Distributed temperature sensors development using an stepped-helical ultrasonic waveguide

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Distributed Temperature Sensors Development Using an Stepped-Helical Ultrasonic Waveguide

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Abstract. This paper presents the design and development of the distributed ultrasonic waveguide temperature sensors using some stepped-helical structures. Distributed sensing has several applications in various industries (oil, glass, steel) for measurement of physical parameters such as level, temperature, viscosity, etc. This waveguide incorporates a special notch or bend for obtaining ultrasonic wave reflections from the desired locations (Gage-lengths) where local measurements are desired. In this paper, a multi-location measurement wave-guide, with a measurement capability of 18 locations in a single wire, has been fabricated. The distribution of these sensors is both in the axial as well as radial directions using a stepped-helical spring configuration. Also, different high temperature materials have been chosen for the wave-guide. Both lower order axi-symmetric guided ultrasonic modes (L(0,1) and T(0,1)) were employed. These wave modes were generated/received (pulse-echo approach) using conventional longitudinal and shear transducers, respectively. Also, both the wave modes were simultaneously generated/received and compared using shear transducer for developing the distributed helical wave-guide sensors. The effect of dispersion of the wave modes due to curvature effects will also be discussed. **Keywords:** Ultrasonic transducer, stepped spring, distributed sensing, high temperature.

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). Thermocouples, radiation pyrometers and resistive temperature devices (RTD) are common temperature sensors used in various industries for different applications. Pyrometers require a line-of-sight that is not feasible in enclosed industrial high-temperature processes. RTD and Thermocouples suffer due to sensor drift during long-term operation, as reported elsewhere, for example, by Bentley[1] and Tooley[2]. The thermocouple can measure the temperature only in one location. A single thermocouple could not be used to measure the temperature in the multiple target locations. 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. For example, many authors have reported[3-11] the benefits of ultrasonic waveguides to measure the physical properties of a surrounding medium such as viscous fluids, mold powder slags, molten glass, vitrification melter temperature, solid surface temperature and fluid level measurements. Here, the liquid level measurement was very critical while using the straight waveguide concept. The elastic moduli of different materials was measured[12-15] at an elevated temperature using the ultrasonic waveguide concept when the waveguide material was surrounded by an air medium.

Different ultrasonic waveguide configurations have been reported by Periyannan and Balasubramaniam[16-23] for distributed temperature sensing. An ultrasonic system was developed for measuring the air temperature based on the phase shift records.[24] In our approach, the ultrasonic reflected signal and the time of flight differences are used for measurement of local temperatures. Multiple notches were machined along the length of the waveguide, each notch acting as a reflector that can be used to measure the local temperature. The configuration of the waveguide can be used straight[9] or can be made into shapes such as helical,[17-19] spiral,[21-22] or bend[14-15, 23] for designing the distributed ultrasonic sensor and tested in a high temperature laboratory furnace. In this paper, our aim to develop a conical waveguide (using Chromel (d)=1.2 mm) with notch-type sensors for measuring the temperature inside the furnace. Also, a stepped-helical waveguide (Copper (d) =1mm) is developed to measure the level of fluids.

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ULTRASONIC WAVEGUIDE SENSORS

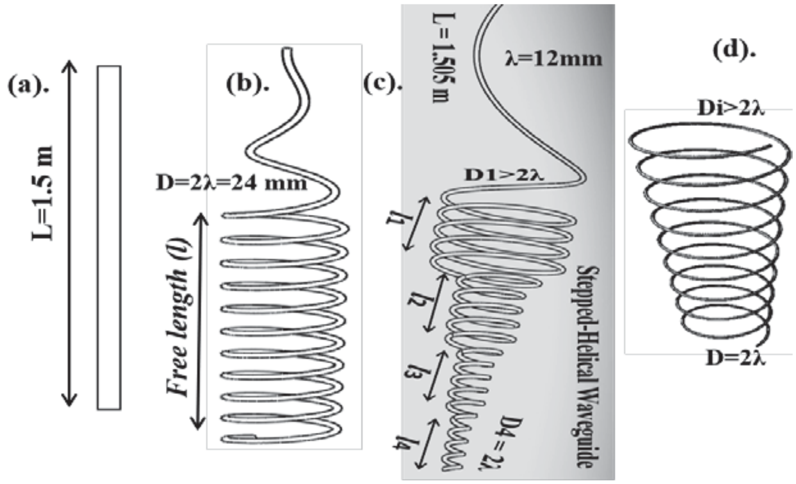

FIGURE 1. Illustration of temperature measurement concept in (a) straight, (b) helical (c) stepped-helical and (d) conical like spring waveguides, respectively.

The waveguide sensors measure the temperature based on the change in time of flight of a sensor region due to change in the material properties of the waveguide. To localize the measurement, embodiments such as notches and bends, among many others, can be introduced into the waveguide, which allows the signals to be reflected from these embodiments. Periodically spaced notches in the waveguide are used to reflect signals from these locations. The earlier reported measurement technique[17-19, 21-13] (relative time of flight (TOF) between two notches) can be used to obtain the temperature between the two notches. In Fig. 1(a), the straight waveguide is illustrated in three different waveguide configurations such as helical, stepped-helical, and conical as shown in Fig. 1(b-d). A straight waveguide sensor system was reported[9] for measuring the vitrification melter temperature. The guided wave behaviour was studied in different curvature structures of helical and spiral ultrasonic waveguide configurations[17-21, 25-26] for designing the distributed temperature measurement sensor. Here, the stepped and conical waveguides are designed based on this approach for measuring the distributed temperature measurements in a high-temperature furnace.

The liquid level measurement was reported[8] based on the strength (Amplitude) of the reflected signal from the waveguide (due to the wave leakage or impedance mismatch between the waveguide and its surrounding medium) when the sensing region of the straight waveguide was immersed in fluids. The guided wave leakage from the stepped-helical waveguide (Fig. 1c) sensor region-l_1 is more than the other sensor regions (l_2, l_3, l_4). Similarly, more leakage is seen in the l_2 region as compared to sensor regions (l_3, l_4). Finally, leakage in l_3 region > l_4, due to added length of wires ($L_1>L_2>L_3>L_4$) or surface area is accommodated in the consequent sensors l_1, l_2, l_3 and l_4, respectively. This wave leakage effect may be increased gradually in each turn of the conical waveguide due to gradual variation in mean diameters along the free length as shown in Fig. 1(d). Hence, the sensitivity of the level measurement is more in particular waveguide configurations (helical, conical, etc.) due to high spatial resolution as compared to straight waveguide. Therefore, the fluid level can be measured efficiently using particular waveguide configurations (stepped-helical, conical, etc.) as compared to straight waveguide sensor. These types of waveguides can be re-configured easily in 2D and 3D distributed temperature, level measurements or based on the applications.

ULTRASONIC WAVES IN STEPPED-HELICAL AND CONICAL WAVEGUIDES

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) [27]. The ultrasonic guided wave propagation in a structure is dependent on the frequency, phase velocity, group velocity and attenuation. The material properties, density (ρ), Young's modulus (E) and the Poisson ratio (μ) of Chromel and Copper were experimentally obtained at room temperature using previously reported approaches[14-17, 21-23, 28] for dispersion analysis. The frequency range was chosen (150 - 450 kHz) 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, and must be considered while designing the stepped-helical and conical waveguide sensors.

In this paper, the fundamental longitudinal and torsional modes of the wire waveguide constituting the stepped - helical and conical embodiments shall be considered. In this work, an operational frequency range (150 - 500 kHz) was chosen for experiments. Here, to ensure low dispersion, an appropriate thickness of the wire and suitable mean diameters (Dm >2λ) of stepped-helical and conical configurations due to curvature effect were considered for selection of waveguide dimensions using our earlier approaches[17-18, 21-23]. Studies of waves in helical waveguides are reported in literature[25-26] with applications in civil structures. The elastic wave dispersion effects were modelled for cylindrical and helix geometries using a finite element approach in a non-orthonormal coordinate system. It has been shown in previous work that by increasing the helix radius, the helix effect on wave propagation and the dispersion caused by curvature can be significantly reduced.

PRINCIPLE OF EXPERIMENT AND MEASUREMENT

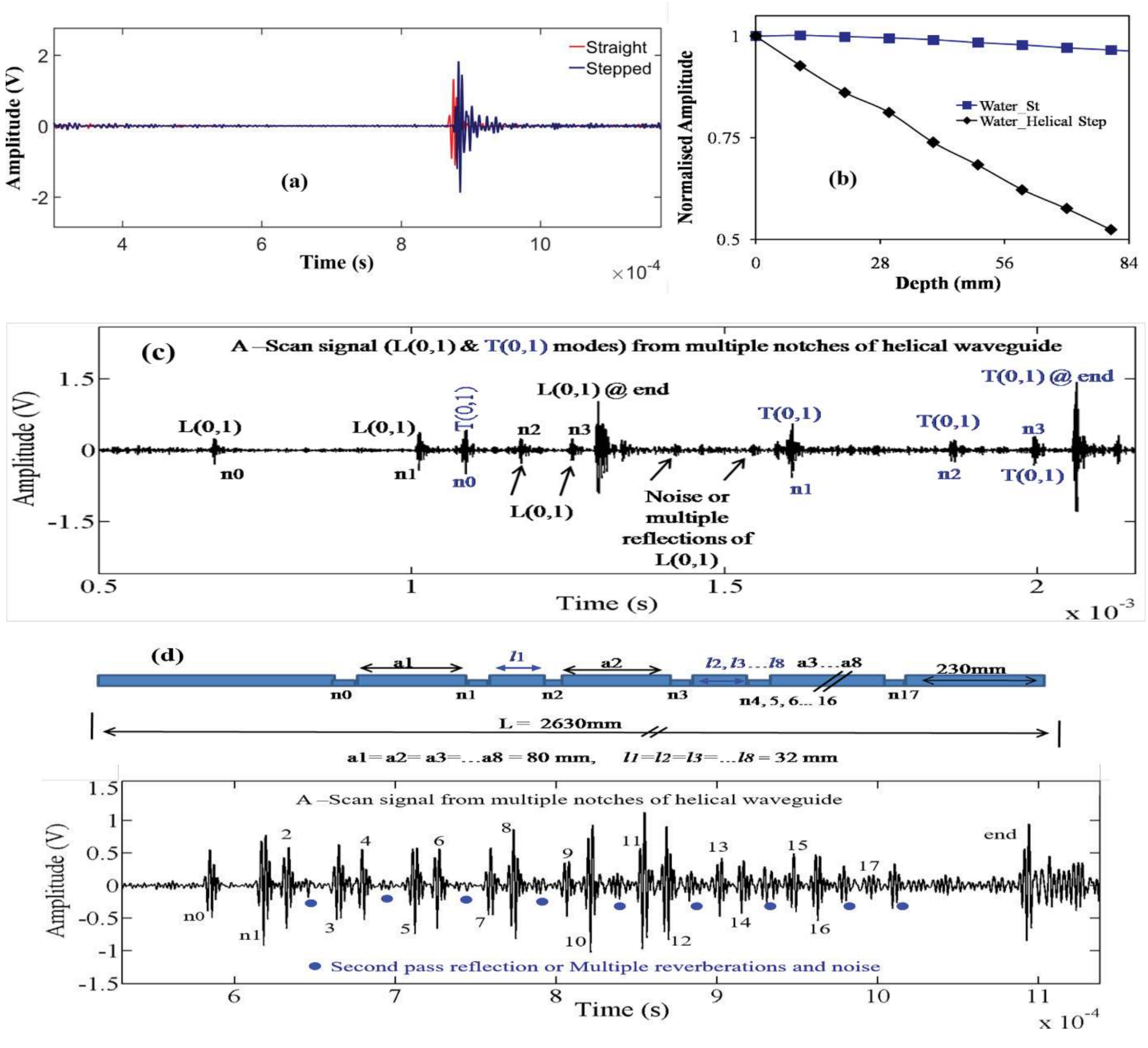

FIGURE 2. Shown are the A-scan signals obtained from the different configuration of waveguides: (a) Straight and stepped-helical waveguides (Copper) using ‘L’ wave mode at 0º orientation; (b) Water level measured using straight and stepped-helical waveguide; (c) L and T wave modes obtained from 0.6 mm (approximately) thickness of Copper waveguide at 45º orientation, and (d) Multiple reflections obtained from 18 sensors of Alumal (d=1.2mm) waveguide.

Both a stepped-helical and a conical waveguide configuration were designed based on the helical[17] and spiral[21] waveguide concepts, respectively. A-scan signals were obtained experimentally corresponding with these waveguide configurations and compared to the straight reference waveguide to ensure waveguide structures were in non-dispersive guided wave behaviour as shown in Fig. 2(a). Minor time of flight variations (3 to 4 µs) were observed between the straight and curved waveguide configurations. An 80-mm depth of water level was measured based on the strength of the reflected signal from the straight waveguide concept. Here, the amplitude variations were measured at each 10 mm of straight waveguide while immersed in the water. Then, using the same water level measured using the stepped-helical waveguide (amplitude variations were measured at each helix turn) it was observed that the sensitivity of the stepped waveguide is more than the straight configuration as shown in Fig. 2(b). Longitudinal and Torsional wave modes were generated/received[15] simultaneously in a helical waveguide, which was made from the thin (approximately r = 0.3 mm) Copper wire. Four notch reflectors were machined along the length of a waveguide sensor at different offset distances. The L and T wave mode reflections were acquired from each notch of the helical waveguide; the corresponding A-scan is shown in Fig. 2(c). Similarly, 18 notches were machined along the length of an Alumal helical waveguide for designing distributed waveguide sensors; the corresponding A-signal is shown in Fig. 2(d).

Figure 3(a) shows the conical waveguide used in the experiment to measure temperature in a high-temperature test furnace. A similar experimental setup, procedure, apparatus and transducer holder setup has been described in earlier literature[14-23]. Multiple invisible notches were machined along the length of the Chromel conical waveguide. Each sensor was positioned at different offset lengths to avoid the overlapping of reflected signals from each sensor as shown in Fig. 3(b).

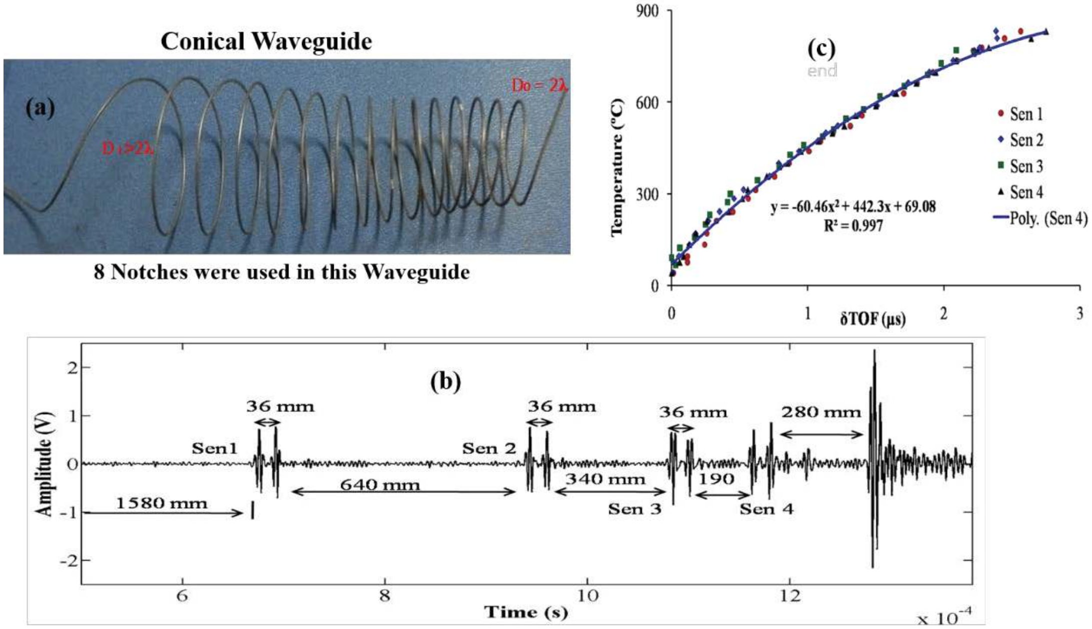

FIGURE 3. (a) Photograph of conical waveguide system, (b) Reflected signals are received from the four pair of notches, (c) δTOF vs. temperature for the calibration curve of conical waveguide sensor.

The longitudinal transducer was acoustically coupled to one end of the waveguide for transmitting/receiving the L(0,1) mode. An 8-bit, 100 MHz sampling rate analogue to digital converter (NI USB-5133) was used to acquire and archive the A-scan signals from the ultrasonic pulser-receiver (Panametrics 5077 p/r) to a Personal Computer. Multiple reflected signals from pairs of notches were continuously monitored using the signal peak-tracking technique method that has been explained elsewhere[14-23]. Subsequently, the δTOF between each pair of notches (one sensor) was measured using Equation (1). The δTOF's of multiple sensors were recorded at different temperatures inside the furnace. Instantaneous time of flight difference (δTOF) of a waveguide is defined below.

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

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.

$$U(T) = -60.46(\delta TOF)^2 + 442.3(\delta TOF) + 69.08 \qquad (2)$$

RESULTS AND DISCUSSION

The conical waveguide was kept in the uniform hot region of the high-temperature furnace. Temperature was uniformly increased inside the furnace for about 3 hours to calibrate the waveguide sensor. A K-type thermocouple was co-located near the conical waveguide, and the corresponding temperature was measured. The calibration equation was obtained based on the time of flight difference (δTOF) at locations in between the pair of notches (one sensor) using the peak-tracking method. The δTOF of each sensor was measured at instantaneous temperature using Equation (1). Conical waveguide sensor number 4 was initially calibrated using with thermocouple output as shown in Fig. 3(c). Equation (2) was found from the calibration plot using the 2nd order polynomial expression. Calibration of sensor number 4 was found to be adequate for the other sensors on the same waveguide. Each sensor δTOF measurements can be related to the local temperature measurement using Equation (2).

CONCLUSION

An ultrasonic conical waveguide temperature sensor provides a more robust, small footprint and cost-effective solution for measurement of temperatures when compared to junction-based thermocouples. This technique uses pairs of notches in a waveguide; each pair of notches is considered as one sensor. The L(0,1) mode was generated and received in the conical waveguide using a shear or longitudinal transducer. A conical-spring 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 obtained for each sensor can be an appropriate empirical equation for local temperature measurement based on the sensor δTOF changes. It is possible to increase the number of sensors in a proper waveguide material. Although preliminary work was conducted for liquid level measurement trials using straight and stepped-helical waveguides, more work is needed to develop the ultrasonic waveguide level sensor.

REFERENCES

1. R.B. Bentley, *Sensors and Actuators–A–Physical*, **24**:1, 21-26, (1990).
2. F. Tooley, Handbook of Glass Manufacturing, 2nd Ed., (1983).
3. L. C. Lynnworth, Ultrasonic Measurements for Process Control: Theory, Techniques, Applications, Academic Press Inc., New York, (1989).
4. K. Balasubramaniam, V.V. Shah, D. Costley, G. Bourdeaux and J.P. Singh, *Review of Scientific Instruments*, **70**:12, 1, (1999).
5. V.S.K. Prasad, K. Balasubramaniam, E. Kannan, K.L. Geisinger, *J. Mat. Processing Tech*. **207**, 315-320, (2008).
6. J.C. Pandey, M. Raj, S. N. Lenka, S. Periyannan, K. Balasubramaniam, *J. Iron Making and Steel Making*, **38**, 74-79, (2011).
7. W. K. Spratt, J. F. Vetelino, and L. C. Lynnworth, *Ultrasonics Symposium (IUS)*, IEEE, pp.702-706, (2010).
8. N. N. Subhash, and K. Balasubramaniam, *Insight*, **56**:11, 607-612, (2014).
9. S. Periyannan and K. Balasubramaniam, *Measurement*, **61**, 185, (2015).
10. V.V. Shah, K. Balasubramaniam, *Ultrasonics*, **38**, 921, (2000).
11. R. Nishanth, K. Lingadurai, S. Periyannan and K. Balasubramaniam, *Insight*, **59**:7, (2017).
12. S. Periyannan, K. Balasubramaniam, *AIP Conference Proceedings*, **1581**:1, 256, (2014).
13. K. Balasubramaniam, S. Periyannan, US patent no. 2016/0153938A1, (2016).
14. S. Periyannan, K. Balasubramaniam, *Experimental Mechanics*, DOI 10.1007/s11340-016-0157-y, **1**, (2016)
15. S. Periyannan, K. Balasubramaniam, *Review of Scientific Instruments*, **86**, 114903, (2015).
16. K. Balasubramaniam and Suresh Periyannan, WO2016162880 A1, (2016).
17. S. Periyannan, P. Rajagopal and K. Balasubramaniam, *J. App. Phy*. **119**, 144502, (2016).
18. S. Periyannan, P. Rajagopal and K. Balasubramaniam, *AIP Advances*, **6**, 065116, (2016).
19. S. Periyannan, P. Rajagopal and K. Balasubramaniam, *Physics Procedia*, **70**, 514, (2015).
20. S. Periyannan, P. Rajagopal and K. Balasubramaniam, "Ultrasonic Waveguide Techniques for Distributed Temperature Sensing," *19th World Conference on Non-Destructive Testing*, pp.1-8, (2016).
21. S. Periyannan, P. Rajagopal and K. Balasubramaniam, *AIP Advances,* **7**, 035201, (2017).
22. S. Periyannan and K. Balasubramaniam, Review of Progress in Quantitative Nondestructive Evaluation, 36, *AIP Conference Proceedings,* **1806**, 030016, 1-6, (2017).
23. S. Periyannan, P. Rajagopal and K. Balasubramaniam, *Ultrasonics*, **74**, 211-220, (2017).
24. W.Y. Tsai, H.C. Chen, T.L. Liao, *Sensors and Actuators–A–Physical*, **132**:2, 526-532, (2006).

25. F. Treyssede, *Wave Motion*, **45**, 457, (2008).
26. F. Treyssede, L. Laguerre, *Journal of Sound and Vibration*, **329**, 1702, (2010).
27. J.L. Rose, Ultrasonic Waves in Solid Media, Cambridge University Press, United Kingdom, pp.143-152, (1999).
28. B. N. Pavlakovic, M. J. S. Lowe, P. Cawley and D. N. Alleyne, *AIP Proceedings*, **16**, 185, (1997).