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Experimental evaluation of ultrasonic oscillating temperature sensors (UOTS) under cyclically changing temperatures

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Abstract— In contrast to most conventional temperature sensors, which need to come to thermal equilibrium with the medium of interest to report its temperature, UOTS interrogate the medium based on the propagation speed of ultrasound, and will return temperature data that are “averaged” for the complete ultrasound pathway. It has been demonstrated that UOTS can provide consistent high-resolution temperature readings under steadily decreasing temperatures using inexpensive ultrasonic transducers and low cost electronic instrumentation.

Keywords— temperature sensor; ultrasonic instrumentation; ultrasonic NDE

I. INTRODUCTION

Temperature sensors are used in automotive, environmental, process industries, consumer electronics, healthcare/medical and some other applications [1]. The estimates for their global market value by 2020 vary from just above \$6 billion [2, 3] to over \$8 billion [4]. By comparison, the global microcontroller market was valued at \$15.8 billion in 2014 [5].

Ultrasonic thermometers address some weaknesses of conventional temperature sensors in several unique ways. These thermometers measure the temperature of the medium of interest instead of the temperature of the sensor itself, featuring negligible response time. They average temperature across the complete ultrasonic pathway instead of sensing at a single point, potentially easing the design of process and climate controllers. They can also provide very high resolution, down to a hundredth of a centigrade [6, 7]. We believe that oscillating ultrasonic temperature sensors (UOTS) are most suitable for measurements of process temperatures in pipes with diameters of around 100 mm [8].

In order to be competitive with conventional temperature sensors at the mass market, ultrasonic sensors need to be of a comparable cost. A non-contact sensor costs \$12 on average, thermocouples cost around \$4 and other contact sensors are even cheaper [4]. An UOTS requires a pair of ultrasonic transducers and driving electronics with supervisory control and output reporting. Realization of the required functionality at low cost can potentially be achieved by using Programmable

System on-Chip (PSoC) microcontrollers with built in analog peripherals, and temperature compensated crystal oscillators [8, 9].

An UOTS can produce smooth and consistent output data when the temperature is changing in one direction only [6]. However, a reliable sensor should work well under changes of the sensed variable in any direction. UOTS have been observed following the measured temperature well but exhibiting some hysteresis when the direction of the temperature change was altered [9, 10, 11].

The aim of the experimental study that is being reported was to find whether the hysteresis is the same for randomly selected transducer pairs and whether it is consistent at different experimental runs.

II. MODULAR ELECTRONIC SYSTEM FOR EXAMINATION OF VARIOUS CONTROL PARAMETERS AND TRANSDUCER PAIRS

Examining UOTS for consistency and control required development of flexible electronic instrumentation which could be controlled programmatically from a host PC. We decided to use electronic modules 5 cm wide that can be connected to each other (Fig. 1).

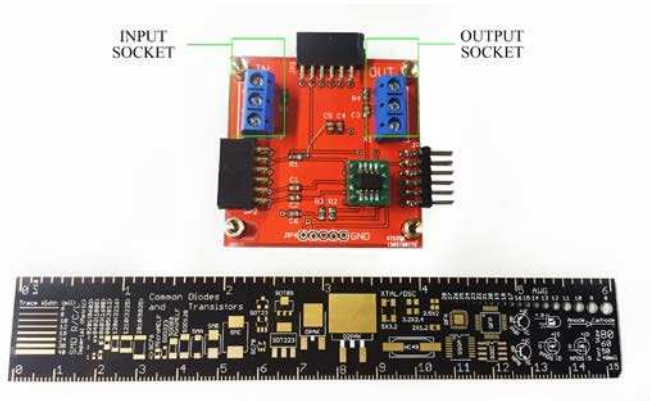


Fig. 1. PSoc-based controllable ultrasonic driver

The electronic driver module shown in Fig.1 contains an amplifier and band pass filter, which are both controllable from the host PC. This module was used to set sufficient gain to sustain the oscillations, and select the desired operating frequency band. Additional modules included two multiplexers

used to connect different pairs of ultrasonic transducers to the driver, and a USB-to-serial converter module that also performed the UOTS output frequency measurement. This module used an oven controlled crystal oscillator as the frequency reference (Fig. 2).

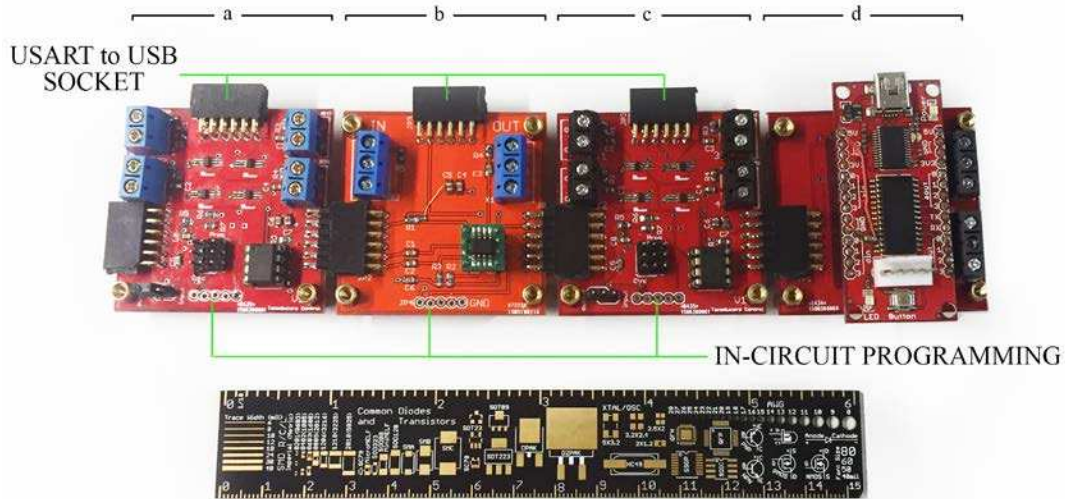


Fig. 2. Assembled PSoC-based Ultrasonic modular system that contains [a] input signal multiplexer [b] ultrasonic driver [c] output signal multiplexer [d] frequency meter with UART to USB converter

III. EXPERIMENTAL PROCEDURE

A translucent plastic tube filled with water was placed inside a thermostatic chamber as shown in Fig. 3. Four pairs of

ultrasonic transducers facing each other were mounted on the tube. The preliminary experiments showed that one pair did not work at all, and a second pair did not oscillate consistently. For these reason only two pairs were used in the experiment.

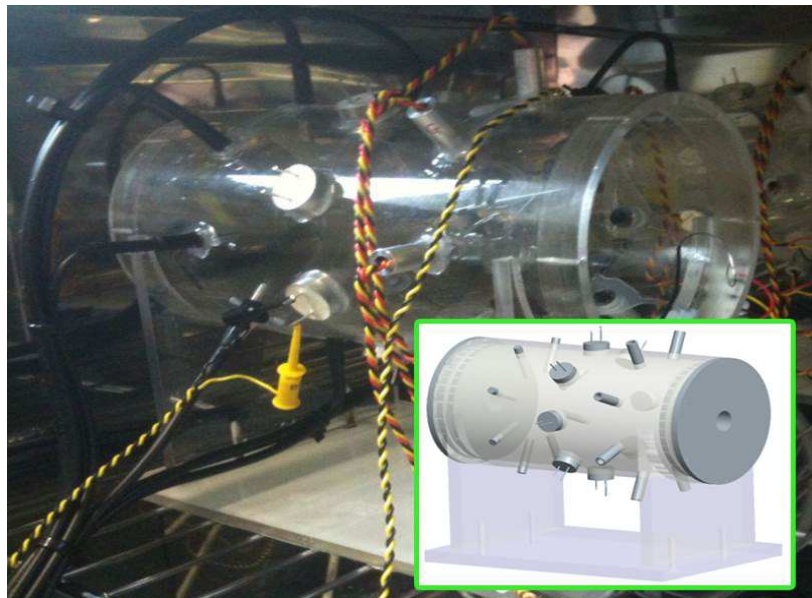


Fig. 3. Experimental setup, plastic tube with four pairs of ultrasonic sensors and eight one-wire temperature sensors mounted on the tube.

The plastic tube also housed eight conventional sensors of type DS18B20, that were calibrated in situ in the thermostatic chamber. Two of the installed sensors exhibited too high standard deviation, and were excluded from further consideration. The average readings from the remaining six sensors were considered to be the true temperature value.

A temperature profile, that was set for the experiment, included two intervals with rising temperatures, each followed by an interval with falling temperature.

The electronic driver was connected to the two selected pairs of ultrasonic transducers in turn every minute, and the output frequency of each UOTS was recoded along with the readings from the conventional temperature sensors.

The parameters of the electronic driver were kept unchanged throughout these experiments.

IV. EXPERIMENTAL RESULTS

The obtained experimental results are presented in Fig. 4. The output frequency for both the UOTS followed the temperature measured by the conventional sensors but the UOTS exhibited different sensitivity. There were some spikes in the output frequency of each sensor that appeared infrequently and sporadically. At one quite continuous interval, for about six hours, both the UOTS produced very close output frequencies (Fig. 5).

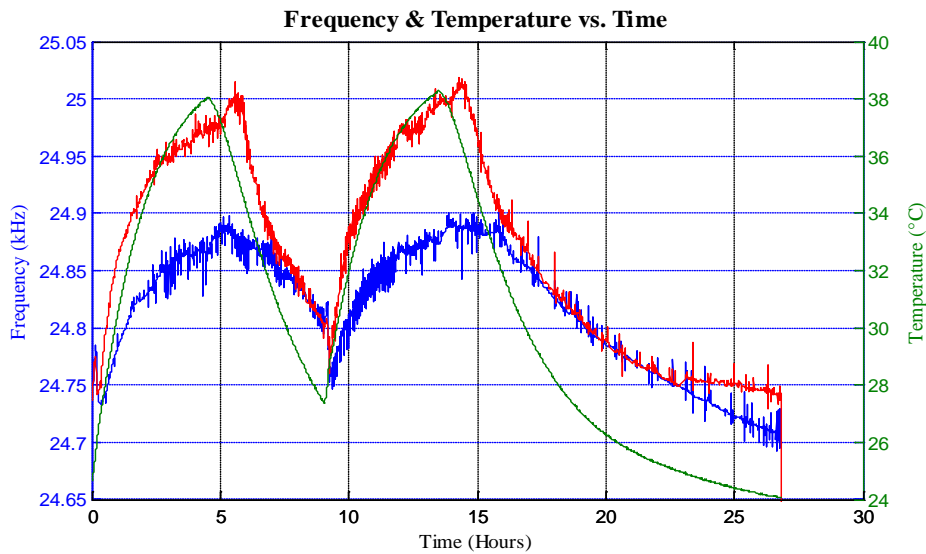


Fig.4. UOTS output frequency and temperature under cyclically changing the temperatures; the green curve represents the averaged temperature of the conventional temperature sensors; red and blue curves represent the output frequency of the first and second ultrasonic transducer pairs respectively

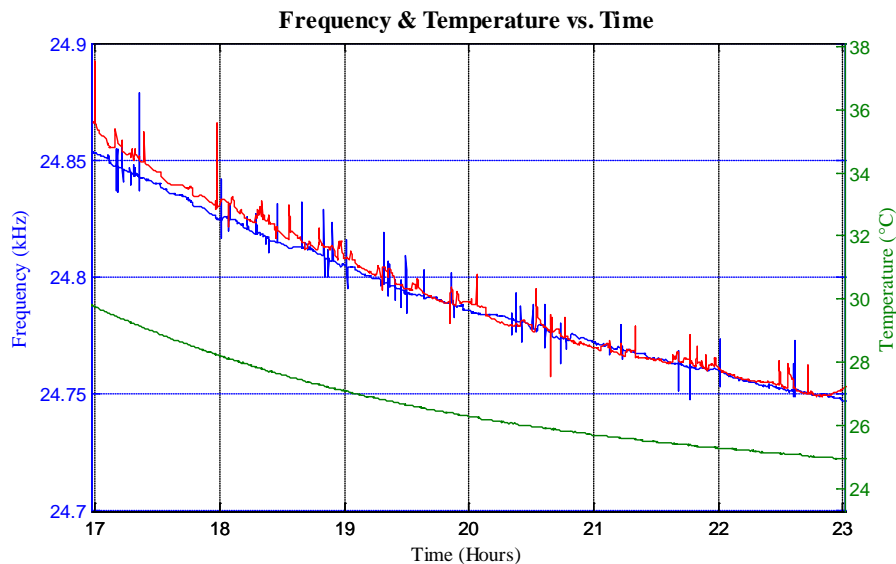


Fig. 5. Zoomed and calibrated area from Fig. 4 for the time interval from 17 to 23 hours of the experiment.

Fig.6 presents the UOTS frequencies versus temperature. An ideal sensor would have a straight line on the

graph; a good sensor would have a one frequency to one temperature relationship.

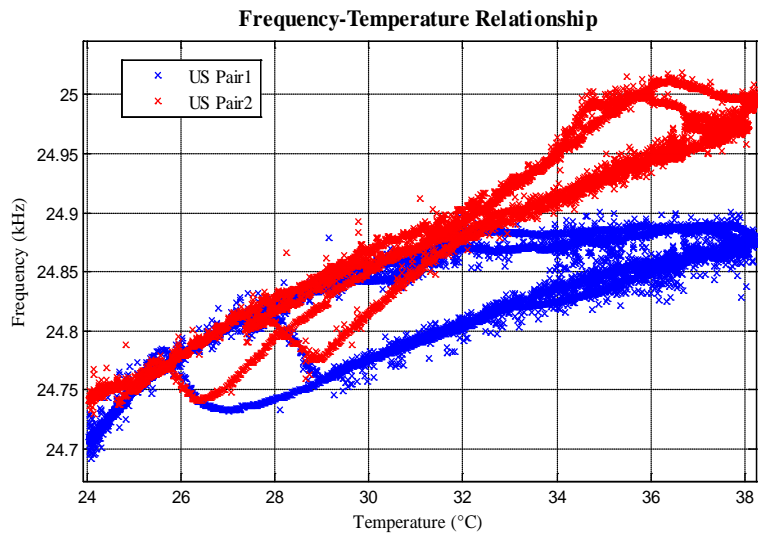


Fig. 6. Ultrasonic frequency versus temperature relationship which clearly shows the existence of hysteresis effect

In contrast, the presented graph features several output frequencies for the same temperature, making temperature measurements ambiguous. We believe that this behavior was caused by the thermal hysteresis common to piezoelectric devices [12, 13].

V. CONCLUSIONS

The reported experimental data showed that, even for the same driving electronics, the output frequencies of the notionally the same transducer pairs placed at the same distance could be quite similar and quite different at the different parts of the of the temperature changing process. We believe that the generation of the same output frequency at different temperatures was caused by the hysteresis common to piezoelectric devices. We plan to tackle the hysteresis by either tuning the parameters of the electronic driver depending on the present output frequency and/or keeping the ultrasonic transducers at a constant temperature and/or employ data fusion of the UOTS output frequency with the data from a conventional temperature sensor.

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