}
\]

\[
\text{Mean diameter of the helical waveguide (D) = a}\lambda; (a = 0.78 \text{ to } 3.12) \tag{3}
\]
### Table 1: Material Properties and Helical Waveguide Parameters for Finite Element Simulation

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass Density-ρ (Kg m⁻³)</th>
<th>Young's Modulus-E (GPa)</th>
<th>Poisson Ratio-μ</th>
<th>Element Size (mm) &amp; Type</th>
<th>No of cycle (n), Freq f- (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromel (Chr)</td>
<td>8650</td>
<td>214</td>
<td>0.3</td>
<td>λ/28, 8-node Brick</td>
<td>6, 400e3</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>9000</td>
<td>127</td>
<td>0.34</td>
<td>-------</td>
<td>-------</td>
</tr>
</tbody>
</table>

Figure 2 (a) Dispersion curves (Phase velocity-\(V_p\) and Group velocity-\(V_g\)) for a straight Chromel and Copper (d=1.2mm) wire, (b) Chromel helical waveguide dimensions at different parameters, (c) A-Scan of the far end reflected signals obtained in pulse echo mode at different D and l values.

The longitudinal L(0,1) mode A-Scan signals that represent the free far end reflections in waveguides without any embodiments (notches) using pulse-echo mode for the different dimensions of the helical waveguides (with varying D and l values) as shown in Figure 2(b). The corresponding time of flight (TOF) arrivals, and dimensions are marked in the A-Scan plots. Significant change in L(0, 1) mode group velocity (\(V_g\)) and different levels of dispersion were observed due to a change in mean coil diameters of the helical waveguide (ref: D1, l and D4, l in Fig. 2c). It was observed that as the mean coil diameter decreased, the group velocity decreased and the signal were observed to be relatively more dispersive in nature. A very small change in velocity was observed with the change in pitch P of the helical waveguide while keeping D a constant [11]. The studies on waves in helical waveguides have been previously reported on acoustic waves [24], electromagnetic waves [25] and elastic waves for structural health monitoring [26] with applications in civil structures. For avoiding dispersion effects due to curvature (mean dia D) and mild velocity variations as a function of pitch (P) effect are briefly described [11, 26-27].
Hence, it is observed that the wave propagation behaviour is more significantly influenced by the selection of the mean coil diameter and it is recommended that D must be carefully selected [11]. It is concluded that for a helical waveguide dispersion effects are dependent on mean coil diameter (due to stiffness effect), excitation frequency (wavelength-λ) and velocity of the material. The modes are more dispersive in nature when the mean coil diameter is < λ. Hence, in the experiments, the L(0, 1) mode wavelength was chosen to be less than the mean coil diameter of helical waveguide.

3.3. Experimental Details

In this work, the Panametric 5077 ultrasonic Pulser/receiver was used. The National Instruments USB 5133, 100 MHz 8 Bit analog to digital convertor was used to acquire the data from the Pulser receiver and archive in the PC. A resistive heating furnace was used with a maximum operating temperature of 1450 °C with the help of Shinko programmable temperature controller. The experimental procedure was followed by the earlier approaches [11, 12]. The ultrasonic pulse-echo mode was used and the piezoelectric crystal based broad band ultrasound transducer was acoustically coupled to the helical waveguide (Chromel) as shown in the Fig.1b. The ultrasonic pulses were transmitted and the reflected waves are received using a conventional longitudinal wave transducer. Here, the helical portion of the waveguide (Chromel) was in a uniform temperature region of interest for initial calibration of waveguide using co-located thermocouples [11]. The waveguide calibration was based on time of flight difference (δTOF) between pair of notches (one sensor) using Equation 4 at various temperature.

The Fig. 3(a) shows a typical longitudinal A-scan signal from the helical waveguide (Fig. 1b) at room temperature(T₀). The A-scan describes multiple reflected signals from notches and end of the waveguide. The reflected signals from notches of an each waveguide were continuously monitored using that signal peak-tracking technique method that has been described elsewhere [8, 11-12, 15, 16]. The same peak tracking technique was used to continuously measure the time of flight difference (δTOF) at different temperatures from multiple notches of interest of each waveguide, for entire heating cycle. Here, an operational frequency range of 200 - 500 kHz was chosen.

\[
(δTOF_{n+1})_i = [(TOF)_{(n+1)i} - TOF_{mi}] - [TOF_{n+1} - TOF_{n}] \quad (4)
\]

TOF difference between a pair of notches at T₀ (or) a sensor TOF

\[
δTOF_{n+1} = [TOF_{n+1} - TOF_{n}] \quad (4a)
\]

where,

TOFᵢ, TOFᵣ → Instantaneous (i) TOF at various temperatures (Tᵢ) and TOF at room temperature from each notch
(δTOFₙ₊₁)ᵢ → Instantaneous change in TOF from each sensor (between pair of notches)

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

A Chromel helical waveguide system as shown earlier in Fig. 1(b) with 4 notches was used. Each sensing region was kept at 20 or 40 mm spacing by adjusting the pitch of the helix. In this initial case study, the entire helical waveguide system was positioned in the
uniform temperature region inside the furnace. For each sensor δTOF was measured from a helical waveguide using Equation (4) as in Fig. 3(b) at various temperatures, and the corresponding temperature was monitored using co-located thermocouples. The calibration plots were obtained (as shown in Fig. 3(b)) for each sensor [11]. Finally, the Chromel helical waveguide system was moved for temperature measurement at the temperature gradient region (multilevel; 40, 80, 120, 160 mm) of furnace. Next, a 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 calibration equations in Fig. 3(b). The temperatures were also obtained using co-located K-type thermocouples and plotted along with the ultrasonic measurements. Fig. 3(c) shows a plot of different time instances (only a few time instances are provided in this plot) and the temperatures at 4 levels (40, 80, 120, and 160mm) are obtained by adjusting the free length of coil. It can be observed fine correlation between the ultrasonic waveguide measurements and the thermocouple outputs.

Figure. 3(a). A- scan signal for the helical waveguide sensors and the dimensions are marked, (b) The δTOF vs. Temperature calibration plots obtained from multiple sensor of helical waveguide; (c) Ultrasonic (U) and Thermocouple (T) measurements from different depths using 160 mm free length at different time instances during a heating cycle inside a furnace.

3.4. Copper Helical Waveguide Design using 5 notches

The L(0,1) mode velocity of Copper is relatively less when compared to the L(0,1) velocity of Chromel. Hence, the L(0, 1) mode wavelength of Copper is less than the Chromel and the mean coil diameter D=28 mm is even more suitable (due to reduced dispersion effects). A-scan signal was obtained for Copper helical waveguide at room temperature and reflections from the 5 notch sensors is shown in Fig. 4. Dimensions of
waveguide are marked in A-scan plot. The A-scan clearly shows that even common materials such as Copper can be utilized for developing helical waveguide sensors.

**Figure.** A-scan signal from Multiple notches of Copper Helical waveguide

Summary

A novel helical waveguide based ultrasonic temperature measurement technique is reported here. The L(0,1) mode can be reliably generated and received by using a conventional longitudinal transducer for different material of helical waveguide. Using a 3D FEM simulation study, it was determined that the mean helix diameter of helical waveguide must be greater than wavelength in order to avoid dispersion effects due to the helix curvature. The technique relates the δTOF parameter to local temperatures. This technique was demonstrated to measure the temperatures at multiple levels inside a furnace. Grating spacing can be easily varied using the helical waveguide. This allowed for the demonstration of the temperature monitoring at multi-level inside a hot chamber in the laboratory and verified with thermocouples. The ultrasonic distributed temperature sensor provides a more robust and cost effective solution for measurement of temperature gradients, when compared to junction based thermocouples.

**References**


