Sensor data fusion for responsive high resolution ultrasonic temperature measurement using piezoelectric transducers

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ABSTRACT

Ultrasonic temperature measurement allows for responsive measurements across an entire ultrasonic pathway, unlike most conventional temperature sensors that respond to the temperature at the point of their placement only after a notable response time. The high cost of required ultrasonic instrumentation can be reduced substantially by using ultrasonic oscillating temperature sensors (UOTS) consisting of inexpensive narrowband piezo transducers and driving electronics. An UOTS produces sustained oscillations at a frequency that relates to the temperature of the medium between the transducers. The existence of thermal hysteresis in UOTS readings, observed experimentally and apparently related to the fundamental properties of piezoelectric materials, makes conversion of the output frequency readings to the temperature values ambiguous. This makes it complicated to calibrate and use UOTS on their own. In the reported experiment (heating, then naturally cooling of a water vessel equipped with both UOTS and conventional sensors), this hysteresis was solved by fusing UOTS data with conventional temperature sensor readings. As the result, the combination of one UOTS plus one conventional reference sensor allowed improving both the temperature resolution and responsiveness of the latter and ambiguity of the readings of the former. Data fusion effectively led to calibrating the UOTS at every change of the conventional sensor's reading, removing any concerns related to the thermal expansion/contraction of the ultrasonic pathway itself and/or hysteresis of piezoelectric transducers.

1. Introduction

Why sense the temperature ultrasonically?

Temperature sensors are ubiquitously used in various consumer, domestic, transportation, and industrial applications. The global market value of these sensors was over US $5 billion in 2016 [1]. Conventional temperature sensors are placed at specific location(s) where the temperature is to be assessed. They need to reach thermal equilibrium with the environment in order to produce accurate readings, and report their readings using a variety of interfaces. The cost of mass-produced temperature sensors varies from a few cents for thermistors with analogue output to up to a few dollars for better-specified sensors with standard digital communication interfaces. However, conventional sensors have some shortcomings, which originate from their operating principles. First, a conventional temperature sensor only operates at a single local point, making it necessary to deploy a set of sensors to estimate the average temperature in a room, a car, a process vessel, etc. Second, any temperature changes in the environment require a certain amount of time (called settling time or response time) to affect the sensor's readings. Third, the cost of high accuracy/resolution sensors escalates very quickly.

Ultrasonic temperature sensors operate by propagating ultrasonic waves through the medium of interest, and they produce readings based on the wave velocity's dependence on the temperature. As the waves propagate several hundred meters per second in gases and several kilometres per second in liquids and solids, ultrasonic sensors can potentially detect sudden temperature changes almost instantly. Sensor readings are affected by the temperature profile along the entire ultrasound pathway; this results in integrated (instead of local) temperature estimates. The possibility of using ultrasound for temperature measurement was first reported in 1873 [2], and by 1975, approximately 500 industrial ultrasonic thermometers, operating at temperatures ranging up to 20,000ºC in gases, were sold [3]. Table 1 presents several use cases in which ultrasonic temperature sensors demonstrated clear advantages over conventional sensors.

Advantage	Application area	Length of the ultrasonic pathway	Quantification / Notes
Low measurement uncertainty	Healthcare / Hyperthermia	0.6 m	RMS noise of temperature readings of 5 μK [4]
Measurement speed	Precision manufacturing / Small arms firing tests [5] Large caliber guns firing tests [6]	Contact measurement	Measurement interval of 1 ms [5] or 0.2 ms [6]
Measuring average temperature	Transportation / Car air conditioning	1 m	Obtained readings within ±0.4 K of a conventional single point sensor [7]
Temperature profiling	Metallurgy / hot billets [8] furnace [9]	Contact measurement on a probe	Multiple reflectors inserted into the probe
Heat flux measurement & temperature profiling	Materials science/ Hypersonic vehicle aero shell [10] Industrial materials [11]	Contact array [10] BAW or SAW [11]	Estimates obtained based on solving an inverse problem

Table 1. Examples of quantitative advantages of ultrasonic temperature sensors

Besides the general arrangements indicated above, ultrasonic thermometers may utilize pathways that include reflections from single-zone or multi-zone reflectors, potentially useful for temperature profiling [8, 9]. (It should be noted that not only ultrasound but also acoustic waves in the audible frequency range could be used for thermometry applications in large boilers [12].) In some measurement systems, whose primary purpose is to sense a measurand other than temperature, for example, flow within a pipe or pipe integrity, temperature still may be sensed as a by-product.

Among potentially interfering variables, one should consider the purity of the environment through which ultrasonic thermometry pathways are utilized as any inclusions or contaminants could affect both the ultrasound velocity and its temperature dependence.

As ultrasonic thermometers are considerably more expensive than conventional thermometers, their use is currently limited.

Development of ultrasonic oscillating temperature sensors

Although temperatures can be estimated from time-of-flight (TOF) ultrasonic measurements [13, 14], oscillating architecture has been identified as a potentially lower cost alternative [15]. Ultrasonic oscillating temperature sensors (UOTSes) operate a pair of inexpensive mass-produced narrowband ultrasound transducers in the through transmission mode, and they use a positive feedback loop to sustain oscillations whose frequencies represent the sensor's output with the mechanism similar to that of acoustic feedback or used in surface acoustic wave (SAW) oscillators. Fig. 1 presents a block diagram of an UOTS.

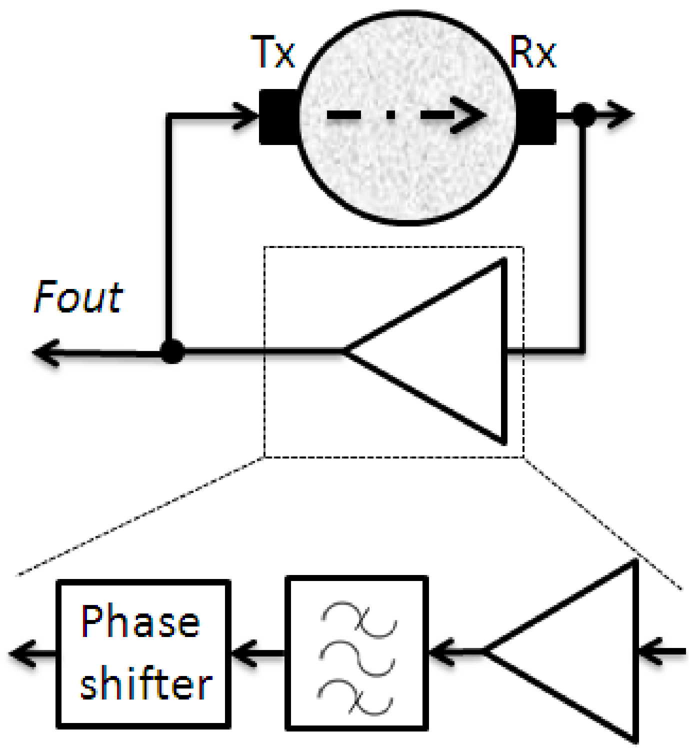

Fig.1. Block diagram of an UOTS [18]

The amplifier is required for compensation of all the conversion and transmission losses in the electrical and ultrasonic pathways, making the overall gain in the open loop greater than unity. The optional phase shifter enables tuning the sensor to a particular frequency at a required temperature as an UOTS oscillates at the frequency at which the overall phase shift in the open loop equals $n \times 360°$, $n \in Z$. In order to limit oscillations to a particular frequency range, an optional band pass filter can be employed. Recently, our research group has focused on developing UOTSes with a low end-to-end cost that can be used in industrially-relevant conditions with as low instrumentation error as possible (Table 2).

Reference	UOTS center frequency	Approximate sensitivity	Length of the pathway	Comments
[15]	330 kHz	280 Hz/K	0.03 m	Consistency of UOTS output frequencies versus temperature at decreasing temperatures was reported
[14]	25 kHz	40 Hz/K	0.19 m	Different start up frequencies from the same UOTS in different experiments were observed
[16]	29 kHz	Tilt sensor	0.05 m	Reliable method to measure UOTS output frequency with any required resolution was presented
[17]	22 kHz	50 Hz/K	0.10 m	Implementation options for the electronic driver (including PSoC1*) were discussed
[18]	25 kHz	25 Hz/K	0.10 m	Comparison of ultrasonic thermometer architectures was conducted
[19]	46 kHz	60 Hz/K	0.10 m	Use of an UOTS for overnight measurements and observed hysteresis were reported
[20]	25 kHz	20 Hz/K	0.10 m	Simultaneous use of two UOTSes for the same process, modular design of the electronic driver, and thermal hysteresis for the recorded data were discussed
[21]	27 kHz	30 Hz/K	0.10 m	Differential temperature measurement using two UOTS was reported
[22]	27 kHz	30 Hz/K	0.10 m	UOTS and conventional temperature sensors were compared for a posteriori detection of the temperature extremum point

**PSoC1 refers to the programmable systems on chip series 1 device, which is a highly versatile electronic part manufactured by Cypress Semiconductor.*

Table 2. Previous UOTS development

In our research group, the feasibility of building low cost, high resolution UOTS was confirmed at every stage of development. However, we found that the main obstacle to UOTS usability was the difference in their output frequency at the same temperature, depending on the sign of the temperature gradient (hysteresis). This phenomenon led to ambiguities as well as other complications when we attempted to convert the UOTS readings to temperature using a single calibration curve.

Hysteresis in piezoelectric transducers and the possibility of its mitigation

Piezoelectric materials feature a strain/electric field hysteresis, which is dependent upon the ambient temperature [23]. Not being an issue of primary interest for most piezoelectric actuators, temperature-dependent hysteresis presented a significant challenge for manufacturers of precision oscillators. This problem was solved over time by improving the piezo materials, the temperature retention techniques and temperature-compensated devices [24]. We have recently presented several sets of UOTS experimental data obtained during heating/cooling cycles, which exhibited similar hysteresis [19-21].

It is worth noting that different readings at the same temperature, depending on the sign and/or magnitude of the temperature gradient, have been observed for low frequency UOTS as well as for high frequency ultrasonic TOF measurement instruments [25] and low frequency ultrasonic oscillating tilt sensors [26].

Our numerous experiments with UOTS showed that, although thermal hysteresis was not random, it was very unpredictable from one experiment to another. The extent of hysteresis depended upon the past temperature values, and this complicated the development of a single calibration procedure that could, later, be confidently used with an UOTS on its own.

A similar behaviour was observed in a study of crystal oscillators, during which 720 temperature-frequency curves were experimentally collected and analysed [27]. Although the maximum differences in the oscillator's output frequencies at the same temperature were very consistent from one experiment to another [27, Fig. 4], the curves were found to be notably different [27, Fig. 3]. This study did not analyse the differences in the curves in detail because the primary interest of the authors was a specific measure of hysteresis, as defined by a military standard [28].

For this reason, we came to the conclusion that the development of usable UOTS could progress further with the aid of a conventional temperature sensor, which would constantly provide the reference data. The UOTS readings would be fused with these reference data when producing the temperature estimates from the UOTS readings. The following potential benefits of UOTS were expected to be sacrificed if this approach was used:

- The accuracy of the fused sensor could not be better than the accuracy of the reference sensor;
- There could be significant dynamic differences between the reference values and the UOTS readings because of the thermal inertia of the former;
- The reference values would come from a single point (or from only a few points if several conventional sensors were used), which might not be a good representation of the entire ultrasonic pathway.

Nevertheless, a fused sensor was expected to retain the following UOTS advantages:

- Fast detection of changes in the sign and/or magnitude of the temperature gradient;
- Increased resolution of temperature readings between the discrete values provided by the reference temperature sensor.

This paper describes a laboratory experiment related to external heating, followed by natural cooling of a water filled chamber, which was instrumented by several conventional temperature sensors and a UOTS. It also discusses the analysis of the recorded data and the removal of UOTS outliers, and describes the quantification of the observed thermal hysteresis and the developed data fusion procedure. It is concluded that UOTS enabled much faster detection of the temperature extremum point, which is useful for early prevention of thermal runaways and/or detection of process equipment failures. Simultaneous use of a conventional temperature sensor with an UOTS increased the resolution of the temperature readings, although some of the fused readings were found to be notably off, especially around the extremum point. We believe that was due to the thermal lag of the reference sensor.

2. Experimental setup and procedure. Acquisition and preliminary processing of the sensor data

A transparent plastic tube, with a diameter of 0.1 m and a length of 0.5 m, was used as the experimental vessel. It contained the conventional temperature sensors, the UOTS, and a substantial amount of water (over 3.5 kg). The water acted as a thermal buffer to eliminate any sudden temperature changes in close proximity to the sensors that could otherwise affect their readings, thereby providing quasi-static changes of the temperature. The sides of the tube were sealed during the experiment. Eight DS18B20 One Wire® temperature sensors [29], encased in a stainless steel protective cover, were equidistantly placed at a cross-section of the tube close to its base. Four pairs of ultrasonic transducers were equidistantly placed at another cross-section at the centre of the tube. Another set of eight bare DS18B20 sensors were equidistantly placed close to the other base of the tube (Fig. 2). The distances between these cross-sections and the bases were kept approximately the same.

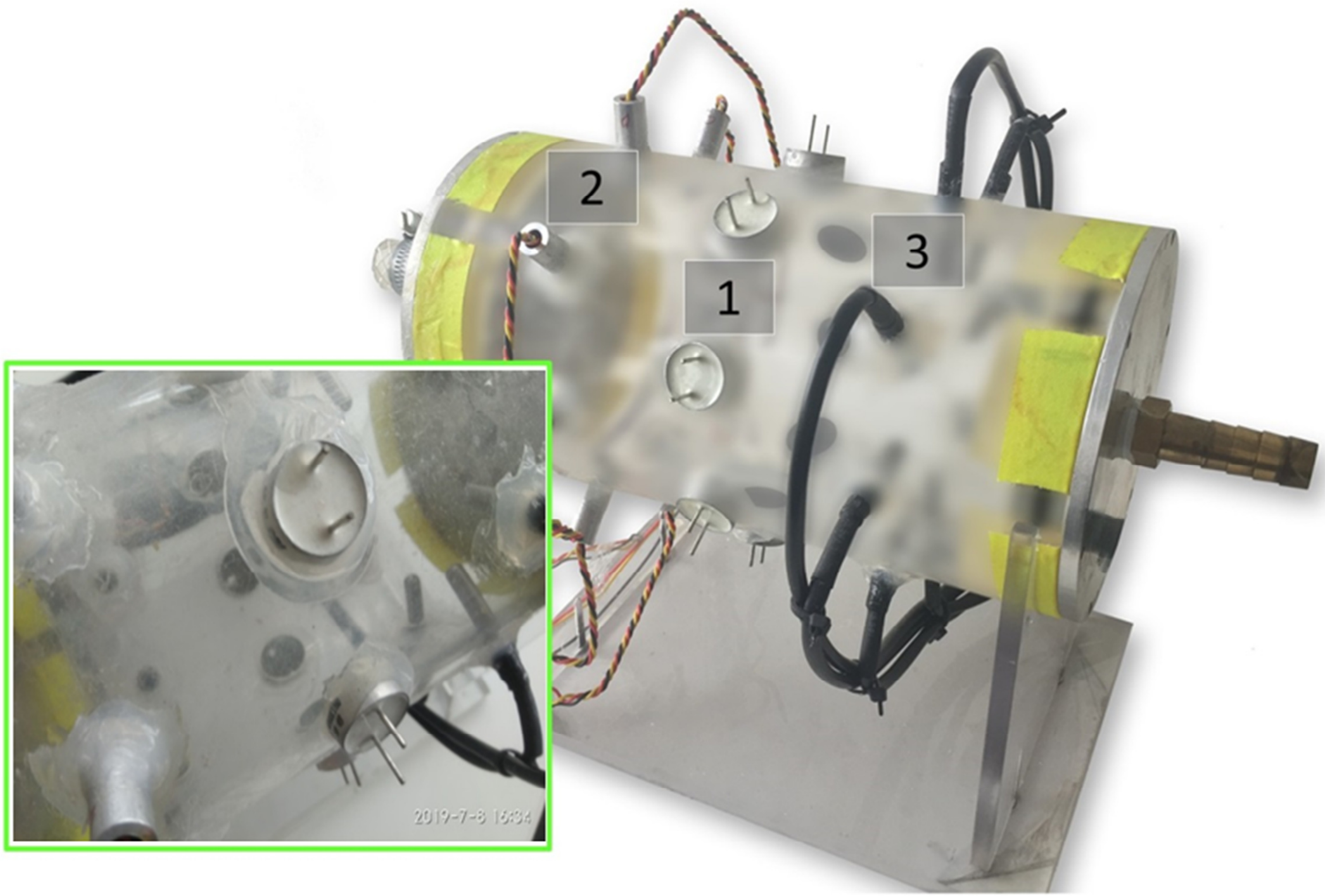

Fig. 2. Full view and close up photographs of the experimental vessel with the transducers labelled (1 - ultrasonic transducers, 2 - case less DS18B20, 3 - encased DS18B20)

The UOTS was implemented by complementing one transducer pair with a modular ultrasonic driver [14], which consisted of two PSoC1 modules. One module was used for amplifying and band pass filtering the loop signal, and the other module was used to measure the UOTS output frequency and communicate it to the host via a suitable USB module. The output frequency was measured with the aid of an additional 10 MHz oven controlled crystal oscillator (OCXO), which was the source of the reference pulses. We used OCXO because its tolerance and stability well exceeded those of the UOTS; a lower cost temperature compensated crystal oscillator (TCXO) could have been used instead, as discussed in [12, Section 3].

Each set of DS18B20 sensors was connected to a separate One Wire® bus. Only encased sensors were used in the experiment because their readings were found to be less scattered than the readings of the bare sensors. A separate PSoC1 based module was used to broadcast the "start measurement" command to all the encased sensors at the same time. It then collected their individual readings over the same bus by addressing them in turn. The sensor data, obtained for the same broadcasted "start measurement" command, were communicated to the host using a suitable USB converter as one data packet.

The experimental setup was placed inside a thermal chamber equipped with a thermostat (not used on this occasion), and it reached thermal equilibrium with the environment at 25.7 °C before the experiment began. Then, the chamber's built-in heater was switched on, heating its internal air, which, in turn, heated the experimental vessel. When the water in the vessel was increased by >3.5 K, the heater was switched off and the vessel started to cool down naturally, eventually returning to thermal equilibrium with the environment. Both the temperature and the UOTS readings, reported as text strings, were continuously saved into separate files by the host PC. The complete experiment took 4054 s.

Collecting a single set of data from the conventional temperature sensors and communicating it to the host took approximately 12.1 s; measuring and communicating a single UOTS output frequency took approximately 1.52 s.

Because the DS18B20 sensors used in this experiment were not individually calibrated by the manufacturer, and, additionally, they were encased, some of the readings varied from one sensor to another. For example, when the temperature increased, the sensors produced the next higher discrete output value at different times. This observation can be attributed to the varied thermal biases specific to different sensors and uneven temperature distribution inside the tube. On the positive, these factors allowed averaging the temperatures across the sensor array. (It would be meaningless to average these digital readings if they were all the same at all times.) When the average temperatures over time were calculated, standard deviations (STDs) were computed for each sensor. The STDs of six sensors were found to be similar, and the STDs of the other two sensors were approximately 50% higher. We decided to exclude the latter two sensors from further consideration, and recalculated the average temperatures over time for the six selected sensors. Fig. 3 presents the average temperatures along with the readings recorded for a single sensor, which readings tracked the average temperature most closely, and that was later used as the reference sensor for the data fusion, for comparison. It can be seen that the averaging allowed for smoothing the stepwise digital readings of the individual sensors.

In order to quantify UOTSes hysteresis, the raw temperature data set needed to be interpolated to the same points in time at which the UOTS output frequencies were measured. We used spline interpolation for the average temperatures. The sensor 2 readings were assumed to be identical to the readings obtained before the experiment and up to the moment when a different value was recorded; from that moment, the readings were assumed to be equal to the new value until the value changed again. The interpolated average temperatures are presented as a dotted line in Fig. 3.

The recorded UOTS output frequencies exhibited some intermittent jumps away from the smooth trend line, returning to the trend over time (Fig. 4).

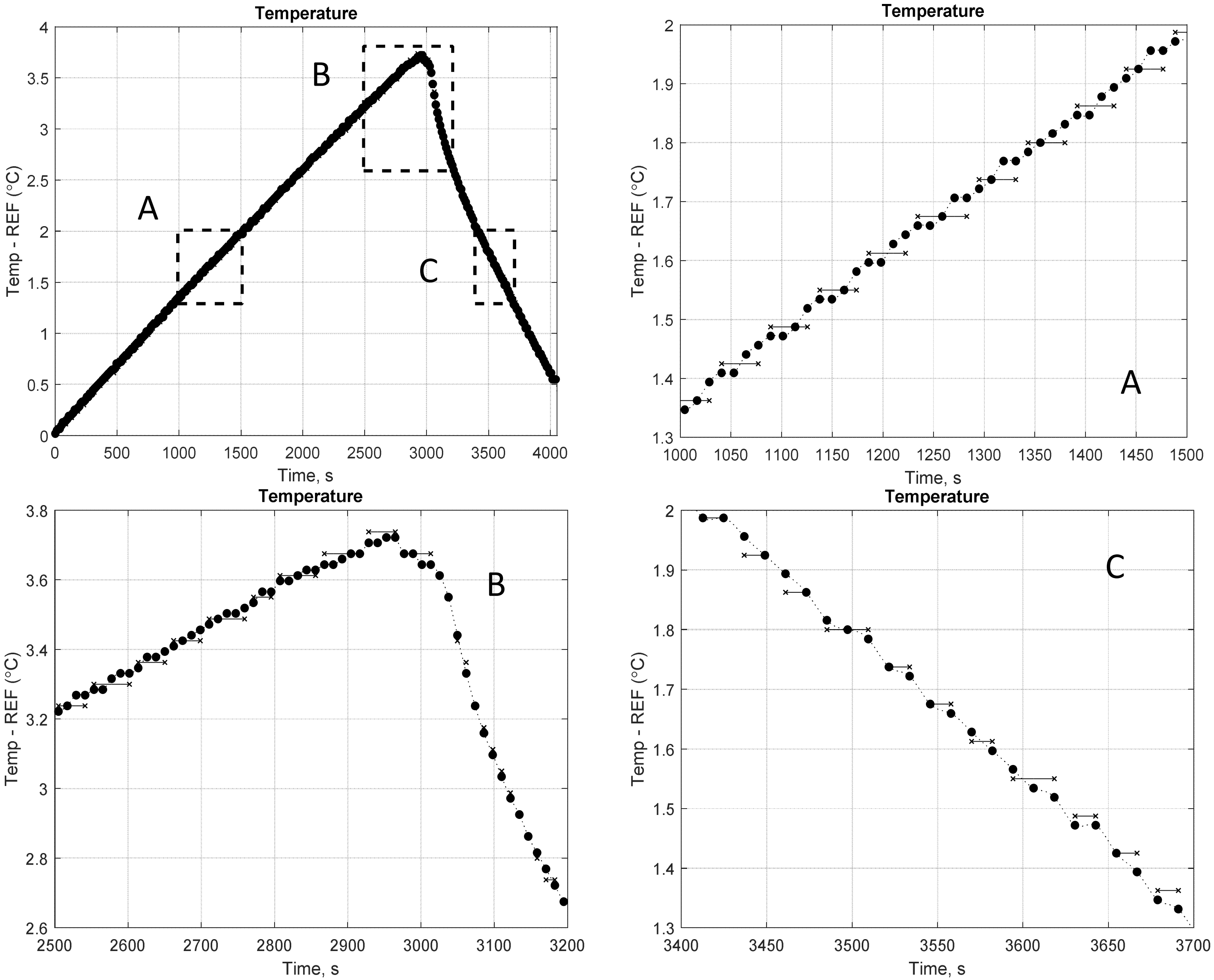

Fig. 3. Average temperature (dots), reference sensor readings (stepwise solid line), and spline interpolated average temperature (dotted line) presented for the complete experiment (top left pane) and heating, maximum temperature and cooling stages (A, B and C panes respectively). The reference temperature was 27.5 C.

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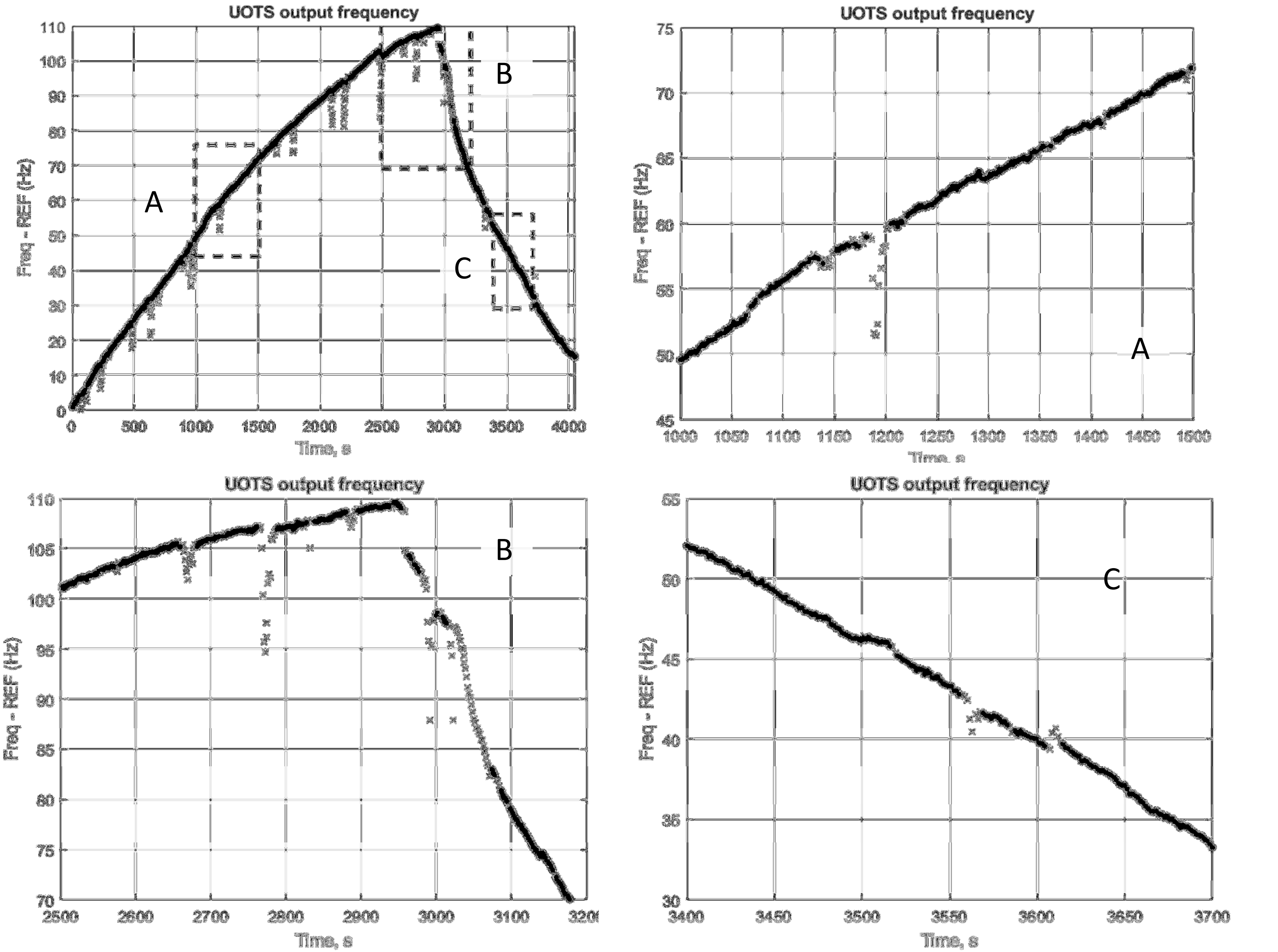

Fig. 4. Recorded (crosses) and accepted (dots) UOTS output frequencies presented for the complete experiment (top left pane) and heating, maximum temperature and cooling stages (A, B and C panes respectively). The reference frequency was 27,168 Hz.

Such behaviour was observed for various UOTS in spite of the continuing refinement of the electronic instrumentation. The magnitudes of the jumps, typically in the order of a few Hz or about 0.01% of the output frequency, would be considered acceptable for a majority of crystal-less oscillators. For example, the frequencies of the internal oscillators of modern microcontrollers are commonly specified to be within ±1% tolerance of their nominal frequency, and they are very sensitive to ambient temperature. Nevertheless, a change of only 0.3 Hz with a typical UOTS sensitivity of 30 Hz/K would correspond to a sudden change of temperature by approximately 0.1 K. Although these jumps might have been influenced by some heat exchange phenomena in liquids, a safer explanation would relate the jumps to the collective influence of random factors, which temporarily and intermittently shifted the UOTS loop out of the steady state. We eliminated most of these jumps, assuming that the UOTS readings would not change too rapidly from one reading to another due to the significant specific heat capacity of water. Fig. 5 presents a graphic representation of the acceptance criterion: every recorded output frequency reading was compared to its three neighbors from each side.

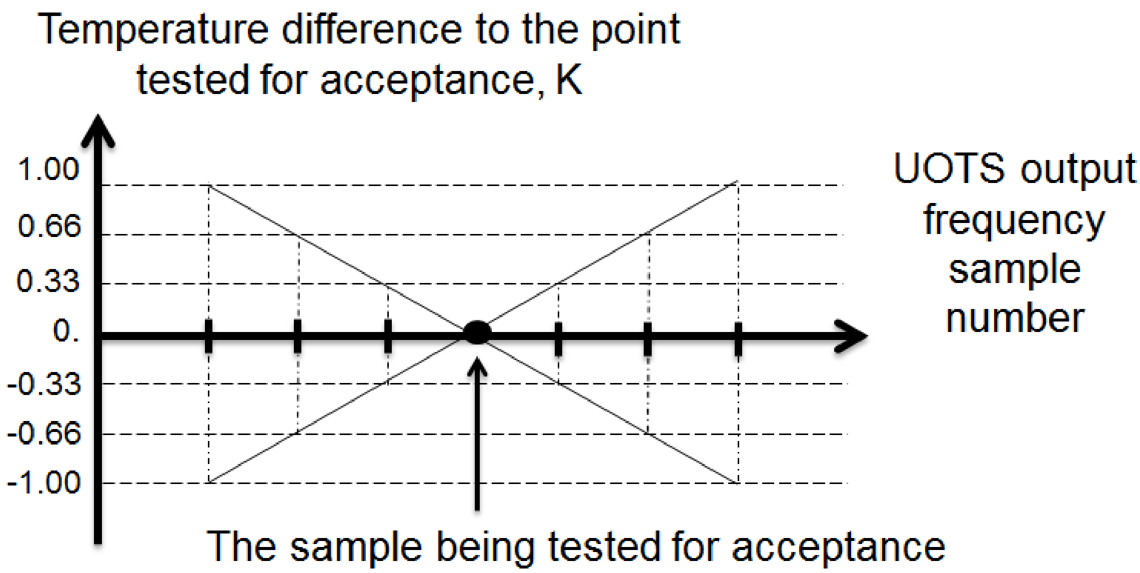

Fig.5. Acceptance criterion for the recorded UOTS output frequencies

As shown, all of the output frequencies are within the allowed boundaries for the considered frequency reading to be accepted. These boundaries were selected by trial and error to achieve some balance between removing the outliers while retaining the valid data despite the fact that it was slightly noisy; using this criterion, 77.8% of the recorded measured points were retained.

3. Quantification of the observed temperature-dependent hysteresis

The existence of hysteresis becomes very clear if the experimental data for frequency and temperature versus time are plotted on the same graph using appropriate scaling (Fig. 6).

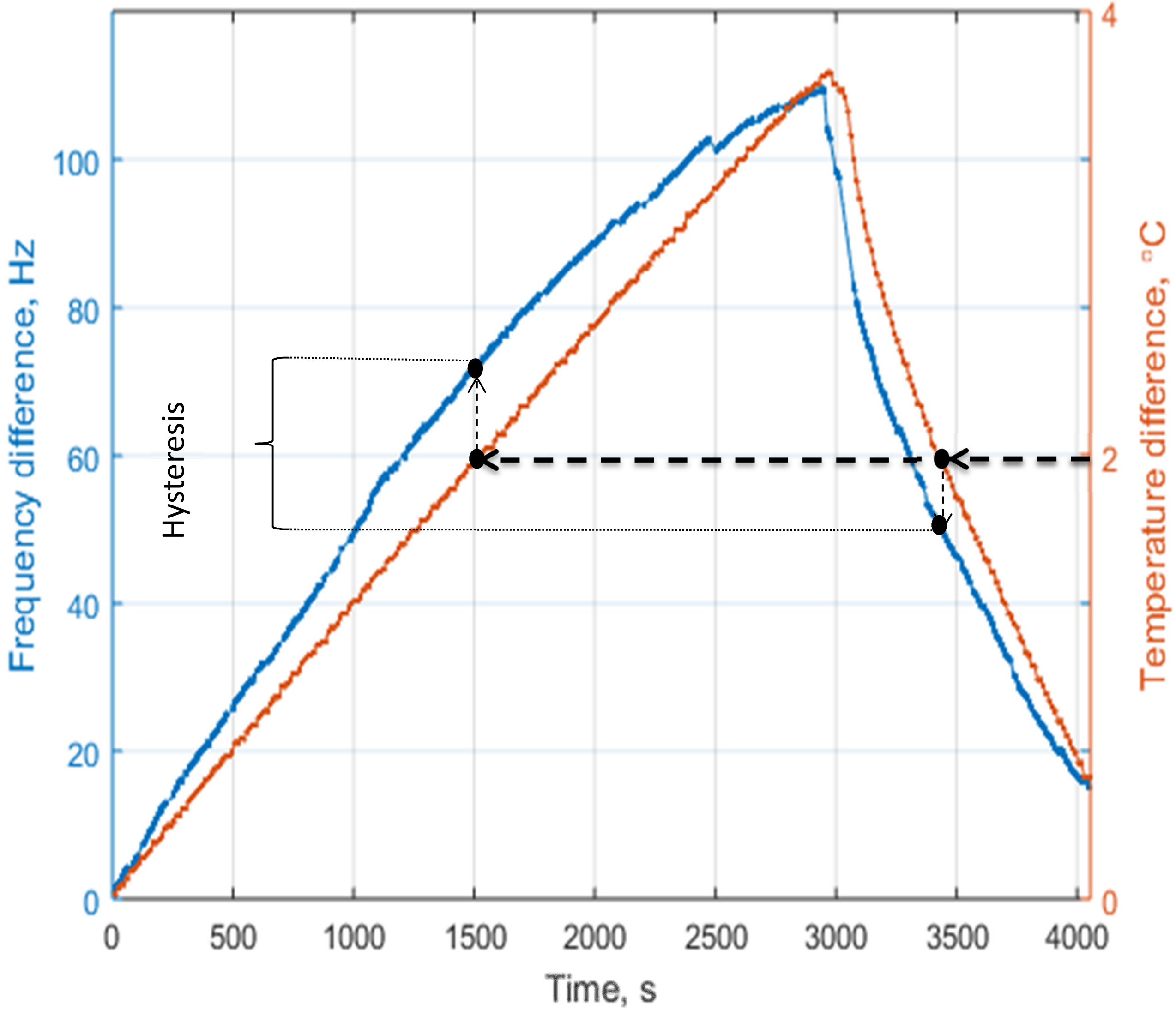

Fig.6. Experimental data for the UOTS output frequency and average temperature vs. time plotted on the same graph using appropriate scaling.

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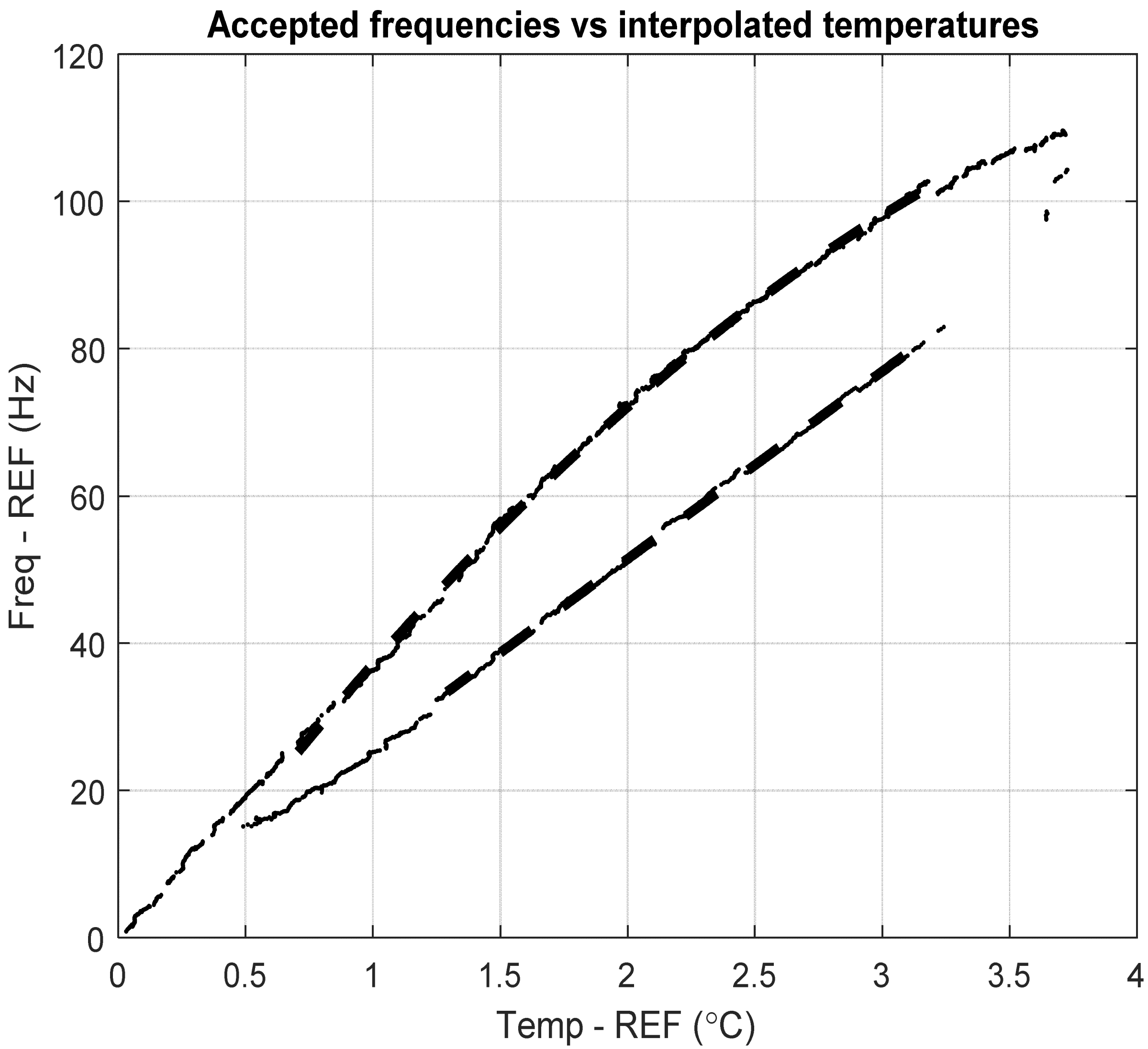

Fig.7. Accepted UOTS output frequencies versus temperature differences (dots), their approximations at the heating and cooling stages (thick dashes).

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For any temperature difference of interest, one can find two associated points at the temperature curve and determine that, at the heating stage, the corresponding frequency is located above the temperature curve, while at the cooling stage the corresponding frequency is located below the curve. This results in a considerable temperature difference. UOTS output frequency versus interpolated average temperature is graphed in Fig. 7.

As seen, the UOTS sensitivities were very different at the heating and cooling stages of the experiment. From the information presented in the graph, it seems that, at the temperature extrema point, some of the physical properties of the UOTS exhibited a step change similar to the changes observed for crystal oscillators [24, 28]. As we observed experimentally on several occasions, the hysteresis of the UOTS sensitivities at the heating and cooling stage could vary significantly, depending on the history of the temperature changes before the most recent temperature extremum. This phenomenon makes it very difficult to calibrate an UOTS. Thus, it is necessary to use an additional conventional temperature sensor as the reference in order to convert the UOTS readings into temperatures.

4. Sensor data fusion procedure

The data fusion procedure that we developed was based on a first order approximation of the UOTS output frequency (*f*) versus ambient temperature (*T*)

$$T = T_0 + \left[\frac{\Delta \mathrm{T}}{\Delta \mathrm{f}}\right]_0 (f - f_0), \qquad (1)$$

where subscript 0 relates to the most recent moment in time when the reference sensor data were used to numerically estimate the gradient. For this estimation, the recorded temperature and the UOTS output frequency are saved as the present values every time the digital reading of the reference sensor changes, and the previously stored frequency and temperature values are moved to the past values storage with the subscript -1, as shown in Fig. 8.

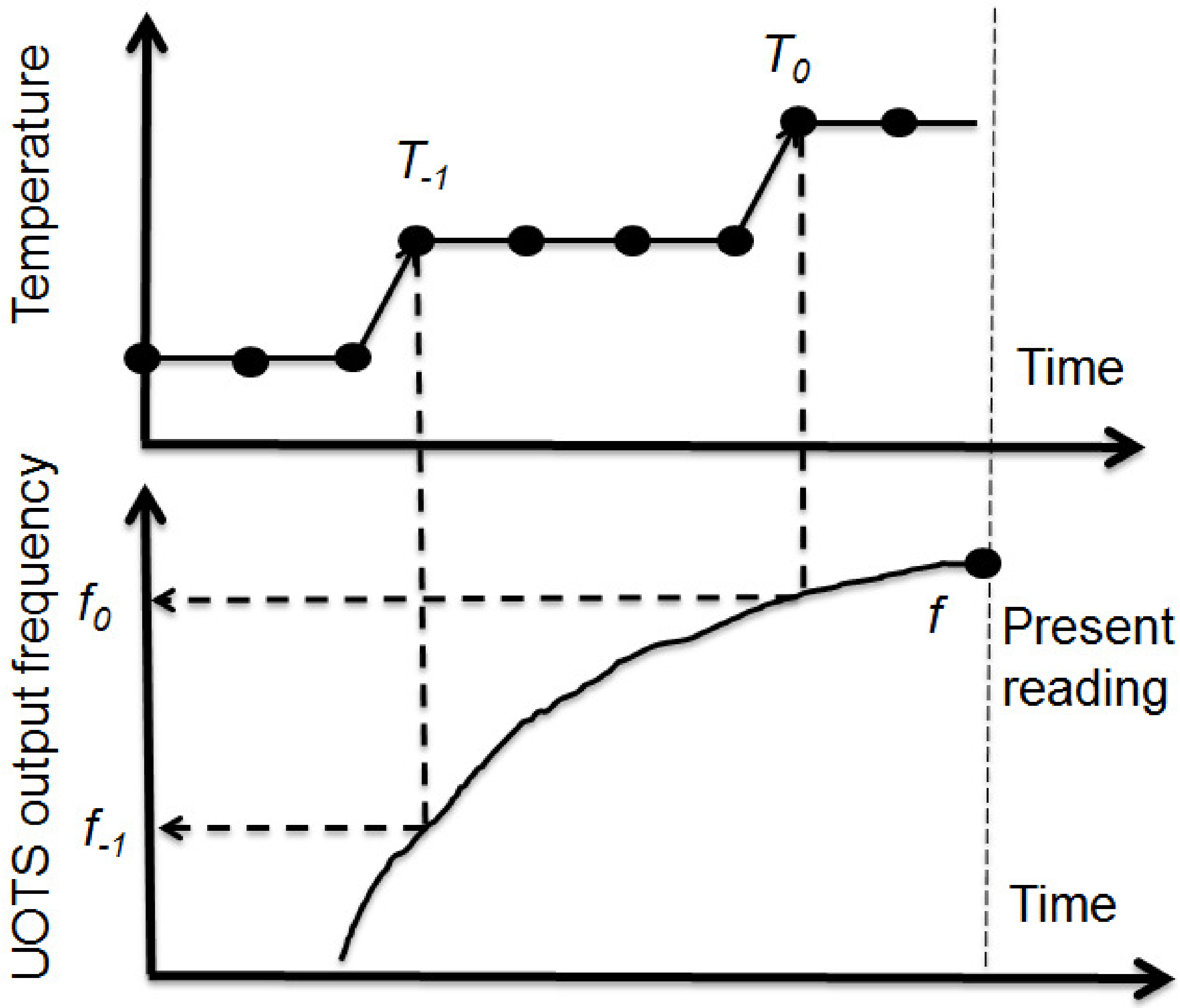

Fig.8. Definition of the experimental readings used for the numerical assessment of the gradient for the frequency/temperature relationship.

Then, the gradient is estimated numerically from the experimental values as follows:

$$\left[\frac{\Delta \mathrm{T}}{\Delta \mathrm{f}}\right]_0 = \frac{T_0 - T_{-1}}{f_0 - f_{-1}} \quad . \qquad (2)$$

The fused temperature estimates are presented in Fig. 9 along with the sensor 2 readings that were used for the data fusion.

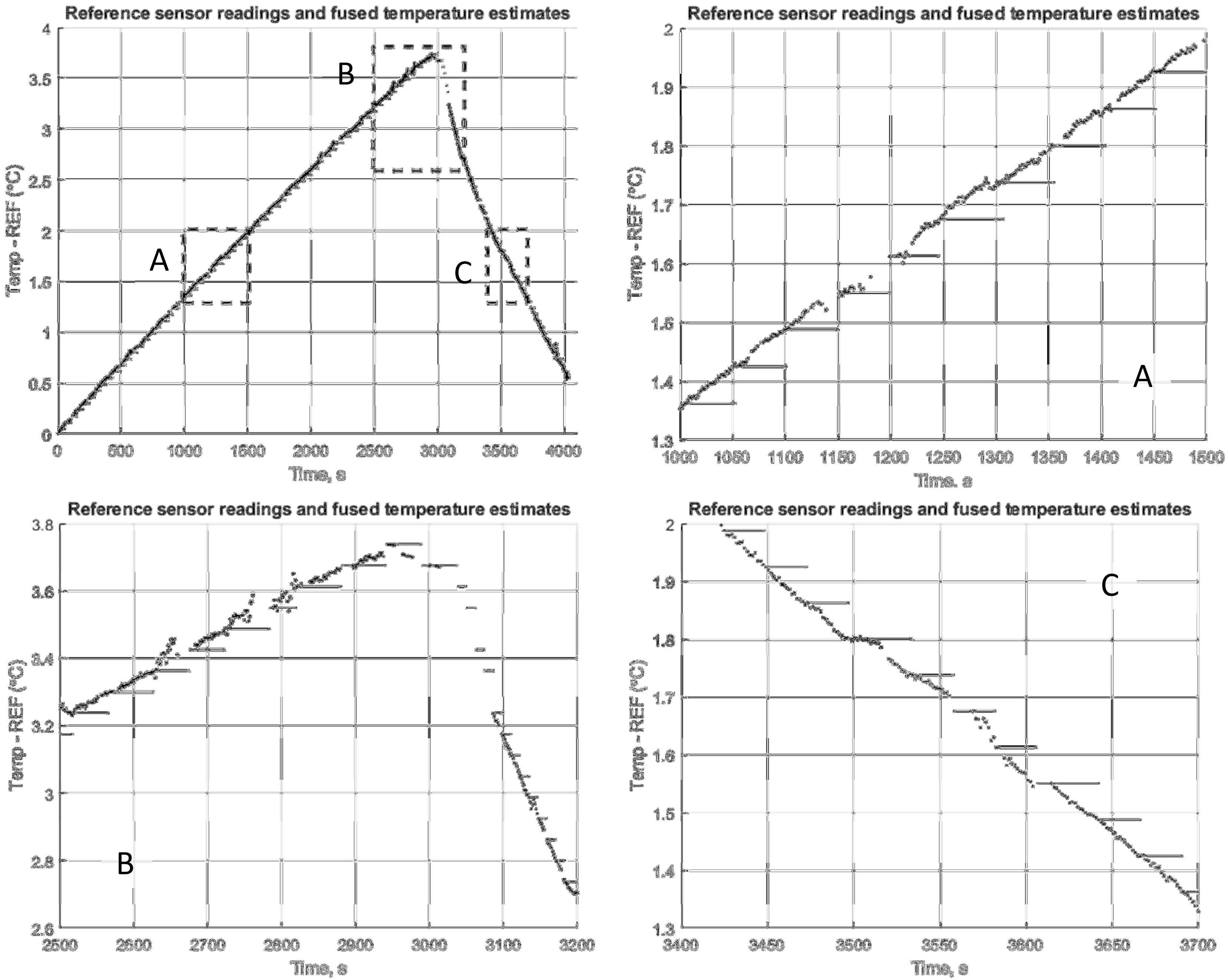

Fig.9. Fused temperature estimates (dots) and stepwise readings of the reference sensor (solid lines) presented for the complete experiment (top left pane) and heating, maximum temperature and cooling stages (A, B and C panes respectively). The reference temperature was 27.5 C.

The estimates did feature some outliers around the temperature maximum point as one would expect, because the readings of the reference sensor notably lagged the temperature. However, for the most part, the UOTS fused data did make sense, allowing clear increases in the resolution of the reported temperature.

5. Summary and conclusions

Realizing the potential advantages of UOTS (fast response time, sensing temperature over the complete pathway and higher resolution), is complicated by the existence of thermal hysteresis in piezo materials. Consequently, UOTS readings at the same temperature vary significantly depending on the sign of the temperature gradient and the past temperature history. Moreover, even the UOTS output frequency's sensitivity to temperature varies, further complicating UOTS calibration.

We conducted an experiment that subjected a set of conventional temperature sensors and an UOTS to a quasi-static heating-cooling cycle to quantify the UOTS hysteresis and to explore the feasibility of fusing the data reported by the UOTS and one conventional sensor.

Outliers in the recorded UOTS output frequency were removed by limiting the allowed rate of the output frequency change to around 0.3 Hz / 1.5 s = 0.2 Hz/s for six readings in close proximity to the reading being tested for acceptance. This acceptance criterion allowed us to retain 77.8% of the recorded output frequencies while automatically removing most of the clear outliers.

The data fusion procedure was used to overcome thermal hysteresis of UOTS. The estimate for the gradient of the UOTS output frequency versus temperature was recalculated every time the digital reading of the reference temperature sensor changed, and it was later used to convert UOTS readings into temperature estimates. Although this procedure resulted in losing some of the advantages of UOTS, it did enable temperature resolution increases and response time decreases in comparison to using a conventional temperature sensor alone.

Data fusion allowed overcoming dependence of UOTS readings on the ultrasonic path length and properties of the medium under test (like density, purity *etc*), and their dependence on the temperature. That was because any UOTS readings became referenced to the temperatures, measured by the conventional temperature sensor.

Overall, UOTS have been shown to be a potentially valuable addition to process control instrumentation. They allowed an improvement in the resolution of the fused temperature estimates and their responsiveness in comparison to a conventional temperature sensor alone. On the downside, UOTS feature intermittent frequency jumps that could lead to out-of-the range estimates if a suitable acceptance analysis is not conducted on the raw data. The developed data fusion procedure is applicable to the UOTSes only.

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