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Torsional mode ultrasonic helical waveguide sensor for re-configurable temperature measurement

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This paper introduces an ultrasonic torsional mode based technique, configured in the form of a helical "spring-like" waveguide, for multi-level temperature measurement. The multiple sensing levels can be repositioned by stretching or collapsing the spring to provide simultaneous measurements at different desired spacing in a given area/volume. The transduction is performed using piezo-electric crystals that generate and receive T(0,1) mode in a pulse echo mode. The gage lengths and positions of measurements are based on machining multiple reflector notches in the waveguide at required positions. The time of fight (TOF) measurements between the reflected signals from the notches provide local temperatures that compare well with co-located thermocouples. [http://dx.doi.org/10.1063/1.4954641]

I. INTRODUCTION

Ultrasonic temperature sensors have the potential for providing robust measurements for many applications including determination of local temperature and temperature profiles of industrial processes in glass and metal melting plants, process industries, nuclear power plants, etc., where temperature control is critical. Ultrasonic methods are well reported in the literature for measurement of temperature, viscosity, level, etc.[1–9]

Thermocouple and radiation pyrometers that are commonly used in the industry, have many issues. The pyrometers require a line-of-sight that is often not feasible in several enclosed industrial high temperature processes. The thermocouples[10] and RTDs (Resistance Temperature Detector) often suffer due to sensor drift during long term operation. 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 in 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. Hence, alternate multi-level sensing technologies that are more robust and that having smaller footprint is desirable. Ultrasonic waveguide technique has the potential to address some of these limitations.

Several waveguide-based ultrasonic sensing of temperature, viscosity, corrosion, etc., have been recently reported in the literature. Huang et al.[11] and Tsai et al.[12] proposed an ultrasonic system for air temperature measurement using changes in the speed of sound calculated from phase shift records; a similar concept was used to measure temperature by Zhan et al.[13] Using a bent waveguide that is surrounded by a fluid, with known properties (such as air), the elastic moduli of the waveguide was obtained at different temperatures by Periyannan and Balasubramaniam.[14–16] Cawley and Cegla[17] have developed an ultrasonic instrument using a thin elongated strip to separate the transducer from a potentially hostile environment associated with the object under test, for thickness measurements. Other efforts include, liquid level and temperature monitoring using single

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torsional acoustic waveguide (TAW) approach[18] as well as monitoring of the liquid level in wine bottles.[19]

Most of the previous approaches described measurements in a single zone of interest. In order to measure at multiple points of interest using a single waveguide, Visvanathan and Balasubramaniam[20] had described the monitoring of a moving air-to-fluid interface signal during a resin filling process inside an opaque model and obtained the dynamics of the resin flow front.

The use of ultrasonic waveguides for measuring elevated temperatures and temperature profiles have been reported earlier by the authors.[1,21,22] The ultrasonic waveguide-based temperature sensing approaches have several advantages over the conventional thermocouples; the advantages include the inherent property of higher reliability, as there is no junction that can fail, as well as the ability to program several zones of measurements in one waveguide. Additionally, the configuration is a helical "spring like" waveguide that allows for the flexibility of making measurements at locations that are very close to each other (by reducing the helix angle i.e. the pitch) or in a relatively sparse spacing (by increasing the helix angle).

In this paper, we explore the feasibility of using multiple "notch" embodiments as reflectors that are positioned along the length of the waveguide and their ability in making multiple measurements using a single ultrasonic probe that is generating a torsional guided wave mode. In this work, the temperature measurement at multi-levels in a furnace using such a reconfigurable waveguide that supports a torsional wave T(0,1) is discussed and compared with thermocouple measurements. The T(0,1) results are compared with the results from using the L(0,1) mode that has been reported elsewhere.[21]

II. BACKGROUND

A. Waveguide Temperature Sensors

Waveguide temperature sensors measure changes in time of flight of an ultrasonic wave mode caused due to the changes in the material properties of the waveguide (l. α, E, G and ρ) as a function of temperature.[1] Here, l is the gage length, 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, bends and gratings can be introduced in the waveguide that allow signals to be reflected from these embodiments. The gage length of measurement would be the free length in between any two embodiments. The measurement of the relative time of flight (TOF) between these reflections can be monitored and used to obtain the temperature of the waveguide within the waveguide. For a reliable TOF measurement, the reflected signals must be time resolved and identified, for which spacing between the embodiments must be optimized. For a straight waveguide, the gage length is pre-determined and often will be of the order of 30-40 mm. Also, the measurement shall be an averaged TOF over this gage length. Periodically spaced notches are introduced in the waveguides that provide reflected signals from these locations. The difference in TOF between any two subsequent reflections of the T(0,1) wave modes was used to determine the average temperature of the waveguide material, and consequently the temperature of the surrounding medium, in the region in between the notches. In Figure 1(a) and 1(b), the helical waveguide is illustrated in two possible helix angle configurations (achieved by changing the pitch between sensors) i.e. two different gage lengths. The compressed position in Figure 1(a) allows for temperature measurements that are relatively closely spaced compared to the expanded helix waveguide shown in Figure 1(b). By altering the helix angle, the waveguide may be reconfigured to measure at points with preferred spacing, while the number of points of measurement will remain the same. Figure 1(c) shows the dispersion curve for both the L(0,1) and T(0,1) modes in the range of frequencies of interest.

The design of the helical waveguide can be modified by (a) increasing the number of active coils, (b) adjusting the mean coil diameter, (c) varying notch depth and notch type, and (d) altering the helix angle and thereby changing the relative spacing between the embodiments (that is, pitch between the sensors). In the present study, notch type of embodiments (0.5 mm deep and 3 mm long along the axis of the waveguide) were machined along the length of the 1.18 mm diameter waveguide to provide reflected signals from each embodiment. Hence, the sensing region and the

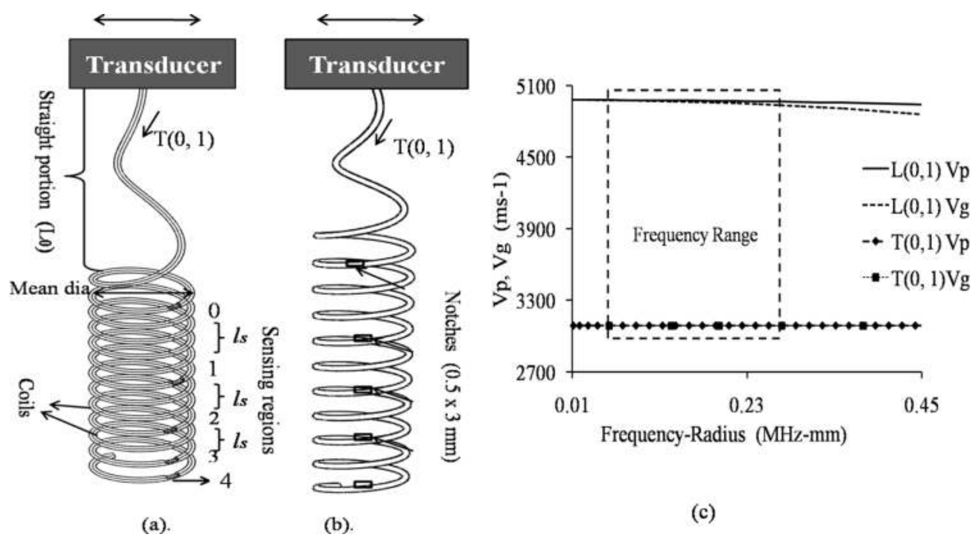

FIG. 1. Illustration of temperature gradient measurement concept in (a, b) Helical waveguides at two different helix angles, and (c) Dispersion curves phase velocity V_p and group velocity V_g of straight Chromel wire.

spacing between the measurements may be adjusted in the radial as well as the axial directions (1D, 2D or 3D) based on requirements and through appropriate waveguide design.

B. Ultrasonic waves in "spring-like" helical wire waveguide

In a cylindrical waveguide, there are three families of modes namely, longitudinal (L), torsional (T) and flexural (F) that propagate in the axial direction (z) of cylindrical coordinate system (r, θ and z).[23] The phase velocity and group velocity dispersion curves for the two fundamental axi-symmetric modes L(0,1) and T(0,1) obtained using DISPERSE,[24] for a typical high temperature material waveguide (Chromel) are shown in Figure 1(c). It must be noted here that dispersion effects can be observed due to (a) geometry of the waveguide, (b) frequency of operation, and (c) due to the curvature effects of the helix. In this paper, we shall concentrate on the fundamental torsional mode, T(0,1). This mode is non-dispersive (due to the effects (a) and (b)) over the entire range of frequencies for the range of high temperature materials of interest here, as listed in Table I. In comparison, the L(0,1) mode is non-dispersive (due to the effects (a) and (b)) only in the low frequency regime. Absence of dispersion of the wave will ensure that the pulse width of the signals remains relatively unchanged, thus improving the reliability of TOF measurements. In order to reduce the dispersion effects due the curvature of the helix, the mean coil diameter (D) of a spring waveguide was selected to be greater than wavelength (approximate helix diameter 3.2λ) as discussed in Ref. 21.

Hence, in order to keep dispersion to a minimum, an operational frequency range of 200 - 500 kHz. and a waveguide made of Chromel with 1.18 mm with a mean helix diameter D of 28 mm was chosen for all experiments in this paper.

III. HELICAL WAVEGUIDE DESIGN

The material properties and helical waveguide parameters are listed in Table I. The Elastic Moduli of the waveguide material were obtained using two measurements of velocities of L(0,1)

TABLE I. Material properties and helical waveguide parameters.

Material	Mass Density-ρ (Kg m^{-3})	Young's Modulus-E (GPa)	Poisson Ratio-μ	Wire dia (d) (mm)	Free Length-*l* (mm)	Mean dia (D) mm
Chromel	8650	214	0.3	1.18	80, 160	28

wave mode and T(0,1) wave mode as explained elsewhere;[14] density of the material was measured using the mass and volume measurements.

In this experiment, the Chromel waveguide in a straight configuration, was employed and the velocities obtained experimentally were V_g for L(0, 1) = 4980 m/s and V_g for T(0, 1) = 3080 m/s at room temperature.

The studies on waves in helical waveguides have been previously reported on acoustic waves,[25] electromagnetic waves[26] and elastic waves[27,28] with applications in civil structures. For avoiding dispersion effects due to curvature, the recommended helix diameter[21] is such that the ratio ***a*** of the helix diameter (D) to the torsional mode wavelength (λ_T) must be maintained above 2 as defined below:

$$\text{Mean diameter of the helical waveguide (D)} = a\lambda_T; (a>2) \tag{1}$$

Here, in the experiments described below, this ratio ***a*** was 3.3 and hence the effect of dispersion of the Torsional mode T(0,1) was expected to be minimal.

IV. RESULTS AND DISCUSSION

A. Experimental Apparatus Description

Figures 2(a)-2(d) describe the apparatus used in the experimental work for temperature measurements at multi-levels in a high temperature test furnace. A similar experimental setup, procedure, apparatus and transducer holder was described earlier in the literature.[1,29,30]

In this paper, the use of torsional wave in helical waveguides was studied and its improved sensitivity due to the slower velocity and non-dispersive nature of the T(0,1) mode was demonstrated.

Multiple notches were machined along the free length (l = 80, 160 mm) of the Chromel helical waveguides as shown in Figures 2(a), 2(b). Figure 2(c) describes the orientation of the waveguide (at the point of generation/reception of the wave) with respect to particle vibration on the face of the ultrasonic transducer.[29]

Here, the two key parameters are the mean helix diameter D and coil pitch P as described earlier.[21] The axial spacing between the notches can be adjusted by varying the pitch (P). In this system (Fig. 2(a), 2(b)) multiple notches were separated along the length of the helical spring in order to avoid overlapping of signals from each notch, as shown in Figures 2(e), 2(f). It was also observed that the T(0,1) mode velocity of helical waveguide was invariant to the helix angle (free length changes by stretching of waveguide), as shown in Figure 2(e), 2(f). The reflected signals as received from the 4 notches and the end of the helical waveguide is illustrated here.

The ultrasonic pulse-echo mode was used and the piezoelectric crystal based broadband ultrasound shear wave transducer (Panametrics V151) was acoustically coupled to one end of the waveguide as shown in Figure 2(c), 2(d) using a very thin layer of viscous Silicone based ultrasonic couplant. The face of the transducer is perpendicular to the axis of the waveguide during generation and reception. An 8 bit, 100 MHz sampling rate analog to digital converter (National Instruments USB 5133) was used to acquire and archive the A-scan signals from the ultrasonic pulser-receiver (OLYMPUS Panametrics PR5077) in a Personal Computer (PC). Multiple reflected signals from multiple notches were continuously monitored using the signal peak-tracking method that has been described elsewhere.[1,21,29,30] The peak tracking approach ensured that the specific peaks in different signals of interest were continuously tracked during the heating cycle, in order to ensure reliability of TOF measurements. Subsequently the δTOF between each pair of notches (one sensor) were measured using Equation (2). The TOFs and the δTOFs of multiple notches (gage lengths) in the waveguide were recorded at different temperatures in the furnace. The temperature was measured using calibrated reference thermocouple (K-type thermocouples TC), that were co-located in between each notch position, during this initial calibration procedure. The surface temperatures of the transducers were verified using a pyrometer during each experiment and were found to be the same as the ambient temperature proving that the heat was not conducted to the transducer along

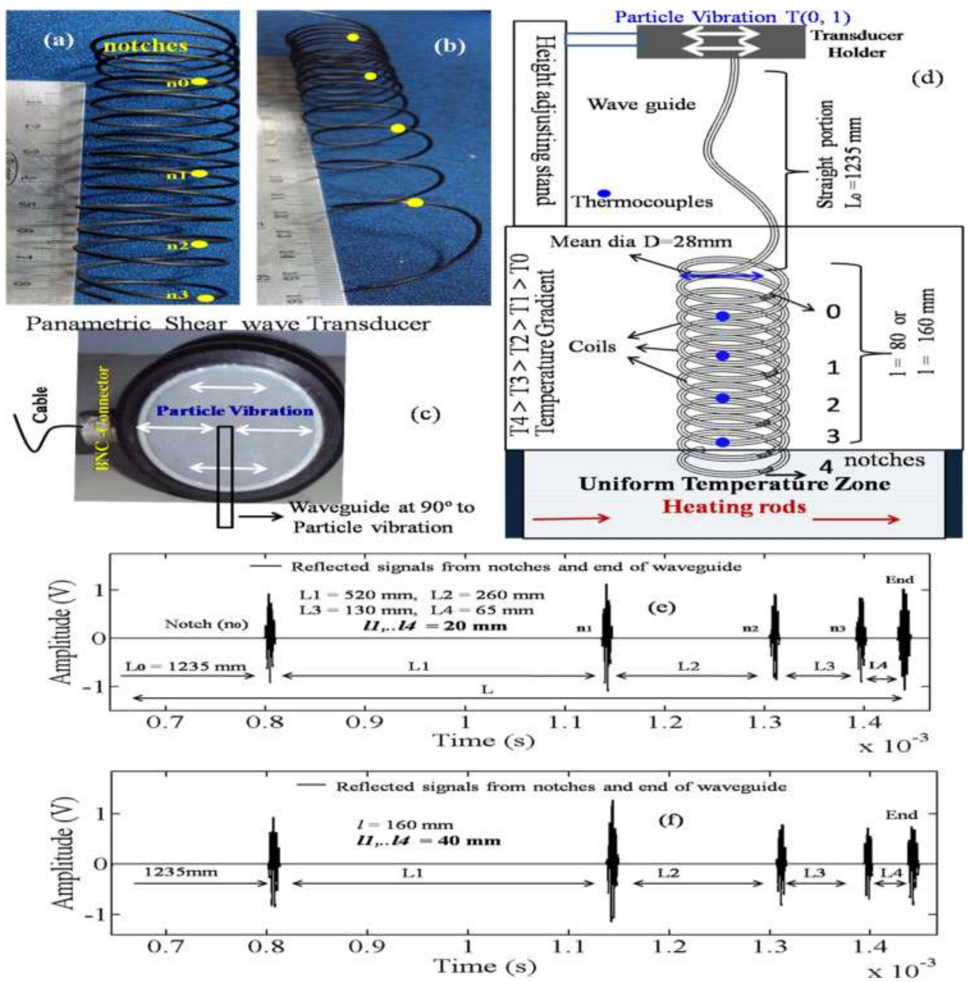

FIG. 2. (a, b) Photograph of Chromel helical waveguide with notches at free lengths 80, 160 mm, (c) Waveguide orientation at 90° to particle displacement orientation, (d) Schematic diagram of helical waveguide with multiple notches (sensors) in a furnace, (e, f) A-scan signals of a helical waveguide at different free lengths l = 80, 160 mm respectively, showing dispersion invariance to helix angle.

the waveguide to the transducer. This is due to the large surface area (more length) and small cross section (small dia) of the thin wire waveguide.

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

$$(\delta TOF_{n+1})_i = [TOF_{(n+1)i} - TOF_{ni}] - [TOF_{n+1} - TOF_n] \tag{2}$$

where, TOF_{ni}, is the instantaneous time of flight of the reflected signal from the notch location "n" at a measured temperature "i" and TOF_n at room temperature,

$$\frac{(\delta TOF_{n+1})_i}{TOF_{n+1} - TOF_n} = \varepsilon_u = \frac{\text{Change in TOF of an each sensor at } T_i}{\text{TOF of an each sensor at } T_o} \tag{3}$$

where ε_u = Instantaneous ultrasonic TOF ratio.

B. Case Study 1, Multiple Sensors Calibration and Measurement in a Uniform Temperature Region

Three case studies using the helical waveguide system shall be used for calibration of waveguide, followed by demonstration of multi-level temperature measurements. A special adjustment fixture apparatus was used to control the pitch of the waveguide. In case study 1, a free length

l = 80 mm of Chromel (1.18 mm diameter) helical waveguide with 4 sensor embodiments was used (made of 4 notches); each sensing region was kept at 20 mm spacing by adjusting (using adjuster) the pitch between notches as shown in Figure 2(a). In this case, the entire helical waveguide system was positioned in the uniform temperature region inside the furnace.

For each sensor, δTOF was measured using Equation (2), from a helical waveguide as in Figure 2(a) at uniform hot zone, the corresponding temperature was monitored using co-located thermocouples. The δTOF vs temperature curves from each sensor followed a different slope as shown in Figure 3(a). In this paper, our scope was to achieve a single calibration curve for measuring temperature at all the temperature zones. When all the TOF ratios (ε_u) from all the notches were plotted as a function of temperature, it is observed that a single calibration curve was obtained as shown in Figure 3(b). This calibration curve relates the measured ε_u using Equation (3) for any sensor to the surrounding temperature. If the temperature (T) is in Celsius and ε_u is dimensionless, the 2[nd] order polynomial expression for this curve was found to be:

$$\mathbf{T = -17477(\varepsilon_u)^2 + 7970(\varepsilon_u) + 25.53} \tag{4}$$

Using the expression in Equation (4), the temperatures were computed at each sensor location using ε_u. The temperatures thus obtained were compared with the thermocouple measurements and plotted in the same graph for a typical 3 hr heating cycle of the furnace as shown in Figure 3(c). As expected, the two methods were found to compare well, with a maximum average error of 3°C-7°C. The result in Figure 3(b) shows that the polynomial fit calibration curve in Equation (4) is acceptable to be used for the waveguide-based measurement of temperature.

This helical sensor waveguide system was then used to measure temperature at different time instances in zones in the furnace with temperature gradients as discussed further in case studies 2 and 3.

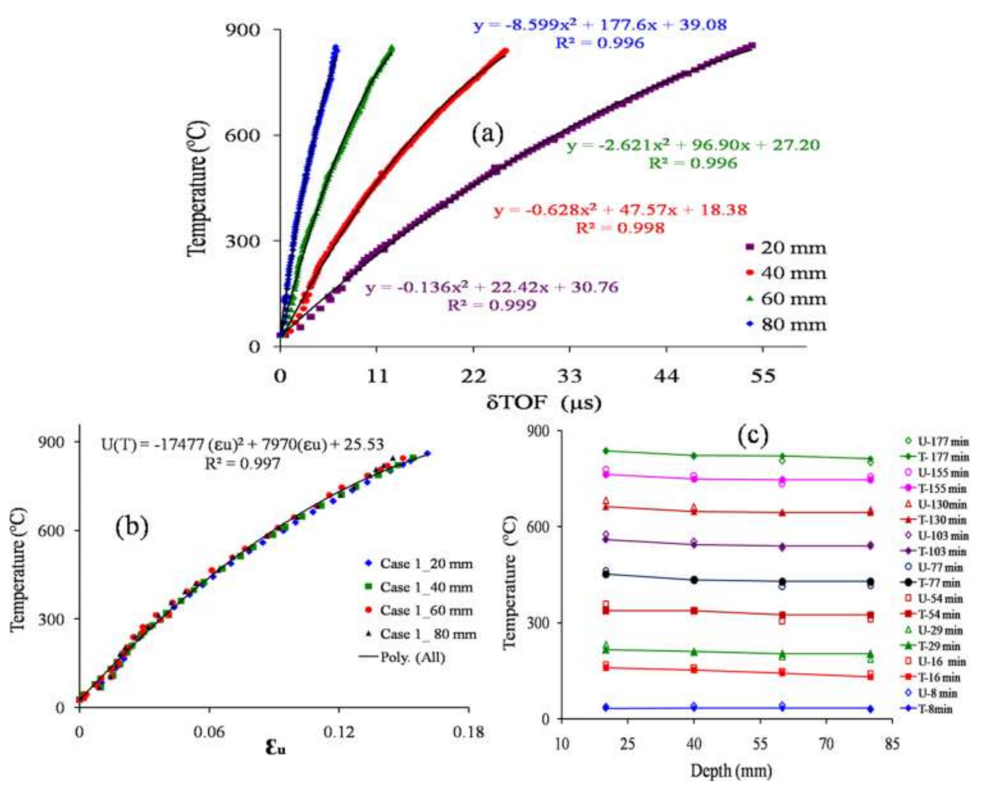

FIG. 3. The δTOFs of each notch sensor at various temperatures, (b) ε_u vs Temperature for all notches representing the calibration curve, (c) Comparison of temperature measurement using ultrasonic waveguide method (hollow) with Thermocouple (solid).

C. Case Study 2 and 3, Multi-level Temperature Measurement in Non-uniform Temperature Region

In case studies 2 and 3, the Chromel helical waveguides were positioned in the insulated region of the furnace as shown in Figure 4(a) where the temperature varied from the uniform temperature zone to the external wall of the furnace. K-type thermocouples were co-located in between each notch position. Two length configurations of the helix waveguide were demonstrated with D = 28 mm, but with different pitch and consequently different free length (l) of the helix.

In case study 2, a free length l = 80 mm (Fig. 2(a)) with 4 notches at 20 mm spacing (along the free length positioned at 20, 40, 60, 80 mm from the bottom of the insulation) was used; and in case study 3, a free length l = 160 mm (Fig. 2(b)) with 40 mm notch spacing (at 40, 80, 120, 160 mm from the bottom of the insulation) was used. In both the case studies, the same waveguide was used and the free length was adjusted to the required length by adjusting the pitch between notches, that is, gage lengths. The bottom most gage length was positioned close to the bottom of the insulation, in the uniform temperature region. Figure 4(a) illustrates the positions and approximate notch configurations of these two case studies.

Steady state of heating experiments were conducted for both the case studies and the δTOF data (using Eqn. (2)) were collected from all sensor locations (notches) at a time interval of 60s. The ε_u values as well as the temperature at the co-located thermocouples, from the 4 sensor locations were measured at different temperatures inside the furnace.

In Figure 4(b), the ε_u vs temperature measured using the thermocouples are plotted for all the 3 case studies, that is, including the earlier case where the entire waveguide was inside the uniform gradient region. This plot shows that the calibration curve obtained earlier is applicable to the temperature gradient cases also and that Equation (4) obtained earlier may be used for this data set. In Figures 4(c) and 4(d), the temperatures measured using the ultrasonic waveguide (U) is compared with the thermocouple reading (T) for the 4 locations at different time instances of

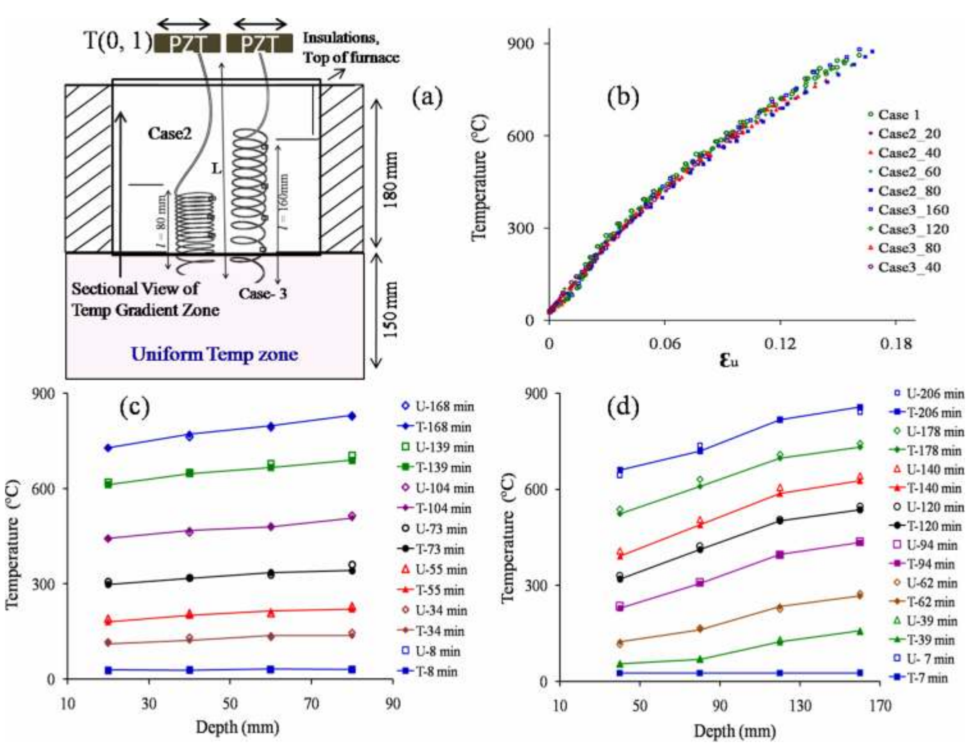

FIG. 4. (a) Multiple sensors of a helical waveguide at insulated region of the furnace, (b) Multiple sensors waveguide calibration from 160 mm depth of temperature gradients, (c) Ultrasonic and Thermocouple measurements from different depths at different time instances using 80 mm free length (case study 2) of helical waveguide, (d) using 160 mm free length (case study 3).

TABLE II. Comparison between L(0, 1) and T(0, 1) ultrasonic wave modes for a Chromel waveguide sensor.

Ultrasonic Wave mode	Group Velocity (m/s)	Wavelength (λ) at 400 kHz	Minimum-D (mm) recommended[21]	Temperature Resolution in °C at 100 MHz digitization *for different length* (L_n) *in (mm)*			
				520mm	*260mm*	*130mm*	*65mm*
L(0, 1)	4980	12.45	25.0	0.27	0.56	1.13	2.24
T(0, 1)	3080	7.7	15.5	0.16	0.33	0.68	1.4

measurements. It may be observed from these results that the ultrasonic waveguide technique can be used for measuring the temperature in a region with varying temperature and that the relative difference between the two readings is relatively small.

The maximum difference between the ultrasonic waveguide reading and the thermocouple reading was 6 °C in the range of measured temperatures from 30 °C to 900 °C; and the average error was less than 1.5 °C with a standard deviation of 0.5 °C. These two case studies also demonstrated the re-configurable nature of the helix waveguide.

V. COMPARISON BETWEEN L(0,1) AND T(0,1) HELICAL WAVEGUIDE SENSORS

The key differences between the L(0,1) and the T(0,1) wave modes based helical waveguide sensors are

a. the mode of excitation i.e. the relative orientation of the excitation vibration with the axis of the waveguide, and
b. the relative shorter wavelength of the T(0,1), thus permitting a smaller helix diameter D, and improved resolution of the TOF measurements and consequently an improvement in the measurement of the temperature of the surrounding fluid.

The T(0,1) wave mode also allows for either a wider range of frequencies of operation or for large diameters of the waveguide because of the non-dispersive behaviour of the wave mode. The key differences between the two modes are listed in Table II.

However, the choice of the wave mode will depend on the application. The torsional mode will be preferred in cases where the surrounding media is inviscid due to the advantages listed above. However, for cases where the surrounding media exhibits viscous or elastic or visco-elastic behaviour, the L(0,1) mode will leak less to the surrounding material and hence may be the preferred choice.

VI. SUMMARY

A torsional ultrasonic wave based reconfigurable temperature sensor mechanism and sensing principle is described here which provides a robust and cost effective solution for measurement of temperature and temperature gradients over a wide range of temperatures compared to junction based thermocouples. This torsional wave technique uses multiple notches that defines the gage lengths for the sensors that can be re-positioned by varying the free length (consequently the pitch) of the helical waveguide. This ultrasonic waveguide sensor employs the guided T(0,1) mode that can be reliably generated and received by using a conventional shear wave transducer. The sensing gage lengths can be easily varied by adjusting the pitch of the helix. It was demonstrated that temperatures could be measured reliably at multiple levels in temperature gradient regions inside a furnace, using a single waveguide.

Different high temperature materials such as Kanthal, Stainless Steel and Platinum may also be used for designing the waveguides. Since the torsional mode velocities are different for different materials, the gage length and the helix diameter must be optimized for each material. Also, the calibration curves for these materials must also be obtained using the technique described in this paper. Here, only 4 notches were used. It must be feasible to increase the number of sensors, but may depend on the material and its ability to sustain the guided ultrasonic waves.

Advantages of the Torsional wave mode used here over the Longitudinal modes in helical waveguides as reported earlier.[21,22] are that (a) slower velocity ensures that the spacing between the embodiments can be smaller, (b) the helix diameter (D) of smaller value can be used and hence the sensor footprint decreases, (c) The sensors can also be employed for measurement of changes in the surrounding media, for example, for the measurement of rheology of the surrounding fluid. The disadvantage of the T mode when compared to the L mode is that the wave will have higher attenuation when surrounded by fluids with viscosity greater than zero and hence may limit the length of measurements in such environments.

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[1] S. Periyannan and K. Balasubramaniam, Measurement. **61**, 185 (2015).
[2] V.V. Shah and K. Balasubramaniam, Ultrasonics. **34**(8), 817 (1996).
[3] K. Balasubramaniam, V.V. Shah, G. Boudreaux, R.D. Costley, C. Menezes, and J.P. Singh, Review of Progress in Quantitative Non-destructive Evaluation. **18**(B), 1163 (1999), DOI: 10.1007/978-1-4615-4791-4_149.
[4] K. Balasubramaniam, V.V. Shah, D. Costley, G. Bourdeaux, and J.P. Singh, Review of Scientific Instruments. **70**(12), 1 (1999).
[5] K. Balasubramaniam, V.V. Shah, D. Costley, G. Bourdeaux, and J.P. Singh, U.S. patent 6,296,385 (2 Oct 2001).
[6] V.V. Shah and K. Balasubramaniam, Ultrasonics. **38**, 921 (2000).
[7] V.S.K. Prasad, K. Balasubramaniam, E. Kannan, and K.L. Geisinger, Journal of Materials Processing Technology. **207**, 315 (2008).
[8] R.D. Costley, K. Balasubramaniam, W.M. Ingham, J.A. Simpson, and V. Shah, Review of Progress in Quantitative Nondestructive Evaluation. **17**, 859 (1998), DOI: 10.1007/978-1-4615-5339-7_111.
[9] J.C. Pandey, M. Raj, S. N. Lenka, S. Periyannan, and K. Balasubramaniam, Journal of Iron Making and Steel Making. **38**, 74 (2011).
[10] R.B. Bentley, Sensors and Actuators- A: Phy. **24**, 21 (1990).
[11] K.N. Huang, C.F. Huang, Y.C. Li, and M.S. Young, IEEE 294 (2003) DOI: 10-1109/APBME.2003.1302700.
[12] W.Y. Tsai, H.C. Chen, and T.L. Liao, Sensors and Actuators A: Phy. **132**, 526 (2006).
[13] T.S. Zhan, S.L. Wu, and W.Y. Tsai, Journal of Scientific & Industrial Research. **68**, 44 (2009).
[14] S Periyannan and K. Balasubramaniam, "Temperature dependent E and G measurement of materials using ultrasonic guided waves," AIP Conference Proceedings. **1581**(1), 256 (2014).
[15] S. Periyannan and K. Balasubramaniam, "Temperature gradients and material properties measurements using Ultrasonic guided waves," in *European Conference on Non-Destructive Testing*, *Prague, Czech Republic*, *October 6-10* (2014).
[16] K. Balasubramaniam and S. Periyannan, "A Novel Waveguide Technique for the Simultaneous Measurement of Temperatures Dependent Properties of Materials," Patent number (World Intellectual Property Organization) WO 2015/008299A2 (2015).
[17] P. Cawley and F.B. Cegla, U.S. patent 8,381,592 (26 Feb 2013).
[18] W.K. Spratt and J.F. Vetelino, IEEE 850 (2009), DOI: 10.1109/FREQ.2009.5168307.
[19] E. Vargas, R. Ceres, J, M. Martin, and L. Calderon, Sensors and Actuators A: Phy **61**, 256 (1997).
[20] K. Visvanathan and K. Balasubramaniam, Review of Scientific Instruments. **78**, 1 (2007).
[21] S. Periyannan, P. Rajagopal, and K. Balasubramaniam, J. App. Phy **119**, 144502 (2016).
[22] S. Periyannan, K. Balasubramaniam, and P. Rajagopal, Physics Procedia. **70**, 514 (2015).
[23] J.L. Rose, *Ultrasonic Waves in solid Media* (Cambridge University Press, Cambridge, UK, 1999), pp. 143-152.
[24] B.N. Pavlakovic, M.J.S. Lowe, P. Cawley, and D.N. Alleyne, DISPERSE, In Review of Progress in Quantitative Nondestructive Evaluation. **16**, 185 (1997), DOI: 10.1007/978-1-4615-5947-4_24.
[25] W. Sollfrey, Journal of Applied Physics **22**, 905 (1951).
[26] S. Ahn and A.K. Ganguly, IEEE Trans. on Electron Devices **ED-33**(9), 1348 (1986).
[27] F. Treyssede, Wave Motion. **45**, 457 (2008).
[28] F. Treyssede and L. Laguerre, Journal of Sound and Vibration. **329**, 1702 (2010).
[29] S. Periyannan and K. Balasubramaniam, Review of Scientific Instruments. **86**, 114903 (2015).
[30] S. Periyannan and K. Balasubramaniam, Experimental Mechanics 1 (2016), DOI 10.1007/s11340-016-0157-y.