Using Ultrasonic Oscillating Temperature Sensors (UOTSes) to Measure Aggregate temperatures in Liquid and Gaseous Media

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Using Ultrasonic Oscillating Temperature Sensors (UOTSes) to Measure Aggregate temperatures in Liquid and Gaseous Media

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***Abstract*—An ultrasonic oscillating temperature sensor (UOTS) features a pair of ultrasonic transducers and an amplifier, which compensates for the energy losses in the signal pathway. An UOTS oscillates with frequency, which is related to the ultrasound velocity in the medium between the transducers, which, in turn, depends on the medium's temperature. In this paper, we discuss our past experiments with UOTSs in aqueous media and the initial results of a feasibility study on the use of an UOTS in air.**

***Keywords*— ultrasonic temperature sensing, ultrasonic oscillating temperature sensors, UOTS**

I. INTRODUCTION (AFTER [1-4])

Ultrasonic technology is extensively used for non-destructive testing (NDT) and non-destructive evaluation (NDE) of opaque and/or conductive objects and media that are difficult to inspect using electromagnetic waves. Furthermore, the much lower velocity of ultrasound makes it preferable for short-range sensing and inspection of small objects. It can be used to detect discontinuities in an object or medium of interest (such as delamination and voids) and assess parameters related to ultrasound velocity or attenuation at a single frequency or a range of frequencies (ultrasonic spectroscopy).

One of the NDE applications of ultrasound, which was first suggested in 1873, is temperature measurement. Ultrasonic temperature measurements are based on the notable dependence of ultrasound velocity on temperature for most media. Such measurements offer the following advantages:

- The temperature of the medium or object of interest is measured directly. Most conventional temperature measurement methods require the use of sensors that need to be kept at thermal equilibrium with the object. Because of the sensor's thermal inertia and long response time, the measured temperature might lag behind temperature changes in the object. On the contrary, ultrasound can cover a few meters in a few milliseconds, potentially providing instant response to temperature changes.
- Ultrasound velocity is affected by the temperatures across the complete pathway rather than those in close proximity to conventional sensors. It allows measurement of aggregate temperatures using a single sensor instead of a sensor array, thus reducing installation and maintenance costs and simplifying data collection, communication and processing.

A substantial number of industrial ultrasonic thermometers use relatively expensive high-frequency broadband transducers and associated electronics. Despite their high cost, they have been applied for measuring very high temperatures (gases up to 20,000 K, solids up to 2,500 K), and approximately 500 ultrasonic thermometers had been sold by 1975.

The expanding use of ultrasonic thermometers from niche applications to mainstream ones requires a step reduction in the costs involved. This can be accomplished by utilising lower-cost, mass-produced narrowband ultrasonic transducers. Ultrasonic oscillating temperature sensors (UOTSs), introduced in 2010 [1], demonstrate that the cost of the components of an ultrasonic temperature sensor could be in the tens of dollars. Moreover, because of the simplicity of UOTSs' operating principle (self-sustained oscillator), they have advantages over other electronic architectures, which can alternatively be employed with narrowband ultrasonic transducers [2].

This paper presents our experiences in developing UOTSs for liquid and gaseous media. Section II discusses the fundamental operating principles of UOTSs. Section III (IV) is dedicated to the operation of UOTSs in liquids (air). A summary and the conclusions are presented in Section V.

II. OPERATING PRINCIPLES OF UOTSES

A basic UOTS consists of two ultrasonic transducers, which are facing each other, and an amplifier whose gain exceeds the ultrasound conversion and transmission losses across the pathway. Such a provision satisfies the Barkhausen stability criterion [5], the necessary condition for ensuring sustained oscillations. A UOTS operates as an oscillator whose resonant element is formed by the ultrasonic transducers and the medium between them. Ultrasound waves

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continuously propagate between the transducers, and any change in the medium's temperature affects the propagation velocity along the pathway. The changed velocity results in phase shift changes between the emitted and received waves, which in turn forces the oscillation frequency to change in order to compensate for the induced phase shift. Measuring the output frequency of a UOTS allows tracking of the changes in the medium temperature.

The simplest amplifier for a UOTS can be constructed using a single operational amplifier (opamp). As dual opamps are widely available with a moderate increase in parts' cost, we used a dual opamp, as shown in Fig. 1. Opamp U1 provides a mid-voltage reference point to opamp U2, which amplifies the received ultrasonic signal. The required gain depends on the transducers' efficiency with the desired medium. An excessively high gain should be avoided because it leads to oscillations that are related not to the ultrasound pathway but to electromagnetic interference inside the circuit.

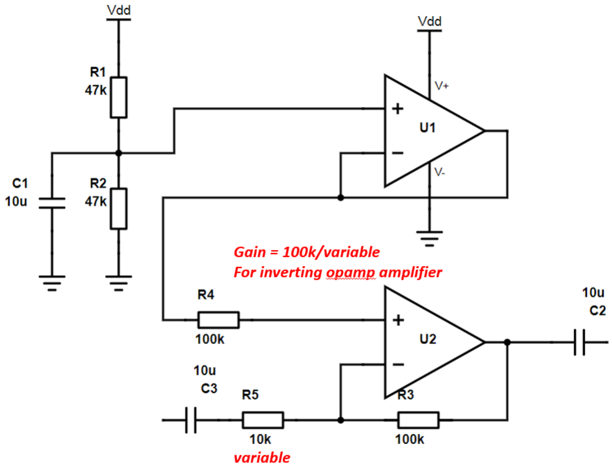

Fig.1. Schematic diagram of an UOTS amplifier using a dual opamp

Although a single amplifier can be sufficient for ensuring sustained oscillations, a UOTS can additionally include a band-pass filter (BPF; for selecting a single operating frequency band out of several possible ones) and a phase shifter (for tuning the UOTS at a particular frequency under certain conditions, which is essential for obtaining consistent readings when using different transducers and/or their fixtures even with the same notional distance between them).

Inexpensive ultrasonic transducers, mass produced for car parking aids and ultrasonic rangefinders, can have centre frequencies in the range of 25–100 kHz, but the most common ones operate at 40 kHz. Both fully encased transducers and transducers with open-to-air piezoelectric elements are available. The former transducers are marketed as splash proof only and thus unsuitable for operation while submerged in liquids for a long time. However, on a number of occasions, we observed no notable deterioration in the encased transducers that were submerged in water for months.

Schematic diagrams for the amplifiers, BPFs and phase shifters, based on conventional opamps, are presented in [6]. Programmable system-on-chip (PSoC), manufactured by Cypress Semiconductor, offers another option for realising UOTS's electronics [3].

Although the Barkhausen criterion concerns the frequency of sine wave oscillations, the output waveforms in practice are clipped (e.g. Fig. 2).

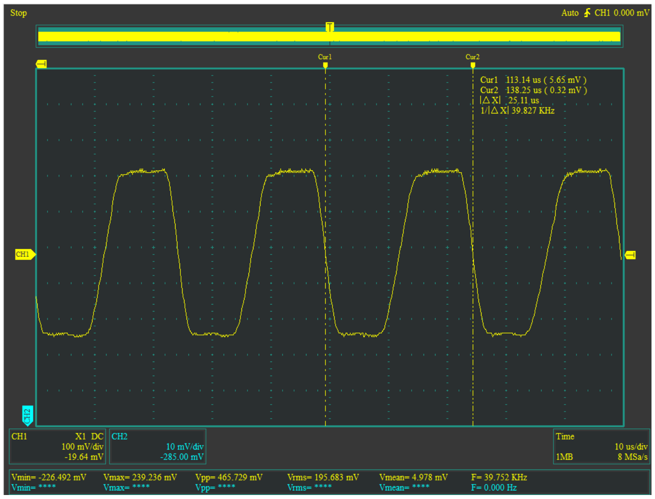

Fig.2. A typical air UOTS output signal – clipped sinewave

The spectrum of the output signal contains odd harmonics with total harmonic distortions in the range of 10–30% (e.g. Fig. 3).

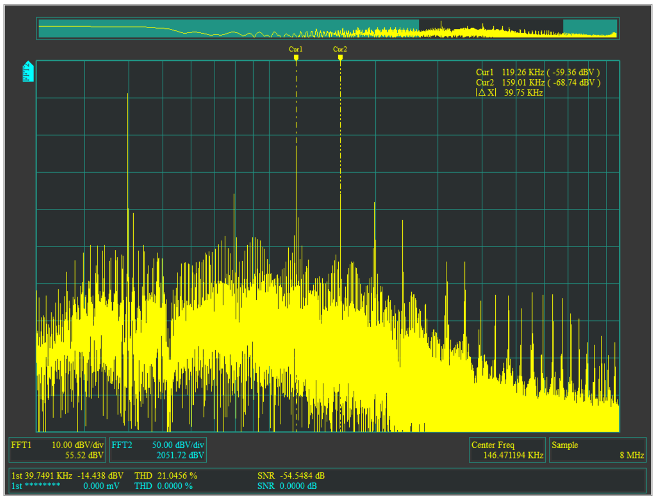

Fig.3. A typical air UOTS output spectrum

The starting oscillation of a UOTS requires a slightly higher gain than does sustained oscillation. This can easily be demonstrated by placing the transducers far apart and moving them towards each other until the oscillations emerge. Afterward, the transducers can be moved away from each other for some notable distance before the oscillations extinguish.

III. UOTSES IN LIQUIDS

For operation in liquids, we used encased ultrasonic transducers with a centre frequency in air of 40 kHz. When this pair was submerged, the UOTS featured multiple operating frequencies (Fig. 4) with a tendency of the highest frequency to take over at power up.

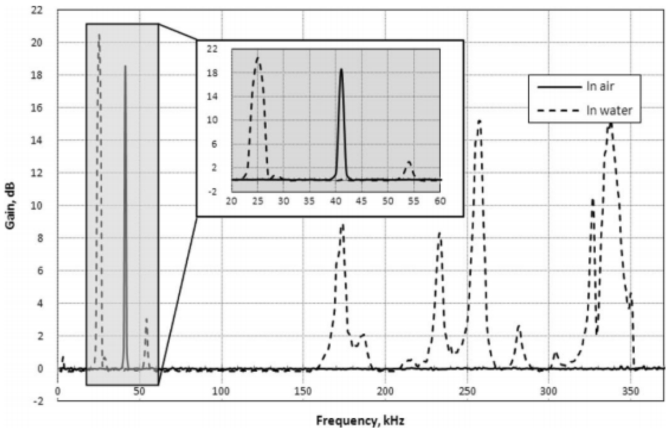

Fig.4. Frequency response of a pair of encased 40 kHz air ultrasonic transducers when submerged in water [1]

The use of higher frequencies during operation allowed obtaining higher temperature resolutions of the UOTS (i.e. change of the output frequency in Hz per change of one centigrade). However, each resonant frequency featured a limited operating frequency band. Thus, employing higher frequencies imposed limits on the range of temperatures that could be sensed. To operate at lower frequencies, we employed a BPF.

Fig. 5 summarises the centre frequencies, sensitivities and lengths of the ultrasonic pathways that were used in some of our experiments [4]. Lowering the operating frequency allowed fitting a few tens centigrade into a 1 kHz UOTS operating band.

UOTS center frequency	Approximate sensitivity	Length of the pathway
330 kHz	280 Hz/K	0.03 m
25 kHz	40 Hz/K	0.19 m
29 kHz	Tilt sensor	0.05 m
22 kHz	50 Hz/K	0.10 m
25 kHz	25 Hz/K	0.10 m
46 kHz	60 Hz/K	0.10 m
25 kHz	20 Hz/K	0.10 m
27 kHz	30 Hz/K	0.10 m
27 kHz	30 Hz/K	0.10 m

Fig.5. Summary of parameters of UOTSes, operated in liquids [4]

The UOTS output frequency had to be measured with quite a high resolution using a frequency reference of appropriate quality ([3], Section 3). A convenient measurement method is the use of a microcontroller with a relatively inexpensive temperature-controlled crystal oscillator (TCXO). Reference pulses are counted by one built-in timer for a selected number of UOTS output pulses, which are counted by another built-in timer.

Developed UOTSs featured reliable and sensitive operation but suffered from hysteresis of the output frequency, i.e. different output frequencies at the same temperatures depending on the direction of the temperature change (Fig. 5).

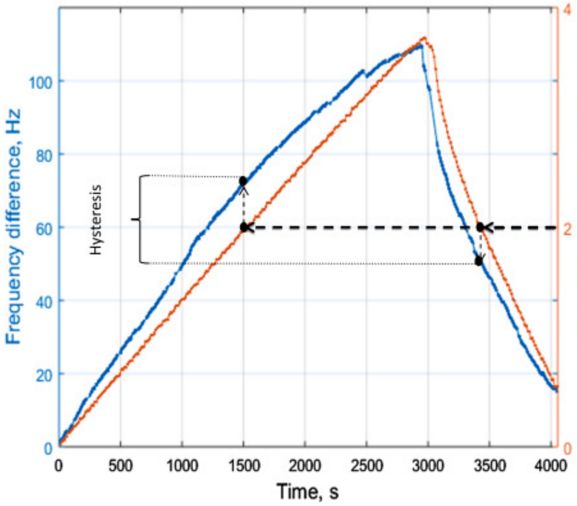

Fig.5. Recorded UOTS output frequency and vessel temperature exhibiting hysteresis [4]

The developed data fusion procedure allowed combining unambiguous readings of a conventional temperature sensor with the responsiveness and aggregate sensing of the UOTS ([4], Section 4).

IV. UOTS IN AIR

We recently started developing a UOTS for operation in air and present here the results of the initial feasibility study. We used 40 kHz air ultrasonic transducers with open-to-air piezoelectric elements, an MCP6022 dual opamp in the amplifier (U1 and U2 in Fig. 1), a seven decade resistor to set the amplifier's gain (R5 in Fig. 1) and the standalone eight-digit frequency meter PLJ-8LED-C (for measuring UOTS frequency every 1 s). The transducers were mounted on a piece of 20 × 20 extruded aluminium profile using Munsen rings; they could slide along the profile or be affixed to it at a required position.

We set a desired gain and placed the transducers away from each other, ensuring that no oscillation was observed. Then, we moved the transducers towards each other and recorded the distance between them and the associated UOTSs' frequency when the oscillation started. To determine the operating frequency range for the set gain, we moved the transducers to the minimal distance possible (around 52 mm) and recorded the maximal and minimal frequencies of the oscillations, recorded along the way (Table 1).

TABLE I. OPERATING DISTANCES AND FREQUENCY RANGES FOR VARIOUS GAINS OF THE AMPLIFIER

Operational parameters	**Resistance / gain**					
	1 kOhm / 100	***2 kOhm / 50***	***3 kOhm / 33***	***4 kOhm / 25***	***5 kOhm / 20***	***6 kOhm / 16***
Distance, mm	198	134	91	72	52	x
Frequency, kHz	39.60	39.40	39.20	39.30	39.49	x
Max freq, kHz	42.80	42.80	42.40	40.80	40.00	x
Min freq, kHz	38.50	38.30	38.60	38.60	38.90	x
Range, kHz	4.3	4.5	3.8	2.2	1.1	x

These results show that higher gains ensure wider operating distances of sensors. At the minimal distance that could be set, the UOTS did not oscillate at gains less than 20 at all. We observed continuous output frequency changes when the transducers were moved; therefore, the temperature dependence of the output frequency at air temperature should have been expected.

For the proof of concept, the UOTS (1 kOhm; 52 mm) was placed inside a test air chamber (a long cardboard box with one side open) along with I2C temperature sensors AHT20 and BME280 connected to a microcontroller module.

A hairdryer, switched on for around 4 s, was placed inside the test chamber to raise the air temperature inside. The microcontroller logged temperature measurements each second to an SD card. The readings of the frequency meter were video recorded and then played back with pauses to observe and record the readings. The results are presented in Fig. 6 (as the readings of AHT20 and BME280 were different by around 1.3 °C, they are shown biased up by this amount).

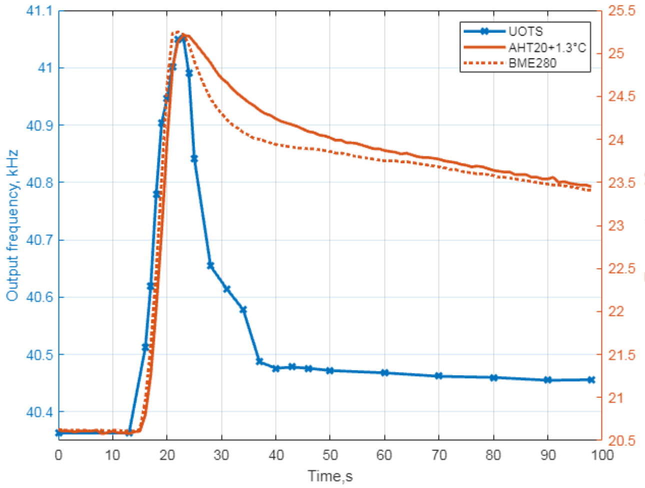

Fig.6. UOTSs' output frequencies and the test air chamber's temperature

All three sensors exhibited about the same response rates to the temperature rise caused by the working hairdryer. The UOTSs' readings returned to their steady state more quickly than did those of the conventional sensors, which is an advantage. The UOTS sensitivity was around 150 Hz/°C, potentially allowing high-resolution temperature measurement.

V. SUMMARY AND CONCLUSIONS

In the paper, we present a motivation for developing ultrasonic temperature sensors, the cost advantages of UOTSs and their operating principles. Likewise, we give examples of past UOTS developments for aqueous media and the results of the initial feasibility study on the use of an UOTS in air.

In its simplest form, an UOTS consists of a transducer pair and an amplifier, which can be complemented by a BPF and/or phase shifter. An UOTS operates as an oscillator whose frequency depends on the temperature in the medium between the transducers. As ultrasound velocity in water and air increases by only around 0.2% per centigrade, an appropriate measurement procedure and frequency reference are required for output reporting. The sensitivity of the developed UOTSs ranges within 20–150 Hz/°C, allowing responsive aggregate temperature measurement with high resolution.

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