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Acoustic waveguides: An attractive alternative for accurate and robust contact thermometry

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ABSTRACT

We report a robust and very precise method of measuring temperature using ultrasonic waves. Solid stainless steel waveguides are used to provide well-defined and stable ultrasonic wave propagation paths. Ultrasonic wave velocity is strongly temperature dependent. The arrival times of the ultrasonic wavepackets along a waveguide are used to infer the average temperature of the waveguide. Our ultrasonic temperature measurements exhibit a high precision (i.e. ±0.015 °C) that is more than two times better than the quoted accuracy of 1/10 DIN resistance temperature detectors (RTDs). The responsiveness of the waveguides was also investigated. While ultrasonic measurements can be made at very high frequencies, the responsiveness is limited by the heat transfer into the active sensing area. The waveguides make it easy to customise the dimension of the active sensing area and a shorter response time than those of RTDs has been demonstrated. The technique presented in this paper is a robust and cost effective alternative to other contact temperature measurements.

1. Introduction

Temperature is one of the most measured physical quantities and the most conventional way of measuring it is through contact thermometry. The net worth of the temperature sensor market is estimated to be $5.13 billion in 2016, and is predicted to increase to $6.79 billion by 2022 [1]. The most common types of contact temperature probes include thermocouples, thermistors and resistance temperature detectors (RTDs). Thermocouples are able to function in wide temperature ranges but are not very accurate. Thermistors and RTDs, on the other hand, are very accurate and sensitive to temperature changes, but have long response times and limited operating temperature ranges. Also, they are relatively expensive (RTDs in particular) [2].

In this paper, we present a method that determines temperatures from measurements of ultrasonic wave velocities. Although this concept has been reported on in the past [3–6], we report an unprecedented precision in our temperature measurements. Carefully designed waveguides enable steady and uncontaminated ultrasonic wave propagation, and give rise to the desired waveforms. Ultrasonic signals are acquired and processed by a finely tuned measurement protocol. After an initial calibration with a 1/10 DIN RTD, temperatures can be determined to a precision of ±0.015 °C, compared to the errors of 0.1–5 °C that were previously reported. Also, the waveguides can be easily customised to control response times.

2. Materials and methods

We used simple, robust 304 stainless steel to make a waveguide for carrying out temperature measurements. It is worth mentioning that the material is not limited to stainless steel and can be anything that is capable of transmitting ultrasonic waves and does not degrade in the measurement environment. The waveguide is a thin, elongated strip, along which shear waves propagate. A detailed study of the wave propagation in the waveguide has been presented by Cegla [7]. This wave propagation setup results in a very high signal to noise ratio (SNR). Fig. 1 shows the waveguide and an ultrasonic signal that was acquired from it. Two notches that are 0.1 mm wide and 0.2 mm deep were manufactured onto the front and the back of the waveguide. The active area needs to be fully immersed in the measurement environment, and it is the spatially averaged ultrasonic velocity in this area that is used to derive temperature. The active area has a low thermal mass which leads to a fast response to temperature changes.

A typical measurement entails sending a 5-cycle Hanning-window sinusoidal toneburst with a centre frequency of 2 MHz into the waveguide using a shear PZT transducer. It has been shown in a previous work that ultrasonic shear waves of 2 MHz are non-

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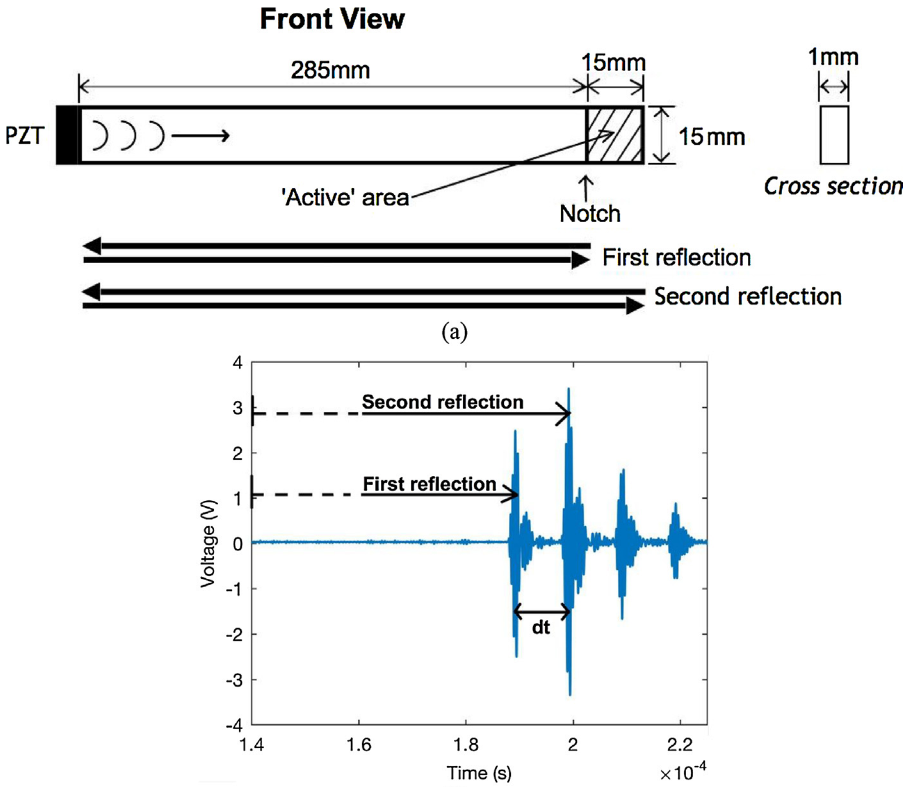

(a)

(b)

Fig. 1. (a) Schematic diagram of the waveguide including the propagation paths of the first and the second reflection. (b) A typical recorded ultrasonic signal showing the first and the second reflection and the difference between their arrival times (dt).

dispersive in waveguides of the configuration that is presented [7]. The wavepacket travels down the waveguide until it is partially reflected by the notch. A fraction of the total energy travels back to the transducer where it is received as the first reflection. The rest of the energy continues down the waveguide until it is then fully reflected by the tip and returns towards the transducer. When this returning wavepacket encounters the notch, some of its energy is reflected again and reverberates within the active area. The rest of its energy travels back to the PZT transducer, resulting in the arrival of the second wavepacket. Any signals detected afterward are the result of the reverberations returning to the transducer. The ultrasonic shear velocity (v) in the active area is calculated by

$$v = \frac{2L}{dt} \tag{1}$$

where L is the length of the wave path in the active area (i.e. 0.015 m).

Fig. 2 shows the experimental setup which was built to test the temperature measurement capability of the waveguide and to compare it to that of a commercial 1/10 DIN PT100 RTD (SE012, Pico Technology, UK). Measurements by the RTD were recorded at 1 Hz by a platinum resistance data logger (PT-104, Pico Technology, UK). Excitation and acquisition of ultrasonic signals were handled by an arbitrary function generator/oscilloscope (Handyscope HS3, TiePie Engineering, Netherlands) at a sampling frequency of 50 MHz. Signals received from the waveguide were amplified by 40 dB by an in-house amplifier before digitisation. A 3D-printed fixture (labelled 'cap' in Fig. 2) was used to hold the waveguide and the RTD whilst they were immersed in the liquid inside a beaker. This also ensured that the two probes were fixed at the same depth in the liquid, and prevented heat loss through the opening of the beaker. A hotplate (PC-620D, Corning Inc., USA) was used to heat and stir the liquid.

The following procedure was adopted to improve the SNR of ultrasonic signals and to determine the arrival times of wavepackets.

- For each measurement, consecutive signals are recorded and averaged.
- The *averaged* signal is filtered by a 5th order Butterworth band-pass filter with cut-off frequencies at 1.6 and 2.4 MHz.
- The *filtered* signal is up-sampled to 800 MHz.
- The *up-sampled* signal is auto-correlated.
- The peaks in the *auto-correlation* correspond to the arrival times of the wavepackets. The exact locations of the peaks are obtained by gradient based linear interpolation.

3. Results

In order to use a waveguide to measure temperature, the relationship between temperature and the ultrasonic shear velocity in the active area had to be determined. This was done by calibrating the waveguide against the previously described RTD. Both the waveguide and the RTD were immersed in water, and measurements were taken at various temperatures below 100 °C during three heating cycles and one cooling cycle. The result of calibration, shown in Fig. 3, indicates that the measurements were stable with respect to time and to the direction of temperature change. The relationship between temperature (T) and ultrasonic shear velocity is observed to be linear and follows the equation

$$T = -1.4v + 4313.9 \tag{2}$$

Note that the coefficients here are for a 0.88 mm thick waveguide.

It was shown in a previous study [8] that for stainless steel 304 operating in a wider temperature range (up to a few 100s °C), the use of a linear fit between temperature and shear velocity does