Elastic Moduli Measurements at Elevated Temperatures using Ultrasonic Waveguide Embodiments

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Abstract. A measurement method is described here using a waveguide based technique with special modifications to the end of the waveguide in order to obtain reliable reflected ultrasonic signals from the end of the waveguide that is inside a heating chamber. The interpretation of the reflected signals leading to a quantitative measurement of moduli of the waveguide material i.e. Young’s (E) and shear (G) at different temperatures. The technique uses guided ultrasonic wave modes, that are generated using an ultrasonic transducer at one end of the wave guide, travelling along the length of the waveguide, interacts with the end of the waveguides, and is reflected back to the transducer. The end of the waveguides has a bend or a step that provides a reference reflected signal. The reflected signal are detected and recorded at different steady state temperatures. The time of flight difference (δTOF), as a function of temperature, between the guided wave reflections from the embodiment and the end of the waveguide, is used to measure the moduli. Here, the L (0, 1) wave mode is used for measuring E and T(0,1) mode for G. The comparison between the literature and the measured values were found to be in agreement.

Keywords: Ultrasonic transducer, waveguide sensor, E and G measurement, high temperature

Introduction

The change in Young’s modulus (E), shear modulus (G) and density (ρ) of materials are inversely proportional to an increase in temperature of an elastic solid. Change in dimensions and coefficient of thermal expansion(CTE) of material is directly proportional to the temperature. The thermal strain and CTE in a material is related to the instantaneous time of flight of a guided wave in a waveguide at various temperatures. Hence, this can be utilized to measure the elastic properties of the material.

Ultrasonic waveguide based measurement methods have been extensively used for developing sensors for level, density, temperature, and rheology measurement of the surrounding fluid [1-13]. 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.

In this paper, the two elastic moduli is measured using the material in the form of round bar (rod) waveguides with two different type of embodiments. The first one is the waveguide with bend and second one is the waveguide with a stepped configuration. Two ultrasonic guided wave modes, i.e. longitudinal L(0,1) and torsional T(0,1), are generated using a longitudinal wave and shear wave transducer respectively. A silicone gel layer was used to couple the wave from the crystal to the waveguide. The longitudinal transducer face was oriented perpendicular to the waveguide to generate the L(0,1) mode. For the shear wave generation/reception, a shear wave probe was oriented parallel to the waveguide. The L(0,1) or T(0,1) wave modes, thus generated propagates along the axis and perpendicular of the waveguide. Reflections from the bend/step as well as from the end of the rod are both captured and the time of flight between the signals are recorded and used to measure the local temperature of the surrounding fluid. The local temperatures of a fluid around the waveguide, as well as the variation of the temperature along the bend portion of the waveguide, influences the time of flight (TOF) for the round trip travel of the L(0,1) and T(0,1) wave modes. The time of flight difference (δTOF defined as the change in time of flight at measurement temperature compared to time of flight at room temperature) is due to both, the change in length of the waveguide due to coefficient of thermal expansion, as well as a change in the L(0,1) or T(0,1) wave velocity of material as a function of temperature.

The change in the TOF due to a change in temperature, henceforth called δTOF, can be used to measures the material properties E and G of the wave guide. The E and G have been measured in the laboratory furnace over the range of 45 °C to 1100 °C. The reflected signals from bends and steps of an each waveguide were continuously monitored using that signal peak-tracking technique method that has been described elsewhere [8-15]. The same peak tracking technique was used to continuously measure the time of flight difference (δTOF) at different temperatures from uniform temperature regions (bend/step) of interest of each waveguide, for entire heating and cooling cycle. Here, an operational frequency range of 200 - 500 kHz was chosen. The E_i(T) measurements (approach [9, 14]) of bend and step embodiments were compared to each other at wide range of temperatures. In the last case, Kanthal material E_i(T) and G_i(T) were measured simultaneously using the approach described earlier [15].

**Guided Waves in Rods**

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 [16]. Ultrasonic Waves in solid Media. 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, \( \theta \) and z). While, many wave modes can be excited in rods, our analysis is presented here concentrates on the fundamental longitudinal and torsional modes are L(0, 1) & T(0, 1) respectively. The mode has smaller levels of dispersion over a wide range of frequencies and can be easily generated in the rods made of high temperature materials.
The group velocity dispersion curves (obtained by DISPERSE [17]) for rods of different diameters made of high temperature materials are shown in Fig.1. The material properties and dimensions of the high temperature waveguides that are explored in this paper are provided by [18, 19] or measurements 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, in order to keep the pulse width of the signals relatively narrow to improve the time of flight measurements. Hence, in order to maintain regions of low dispersion, appropriate diameters of the rods can be chosen. 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 different waveguides 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, reported by Periyannan and Balasubramaniam, [14, 20].

**TABLE 1.** Material properties and dimensions of waveguide materials where l is length of the straight portion of the waveguide and \( l_b \) is the length of the bend portion, \( l_s \) is the length of the step turned portions and d is the diameter.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass Density (( \rho )) Kg m(^{-3} )</th>
<th>Young’s Modulus GPa</th>
<th>Poisson’s Ratio (( \mu ))</th>
<th>Dimensions mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kanthal</td>
<td>7250</td>
<td>216</td>
<td>0.30</td>
<td>( l=740, l_b=36, d=1.58 )</td>
</tr>
<tr>
<td>Inconel 690</td>
<td>8190</td>
<td>211</td>
<td>0.29</td>
<td>( l=545, l_b=129, d=2.38 )</td>
</tr>
<tr>
<td>Inconel 690</td>
<td>8190</td>
<td>211</td>
<td>0.29</td>
<td>( l=854, l_s1=31, l_s2=25, d=3.1 )</td>
</tr>
</tbody>
</table>

Figure 1. Dispersion curves for group velocities of L(0, 1) and T(0, 1) modes for different materials as per Table 1.

**The Bend Waveguide Design**

The Fig.2a is explained the actual schematic view of the experimental set up in this research work. Fig.2b, shows the L- bend waveguide (Inconel-690) dimensions as well as the A-scan signal is collected from the room temperature. In these arrangements the transducer is connected along the axis of the waveguide then longitudinal velocity of the waveguide is measured subsequently validated with the group velocity (Fig.1) of the same material.
Principle of Experiment and Measurement

The ultrasonic pulse-echo mode was used and the piezoelectric crystal based broad band ultrasound transducer was acoustically coupled to the waveguides as shown in the Fig.2a, b. The ultrasonic pulses were transmitted and reflected are received from the waveguide, by a conventional longitudinal wave transducer. Here, we have assumed that the bend/step is in a uniform temperature region of interest while the straight portion of the wave guide is in a temperature gradient region. The temperature of the bent (horizontal) portion and step turned region of wave guides respectively were measured using a co-located K-type thermocouple. The Fig.2(c) shows a typical Longitudinal A-Scan signal from the bend waveguide at room temperature. The A-scan describes two reflected signals, 1\textsuperscript{st} signal is from the bend and 2\textsuperscript{nd} signal is at the end of the waveguide. 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 initial experiments were carried out for different waveguide materials described in Table 1, in order to examine the material properties E and G at various temperatures. Two case studies using different waveguide configurations were used for the demonstration of the $E_i(T)$ measurement. In Case study A, one longitudinal wave transducer was employed, for axial excitation of the waveguide to measures the E for the region of bend. Case study B, the same transducer was employed, for step waveguide to measure the E of waveguide material.
Results and Discussion

The time of flight difference (δTOF)_{L,T} equation has been developed based on the waveguide design in Fig.2b. The (δTOF)_{L,T} Equation 3 and 4, are used to measure the E and G at a given temperature ‘i’ due to a change in L(0,1) & T(0,1) mode TOF at horizontal portion of the waveguide due to temperature various.

\[ \text{TOF}_c = [(\text{TOF}_b - \text{TOF}_a)] \quad (1) \]

\[ (\delta \text{TOF}_{ci}) = [(\text{TOF}_{bi} - \text{TOF}_{ai}) - (\text{TOF}_b - \text{TOF}_a)] \quad (2) \]

Where;

- \( \text{TOF}_{ai,bi} \rightarrow \) Instantaneous TOF at various temperatures from bend (a) and waveguide end (b)
- \( \text{TOF}_{a,b,c} \rightarrow \) Time of flight at room temperatures
- \( (\delta \text{TOF}_{ci}) \rightarrow \) Instantaneous change in TOF at dimension ‘c’

The E and G were calculated from measured (δTOF)_{L,T} & TOF\_c using the eqns. 3 and 4 that are described elsewhere [14]

\[ E_i = \left( \frac{E_0}{1 + 2.5 \times \delta \text{TOF}_{ci} / \text{TOF}_c} \right) \quad (3) \]

\[ G_i = \left( \frac{G_0}{1 + 2.25 \times \delta \text{TOF}_{ci} / \text{TOF}_c} \right) \quad (4) \]

Where;

- \( E_i, G_i \) - Instantaneous E & G of the material at various temperatures
- \( E_0, G_0 \) - E & G of the material is measured by experiments at room temperature,

Case study A: Young’s modulus E measurement using a Bend waveguide of Inconel-690

A L-bend waveguide made of Inconel-690 was evaluated using a longitudinal L(0, 1) mode as shown in Fig.2a. The δTOFs were simultaneously measured at various temperatures using the Equations 1 and 2 respectively. Local temperature was also measured using the co-located K-type thermocouple during the heating and cooling. Fig 3a, shows the (δTOF)\_L of horizontal portion of waveguide at various temperatures. Instantaneous Young's modulus \( E_i \) value was calculated using the eqn. 3, at various temperature and verified with the literature data [18] as shown in Fig 3b.
Case study B: Young’s modulus $E_i$, measured using a step waveguide (Inconel-690)

Fig. 4(a, b) shows a step turned Inconel waveguide and its corresponding A-scan signal at room temperature obtained using the L(0,1) mode. The reflected signals from each step turn were observed in A-scan signal. The experimental procedures and L wave transducer used earlier in the bend waveguide experiments were also used in this experiment. Using each step of the Inconel waveguide $E_i(T)$ was measured at various temperatures as shown in Fig. 4c. The results obtained from the step waveguide was found to compare with $E_i(T)$ values in literature [18] as well as the experimental results obtained using the bend waveguide at various temperature.

Figure 3(a). Shows the $\delta$TOF$_L$ vs. Temperature and Temperature vs. $E_i$ of the Inconel-690 respectively.

Figure 4(a, b). Shows step turned Inconel waveguide dimensions and corresponds to A-scan respectively. (c). Temperature Vs $E_i(T)$ of Inconel material using different waveguide embodiments (bend and step) at various temperatures.
Case C: Simultaneous E and G Measurement for Kanthal using a Bent waveguide

In the last case, a shear wave transducer vibration direction was oriented at 45° inclination to the longitudinal axis of the waveguide such that both L(0,1) and T(0,1) modes could be simultaneously excited and received in a pulse echo mode as described elsewhere [15]. The dimensions of the Kanthal waveguide was followed by Table 1. The A-scan signal of the simultaneous excitation of L(0,1) and T(0,1) modes including the reflected and the mode converted signals from the bend portion and the end of the waveguide is shown in Fig.5a. The earlier procedures and Equations 1-4 were used for simultaneous $E_i(T)$ and $G_i(T)$ measurement of Kanthal material and validated with literature [19] as shown in Fig. 5b. The literature values for $G_i(T)$ were obtained using data reported in reference [19] and using the analytic equation [14].

**Summary**

A novel measurement method was described for the measurement of $E$ and $G$ as a function of temperature using ultrasonic waveguides. The time of flight differences ($\delta$TOF) $L,T_{LT}$ of the L(0,1), T(0,1) modes were used to calculate the $E_i(T)$ and $G_i(T)$ of the waveguide materials. Two high-temperature materials, i.e. Inconel 690 and Kanthal were evaluated and both moduli, as a function of temperature over a range of temperature (30-1100 °C), were measured and subsequently validated with data reported in the literature. The proposed measurement method will significantly reduce the cost and effort of measuring the temperature dependent moduli of materials.

**Reference**


