Portable Ultrasonic Thermometer with Humidity Correction and Audible Sound Thermometry

Lukáš Ondraczka
Department of Measurement
CTU in Prague - FEE
Prague, Czech Republic
ondralu3@fel.cvut.cz

Abstract **– This paper presents portable ultrasonic thermometer developments in humidity and transducer inertia correction. It describes humidity effect on the speed of sound and a method for its correction. Transducer inertia is also described and shown on real measurements, along with a corrective method. Experimental measurement results are presented. Also, audible sound thermometry and its potential advantages and drawbacks are discussed and a simple audible sound preliminary measurement is conducted.**

Keywords-ultrasound; acoustic thermometry; air temperature measurement; audible sound; humidity; inertia

I. INTRODUCTION

This work deals with ultrasonic temperature measurement. It follows up the paper [1], which dealt with general ultrasonic thermometry state-of-the-art study and ultrasonic thermometer development and testing. However, the thermometer in [1] had several drawbacks. It could not do a humidity correction, the transducer inertia caused a delay, which had to be precisely estimated, it had low measuring distance and precision was unsatisfactory in general. This work's aim is to analyze these drawbacks, find a suitable solution and test it in practice while preserving the system portability. The author believes this approach can make the ultrasonic thermometry more suitable for industrial or even home applications.

Ultrasonic thermometry utilizes sound speed dependency on the temperature. Generally, the sound speed rises with square root of temperature in gases, linearly in liquids and falls with rising temperature in solid materials. Thermometer in this work deals with air temperature measurement in the range of -20 to 50 °C.

Sound speed is determined from known propagation distance s and measured propagation time t (1). Propagation distance can be affected by the thermal stretching of the thermometer, therefore a material with low and known thermal expansion coefficient improves measurement accuracy.

$$v = \frac{s}{t} \tag{1}$$

Ultrasonic thermometry measures mean temperature along ultrasound propagation path.

Please refer to our previous work for ultrasonic measurement applications, state-of-the-art, etc. This paper focuses only on new developments in our research.

II. HUMIDITY AND TRANSDUCER INERTIA CORRECTION

A. Humidity Impact on Ultrasonic Thermometry

Humidity affects sound speed. Higher humidity causes lower air density and consequently higher sound speed:

$$c = \sqrt{\gamma \cdot \frac{p}{\rho}} \tag{1}$$

Where c is sound speed, γ is adiabatic index (1.4 for air), ρ is the air density (affected by humidity) and p is atmospheric pressure.

If not corrected, system interprets the sound speed increase caused by humidity as sound speed increase caused by higher temperature. This error is more pronounced in temperatures over 50 °C, where the humidity has bigger impact on sound speed. This can be clearly seen in Fig. 1 from the paper [3].

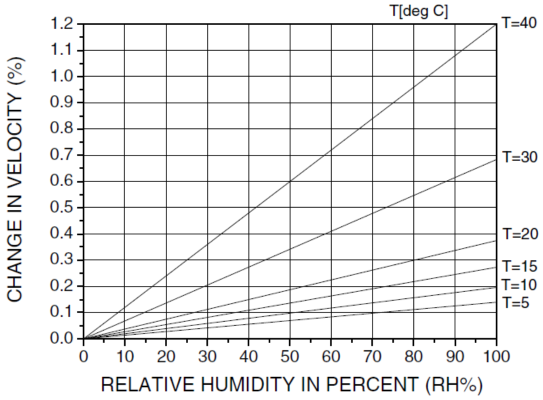

Figure 1. Real gas sound speed correction factor vs Relative Humidity at various temperatures (from [3])

ISBN 978-80-261-0722-4, © University of West Bohemia, 2018

B. *Humidity Correction*

Humidity correction is necessary for precise ultrasonic thermometry measurement. Our approach was to use humidity sensor to get the humidity value and introduce ultrasound speed corrections in order to estimate the temperature value accordingly.

Sound speed calculation in humid air is based on (1). Humid air density can be calculated using (2). It is taken from [5] and simplified by calculating with compressibility factor *Z*=1 and enhancement factor f=1. These factors are very close to 1 in reality [6] [7] and can be neglected in our case.

$$\rho = \frac{p - RH \cdot p_{sat}}{R_{air} \cdot T} + \frac{RH \cdot p_{sat}}{R_{water\,vapor} \cdot T} \qquad (2)$$

Here R_{air} is gas constant of air (287.058 J·kg^{-1}·K^{-1}), p_{sat} is saturated water vapor pressure, $R_{water\ vapor}$ is gas constant of water vapor (461.52 J·kg-^{1}·K^{-1}) and *RH* is relative humidity (0-1). *T* is temperature in K.

Saturated water vapor pressure can be calculated by several approaches. In our work, we use Buck equation from [7], depicted in (3).

$$p_{sat} = 0.61121 \cdot e^{\left(18{,}678 - \frac{T}{234{,}5}\right) \cdot \left(\frac{T}{257{,}14 + T}\right)} \qquad (3)$$

where p_{sat} is in kPa and *T* is in °C.

Using these equations, it is possible to estimate and compensate humidity effect on the sound speed.

Important fact is that the sound speed is no longer independent of the atmospheric pressure as was in case of dry air, where the pressure effect cancelled out (4):

$$c = \sqrt{\gamma \cdot \frac{\cancel{p}}{\frac{\cancel{p}}{R_{air} \cdot T}}} = \sqrt{\gamma \cdot R_{air} \cdot T} \qquad (4)$$

C. *Transducer Inertia*

Piezoelectric transducers do not respond instantly. They display starting and ending inertia that have impact on measurement. It is necessary to precisely calculate delay caused by inertia in applications with threshold detection. Effective way to solve this problem is to produce two independent echoes and measure difference in ultrasonic time of flight between them. With both signals suffering from the same transducer inertia, the delay cancels out.

Our thermometer's inertia effect can be seen in the Fig. 2. It shows transducer starting (energizing) pulse in the upper trace and raw received pulses (echoes), measured directly on the transducer in the lower trace.

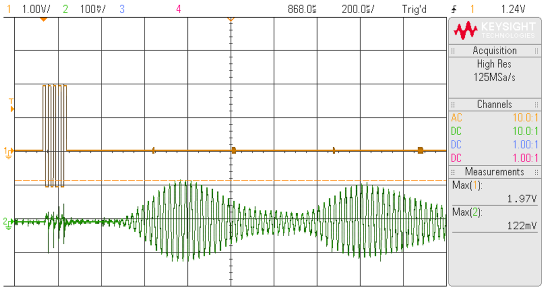

Figure 2. Transducer inertia effect

It is difficult to capture the first received ultrasonic period drowned in noise and detection threshold is usually pre-set somewhere in the middle of the rising signal maximum amplitude in practical applications with threshold detection method. The response delay is subtracted from the measured time. However, it is possible to measure the delay between multiple similar echoes produced by appropriate system of targets. In the case of our thermometer, the echoes are produced by metal sheets installed on stainless steel plate (see Fig. 5). The inertia effect is suppressed, because both echoes suffer from it equally.

III. MEASUREMENTS

We have performed a series of measurements to evaluate the methods mentioned above. First measurements dealt with humidity effect correction.

A. *Measurement with Humidity Correction*

The measurement with humidity correction was performed in a thermal chamber with relatively high humidity (30 – 90%, randomly distributed across the entire temperature range, 10 humidity values out of 13 were between 60 – 90%). The measured temperature before correction was clearly higher with higher humidity, especially on higher temperatures, as expected. With correction according to formulas mentioned in Chapter II. B, the results were much better. Fig. 3 shows the measurement results.

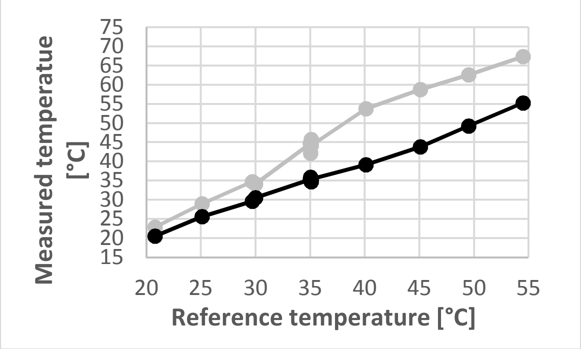

Figure 3. Humidity correction result (light – measurement without humidity correction, dark – measurement with humidity correction)

Maximum measurement error was -1.3 °C and standard deviation was 0.60 °C.

B. *Measurements with Transducer Inertia Correction*

1) *Thermometer Upgrade*

In order to be able to correct transducer inertia effect, our thermometer had to be upgraded accordingly.

We have made several adjustments in the thermometer mechanics, hardware and software.

The polypropylene waveguide was replaced by a stainless steel plate. The thermometer got smaller possible error coming from thermal expansion because the thermal expansion coefficient was reduced from 160 ppm/K (for PP) to 13 ppm/K (Steel). Numerical correction in SW is still important, but any possible errors coming from it are much smaller. The plate has two metal reflectors, in 31 cm and 54 cm distance (see Fig. 5). The reflectors produce echoes of similar amplitude, because the first reflector is much smaller in dimensions.

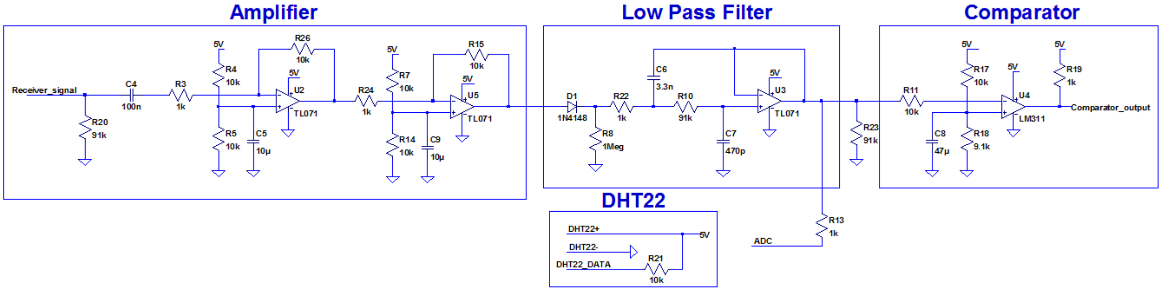

Figure 4. Upgraded receiver circuitry

Receiver circuitry had to be upgraded to correctly respond to both echoes, correctly deal with smaller received signal amplitude, read reference temperature and humidity values and feed data to ADC. New receiver circuitry can be seen in the Fig. 4. LM7805 circuit is used as 5 V reference source.

Humidity meter DHT-22 for Arduino was implemented to provide humidity data for our system. This module also provides a temperature information, which can be used as simple approximate reference in situations without any laboratory reference thermometers with better precision.

Mechanical thermometer concept can be seen in the Fig. 5. A microcontroller measures time delay between the echo from the metal sheet 1 and the echo from metal sheet 2. This can be observed in the Fig. 6, where the measured time delay is marked by the double-headed arrow (number 3).

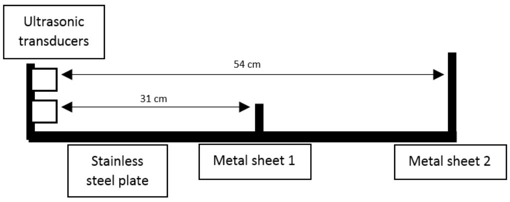

Figure 5. New ultrasonic thermometer concept

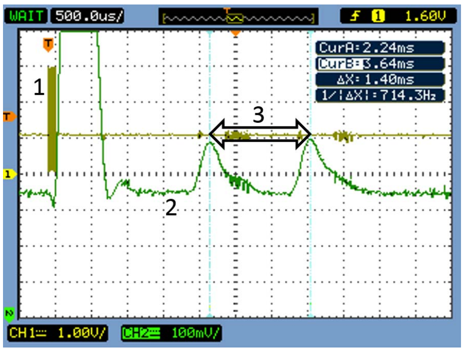

Figure 6. Transmitted signal (1), Received signal (2) and time delay between echoes (3) shown on an oscilloscope

2) *Measurement in Variable Temperature*

Thermometer performance was evaluated outdoor. The ultrasonic system measured 9 temperature-related-time values:

- First and second echo trigger detection by comparator circuit and their difference
- First and second echo maximum detection by ADC and their difference
- First and second echo rising edge detection by ADC and their difference

The measurement duration was 609 minutes (start at 19:25 and end at 5:34) and temperature range 11 – 23 °C. The system measured 6685 samples of each temperature value. Measurement was fully automated, values were sent to PC in 5.5 second intervals. Resolution differs with measurement method and propagation distance (trigger detection method resolution is 0.02 °C in the case of second echo and 0.05 °C in the case of echo difference, ADC resolution is 0.05 °C – 0.13 °C). The environment parameters were not controlled and readings from DHT22 thermometer/hydrometer were used as a reference. DHT22 has maximum errors of ±0.5 °C (temperature) and ±5 % (humidity).

Mean error values are shown in Table 1.

TABLE I. MEASUREMENT RESULTS

Measurement results		**Trigger detection**	**ADC Max detection**	**ADC rising edge detection**
Mean error [°C]	***Echo 1***	0,83	2,52	0,81
	Echo 2	0,29	2,64	0,45
	Echo Difference	1,06	9,28	0,51

ADC Max detection was the least precise method. Peak is probably not sharp enough to provide accurate value.

Trigger detection and ADC rising edge detection methods had both satisfactory results. Best precision was achieved with second echo measurement, probably because of the longest propagation distance. Echo difference measurements were less precise. However, transducer inertia delay time did not need to be determined before these measurements, since it cancels out in calculation. In the case of echo 1 and 2 measurements, the delay time had to be precisely measured by oscilloscope once during thermometer assembly.

Fig. 7 shows echo 2 measurement results and Fig. 8 shows echo 2 error distribution.

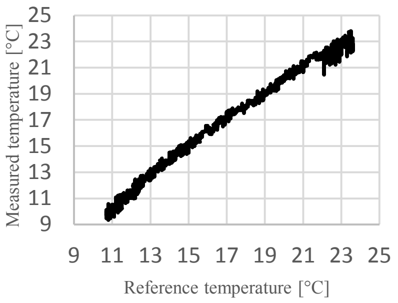

Figure 7. Echo 2 measurement results

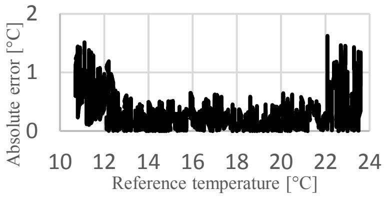

Figure 8. Echo 2 error distribution

IV. AUDIBLE SOUND THERMOMETRY

Important ultrasonic thermometry drawback is a limited transmission distance. Sound attenuation in air rises with higher sound frequency [8]. With audible sound, higher measurement distances can be reached. This allows measurement in more applications and possibly lower error, because the imperfections in signal processing causes smaller relative difference. Disadvantage is the audible thermometer loudness, compared to ultrasonic thermometer. Another disadvantage lies in higher noise levels from disturbance sources in environment present on audible sound frequency range.

A. State-of-the-Art

Audible sound thermometry is already under research in several applications. For example, the papers [9] and [10] deal with audible sound thermometry using tubes filed with argon in high temperature environments. The authors had a 13 °C maximum error in raw values, but estimated an error of ±2 °C after proper sensor calibration, on temperatures up to 1000 °C high.

B. Preliminary Testing

Simple test with Audacity free software was performed. A 1 kHz sound signal was sent across 5 m distance and audacity record from microphone was observed (44.1 kHz sample rate, cell phone speaker and microphone integrated in laptop). As can be seen in the Fig. 9, the signal has acceptable SNR on this distance and is easily detectable by a proper system.

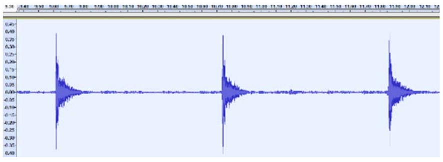

Figure 9. Signal detected by Audacity software

V. CONCLUSION

Humidity and transducer inertia effects on ultrasonic thermometry measurements were evaluated and methods for their compensation were presented.

The humidity correction measurements showed good performance with maximum error of 1.43 °C and standard deviation 0.60 °C. The humidity effect was clearly visible thanks to high humidity environment and the method for humidity compensation successfully corrected the results. As was expected, the improvement was higher on higher temperatures (12.1 °C on 55 °C vs 2.4 °C on 21 °C). In low humidity environments, the humidity correction impact declines.

Transducer inertia correction method was tested in outdoor environment with DHT22 sensor used as a reference. The method successfully excluded the delay time caused by transducer inertia from the calculation, and so the delay does not need to be measured by oscilloscope anymore. Precision was lower in comparison with single echo method, probably because higher distance provides higher resistance to noise (propagation time changes more with temperature and noise causes lower relative difference). The propagation distance difference between second echo and echo difference is 108 cm vs 46 cm.

Audible sound thermometry was investigated and promising preliminary test was performed. We hope the measurement on higher distance can improve the precision of our thermometer.

ACKNOWLEDGMENT

Research described in the paper was supervised by doc. Ing. A. Platil, Ph.D., FEE CTU in Prague and supported by the Czech Technical University in Prague.

REFERENCES

[1] L. Ondraczka and T. Ondraczka, “Ultrasonic thermometry study and portable ultrasonic thermometer prototype,” 2017 International Conference on Applied Electronics (AE), September 2017, pp. 143-148

[2] E. A. Dean, “Atmospheric Effects on the Speed of Sound,” Report for Atmospheric Sciences Laboratory, 1979, pp. 1-60.

[3] W. Tsai, H. Chen, T. Liao, “An ultrasonic air temperature measurement system with self-correction function for humidity” Meas. Sci. Technol. 16, 2005, pp. 548-555.

[4] D. A. Bohn, “Environmental Effects on the Speed of Sound”, J. Audio Eng. Soc. Vol. 36, No. 4, 1988, pp. 223-231.

[5] Picard, R S Davis, M Gläser and K Fujii, “Revised formula for the density of moist air (CIMP-2007)”, Metrologia, Vol. 45, 2008, pp. 1554–1566.

[6] R. H. Perry and D. W. Green. “Perry's chemical engineers' handbook”. New York: MCGraw-Hill. 1984, pp. 3-162.

[7] A. L. Buck, “New Equations for Computing Vapor Pressure and Enhancement Factor”, J. Appl. Meteor., Vol. 20, pp. 1527-1532.

[8] A. Vladišauskas, I. Jakevičius, “Absorption of ultrasonic waves in air”, Ultragargas, Nr. 1(50), 2004, pp. 46-49.

[9] M. de Podesta, G. Sutton, R. Underwood, S. Legg, and A. Steinitz, “Practical Acoustic Thermometry with Acoustic Waveguides,” Int J Thermophys, 2010, pp. 1554–1566.

[10] M. de Podesta, G. Sutton, G. Edwards,L. Stanger, and H. Preece, “Practical Acoustic Thermometrywith Twin-Tube and Single-Tube Sensors,” in 4th International Conference on Advancements in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA), 2015, pp. 1-6.