New implementation of high-precision and instant-response air thermometer by ultrasonic sensors

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Received 12 December 2003; received in revised form 1 June 2004; accepted 1 June 2004
Available online 21 July 2004

Abstract

In this article, a new single-chip microprocessor-based, non-contact thermometer with high-precision and instant-response is proposed. It uses ultrasonic sensors made of piezoelectric devices to detect changes of the speed of sound in the air and calculate the temperature of the bulk air. The changes of speed of sound are computed from combining two variations, time-of-flight (TOF) from a binary frequency shift-keyed (BFSK) ultrasonic signal and phase shift from two frequency continuous waves (TFCW). This technique can work in a wider range than using phase shift alone and is more accurate than TOF. In our experiment, in a temperature-controlled chamber, we placed two 40 kHz ultrasonic sensors face to face with a fixed distance in between. We use BFSK signals and TFCW of 40 kHz and 42 kHz. A single-chip microprocessor-based signal generator and phase detector are used to record and calculate TOF, phase shift and temperature. The calculated results of temperatures are then sent to either an LCD display or to a PC for calibration and examination. In a proof-of-concept experiment, it is accurate to ±0.3 °C from 0 °C to 60 °C with 0.05% resolution and temperature changes are instantly reflected within 100 ms. The advantages of our system are high accuracy, instant detection, non-contact, low cost and easy implementation.

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Keywords: Ultrasonic sensors; Thermometer; Time-of-flight; Binary frequency shift-keyed signal; Microprocessor

1. Introduction

Many techniques have been studied to measure temperature of gas. Various electronic transducers such as the thermistor, thermocouple, and thermopile can detect and measure temperature with good outcomes. These transducers require direct physical contact with the gas being measured.

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The speed of sound in gas has been extensively explored and it is concluded that propagation sound wave are extremely sensitive to atmospheric changes [1,2]. The theoretical expression for the speed of sound $c$ in an ideal gas is:

$$c = \sqrt{\frac{\gamma P}{\rho}}$$  \hspace{1cm} (1)

where $P$ is the ambient pressure, $\rho$ the gas density, and $\gamma$ the ratio of the specific heat of gas at constant pressure to that at constant volume. Moreover, the term $\gamma$ is dependent upon the number of degrees of freedom of the gaseous molecule. The number of degrees of freedom depends upon the complexity of the molecule. Some standard values of $\gamma$ are given below: $\gamma = 1.67$ for monatomic molecules; $\gamma = 1.40$ for diatomic molecules; $\gamma = 1.33$ for triatomic molecules.

Since air is composed primarily of diatomic molecules, the speed of sound in air is:

$$c = \sqrt{\frac{1.4P}{\rho}}$$  \hspace{1cm} (2)

The velocity of sound $c$ in dry air has the following experimentally verified values:

$$c = 331.45 \pm 0.05 \text{ m/s}$$

at 0 °C and 1 atm (760 mmHg) with 0.03 mol% of carbon dioxide.

Substituting the equation of state of air of an ideal gas ($PV = RT$) and the definition of density $\rho = MV$ (mass per unit volume), Eq. (2) may be rewritten as:

$$c = \sqrt{\frac{1.4RT}{M}}$$  \hspace{1cm} (3)
where $R$ is the universal gas constant, $T$ is the absolute temperature, and $M$ is the mean molecular weight of the gas at sea level.

Eq. (3) reveals the temperature dependence and pressure independence of the speed of sound. An increase in pressure results in an equal increase in density. Therefore there is no change in velocity due to a change in pressure. But this is true only if the temperature remains constant. Temperature changes cause density changes which do not affect pressure. Thus density is not a two-way street. Changes in pressure affect density but not vice versa. Humidity also affects density, causing changes in the velocity of sound.

Since $R$ and $M$ are constants, the speed of sound may be shown to have a first-order dependence on temperature as follows:

$$c = \frac{R}{M} \sqrt{T}$$

where $T$ is the temperature in kelvins and $C_0$ equals the reference speed of sound under defined conditions.

The speed of sound is seen to increase as the square root of the absolute temperature. Substituting centigrade conversion factors and the reference speed of sound gives:

$$c = 331.45 \sqrt{\frac{T}{273.15}}$$

where $T_c$ is the temperature in °C. This is why using the speed of sound to calculate the average air temperature on the propagation path is a widely adopted measurement technique.

Conventionally, most of the ultrasonic techniques to measure average air temperature are based on Phase-Echo operation in which distance is calculated from TOF measurement [5,6]. Dividing the distance between transmitter and receiver by the time taken by the ultrasonic pulse to travel over this distance would result in the average speed of sound between transmitter and receiver. And because the speed of sound changes right as the air temperature changes, we can calculate the temperature (in absolute temperature °K) of the air or other known material on the propagation path. Sound of low frequency is more often used in range between 100 m and 1400 m because higher frequency attenuates more quickly with distance [7]. Distances between 10 cm and 100 cm are considered as in the low end of adequate range in TOF technique and thus can result in high errors.

A more accurate measurement can be conducted by comparing data from phase shift of transmitted/received high-frequency continuous waves [8]. On the propagation path with different air temperatures, the phase shift relates to the change in the speed of sound assuming the distance is constant. One of the benefits of high-frequency is that it can accommodate many repeated measurements over a period of time when low frequency can only have one sampling. Phase shift operation offers a special advantage by eliminating a class of attenuation problems that often accompany short-burst transmissions which go through nonlinear signal distortion during start up as a result of transmitting transducer mechanical spring coefficients producing audio signals with slow-onset envelopes. The slow onset makes the exact signal start time unclear to the receiver. Continuous wave transmission has the similar start/stop envelope problems. But during continuous operation these problems are gone. So in an environment where distances are short, a more accurate temperature measurement can be produced by combining the calculations of the TOF and phase shift [9–11].

In this paper, the changes of speed of sound are computed from combining two variations, time-of-flight (TOF) from a binary frequency shift-keyed (BFSK) ultrasonic signal and phase shift from two frequency continuous waves (TFCW). This developed technique can work in a wider range than using phase shift alone and is more accurate than TOF. In our experiment, in a temperature-controlled chamber, we placed two 40 kHz ultrasonic transducers face to face with a fixed distance in between. We use BFSK signals and TFCW of 40 kHz and 42 kHz. A single-chip microprocessor-based signal generator and phase detector are used to record and calculate TOF, phase shift and temperature.

The paper is organized as follows. In Section 2, we describe the ultrasonic temperature measurement method in detail. In Section 3, we describe the system implementations including the hardware modules and software flowchart. In Section 4, we present the experimental results of the proposed ultrasonic temperature measurement system. Finally, some conclusions are presented in Section 5.

2. Method

The ultrasonic temperature measurement system is shown in Fig. 1. The ultrasonic transmitter is placed by the right side of the chamber and the receiver the left side with 100 cm distance in between. We can measure the average temperature of air in the chamber.

2.1. Transmitter and receiver

The transmitted and received signals are shown in Fig. 2. $S_t$ is the transmitting signal from BFSK. It has two frequencies $f_1$ and $f_2$ as shown in Fig. 2(a). $T_1$ is the period of $S_t$. $S_r$ is the received signal corresponding to the transmitted signal in Fig. 2(b).

2.2. TOF calculation

In Fig. 2 the elapsed time $\Delta t$, which is the travel time of the signal from the transmitter to the receiver, can be calculated as $\Delta t = t_2 - t_1$ where $t_1$ is the time when transmitted signal changes frequency from $f_1$ to $f_2$, and $t_2$ is the time when the corresponding received signal changes frequency from $f_1$ to $f_2$. The speed of sound can be expressed as $c = d/\Delta t$, where $d$ is the distance between two transducers.
2.3. Phase shift detection

Two frequency continuous wave (TFCW, also called the two-tone method) is based on the concept that the differential phase shift of two simultaneously propagating waves of different frequencies will generate progressively larger phase shifts, the value of which increases being constant \( \frac{\pi}{p} \), as the travel time or corresponding distance of travel increases. By detecting the two signals at some distance, and knowing the original starting time of each or knowing that they both started at the same time, measured phase shift \( \phi \) can be divided by \( \frac{\pi}{p} \), yielding the number of wave periods which have occurred to generate the measured phase difference, and, given a constant velocity, the distance can then be calculated. This relation is summarized in Fig. 3.

The detection of the phase shift is based on TFCW [12,13]. The method underlying TFCW is as follows. The first frequency \( f_1 \) continuous wave is transmitted from an ultrasonic transducer. The first phase shift \( \phi_1 \), transmitted signal relative to received signal, is calculated by digitized phase information. When the first frequency’s transmission/reception/computation period is completed, the second frequency \( f_2 \) continuous wave is transmitted, yielding the second phase shift \( \phi_2 \). The following will calculate the distance by comparing the two phase shifts. Note the distance between transmitter transducer and receiver transducer remains unchanged.

\[
d = \left( n_1 + \frac{\phi_1}{2\pi} \right) \times \lambda_1 \tag{6}
\]

and

\[
d = \left( n_2 + \frac{\phi_2}{2\pi} \right) \times \lambda_2 \tag{7}
\]

here, \( d \) is the distance between the receiver and the transmitter, \( \lambda \) is the wavelength of the ultrasound, \( n \) is an integer, and \( \phi \) is the phase shift. The expression for the difference of the phase shift due to the difference of the wavelength may be derived from Eqs. (6) and (7) as follows:

\[
d \times \left( \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) = \frac{\Delta \phi}{2\pi} \tag{8}
\]

the integers \( n \) have only two possible values: \( n_1 = n_2 \) and \( n_1 = n_2 + 1 \). So the difference of the phase shifts can be defined by the following algorithm:

1. if \( \phi_1 > \phi_2 \), \( \Delta \phi = \phi_1 - \phi_2 \).
2. if \( \phi_1 < \phi_2 \), \( \Delta \phi = \phi_1 + 2\pi - \phi_2 \).

If the velocity of ultrasound is constant, say \( c \), the wavelength \( \lambda \) can be determined as follows:

\[\lambda_2 = \frac{c}{f_2}, \quad \lambda_1 = \frac{c}{f_1}\]

here, \( f_1 \) and \( f_2 \) are the ultrasonic frequency. From Eq. (8), the ranging distance can be expressed as:

\[
d = \frac{\Delta \phi}{2\pi} \times \frac{c}{\Delta f} \quad \Delta f = f_1 - f_2 \tag{9}
\]
Eq. (9) is similar to Eq. (6). The ranging distance $d$ can be uniquely determined by difference of the phase shifts, $\Delta \phi$ ($\Delta \phi = \phi_1 - \phi_2$) if the maximum fluctuation does not exceed one period of the frequency difference ($\Delta f$). Otherwise a phase ambiguity will occur. The minimum resolution and the maximum range are determined by the choice of frequencies $f_1$ and $f_2$.

2.4. Temperature calculation

Temperature calculation is explained as follows. The distance $d$ can be expressed as $d = c \times \Delta t$ where $\Delta t$ is TOF. In Fig. 4(b), distance $d$ is divided into regions $\{k-1\}l_x, kl_x$ ($k = 1, 2, 3, \ldots$), $l_x$ is the wavelength of $\Delta f$. The distance $d$ can be expressed as $d = (k-1) + \Delta \phi/2\pi \times c/\Delta f$ where $k$ is an integer. The region defined by $\{k-1\}l_x, kl_x$ is called $k$ region. The $k-1$ integer can be obtained by an integer operation $\lfloor \Delta t \times \Delta f \rfloor$. The distance can then be expressed as:

$$d = \lfloor \Delta t \times \Delta f \rfloor + \Delta \phi/2\pi \times c/\Delta f$$

and the speed of sound is then:

$$c = \lfloor \Delta t \times \Delta f \rfloor + \Delta \phi/2\pi \times 1/\Delta f$$

From Eq. (5) we know the temperature is:

$$T = 273.15 \times \left( \frac{c}{(131.43)^2} - 1 \right)$$

The above computation algorithm can be conveniently developed into a digital microprocessor system to detect the air temperature with advantages such as high accuracy and low cost.

3. System implementation

Fig. 1 shows the block diagram of the ultrasonic temperature measurement system which consists of a temperature-controlled chamber, a thermometer made of thermocouple, two acoustic transducers with matching exponential horns, a signal generation system, power amplifier, preamplifier and gain-controlled system, frequency detected system, and digital phase meter. A microprocessor controls the operation of the entire system and a PC will examine the measurement result and do calibration.

3.1. Hardware

The system operation can be divided into six parts. Each is explained as follows.

3.1.1. Transmitted signal source

The transmitted pulse is made up by two sinusoids (40 kHz and 42 kHz). Fig. 5 shows a crystal oscillator circuit is used to generate a steady signal with a base frequency of 80 MHz. The divisors of two dividers are set at 2000 and 1904 which is applied to the base frequency. Two frequencies 40 kHz and 42 kHz are then produced and sent to the multiplexer (MUX). The MUX is controlled by an 89c51 microprocessor. The output of the MUX is a BFSK signal which is similar to the transmitted signal shown in Fig. 2(a). The BFSK signal is generated in digital form and delivered to the power amplifier to provide as a 40 kHz ± 12 V, 42 kHz ± 12 V source signal to the transmitter transducer.

3.1.2. Preamplifier and gain-controlled amplifier

The bandwidth of the ultrasonic transducers used in our system is narrow. To reduce error from acoustic attenuation, the gain of the amplifier must dynamically adjust as the frequency of the ultrasound changes. Therefore the error incurred from acoustic attenuation is minimized in the gain-controlled amplifier by keeping the received signal amplitude dynamically constant. A voltage comparator is used to convert the signal into square wave which is then made TTL compatible by a 0–5 V limiter circuit. This TTL compatible square wave is then sent to frequency detector and digital phase meter.

3.1.3. Frequency detector

Fig. 6 shows the block diagram of the frequency detector. The frequency detector detects the time when frequency of received signal changes from $f_1$ (40 kHz) to $f_2$ (42 kHz). The detected time is then used by the microprocessor to calculate TOF. Two counters are designed to distinguish the $f_1$ and $f_2$ frequency. The clock of counter #1 is the output of
an AND gate with the input of 80 MHz clock and the TTL compatible square wave received signal. If the counted value of counter #1 is around 1000, then the frequency of the received signal is determined as 40 kHz, and the value around 952 corresponding to 42 kHz. Counter #2 is used to latch and reset counter #1 and interrupt the 89c51 microprocessor.

3.1.4. Digital phase meter

The phase shift is transformed into pulse width by two D-type flip-flops, as shown in Fig. 7. A 80 MHz signal is used to count the pulse width. The resolution of the phase meter is 0.05% for a 40 kHz signal. Finally, the counter is cleared by a reset signal generated by the microprocessor for counting the next phase shift.

3.1.5. 89c51 single-chip microprocessor

Our system is controlled by an 89c51 single-chip microprocessor (Atmel, USA). The functions of the microprocessor include controlling the BFSK signals of the ultrasound, obtaining the digital phase shift data, calculating the TOF and the air temperature and displaying it.

3.1.6. Calibration system

As shown in Fig. 1, a chamber with constant temperature inside has an internal fan to maintain the inside air temperature uniform. A thermocouple measures the air temperature inside the chamber. The thermocouple voltage is converted into temperature reading with a Testo 946 thermometer. The accuracy in the specification of this instrument is said to be ±0.2 °C. We use an ice-water bath to check the accuracy. The difference from the actual temperature at 0 °C was +0.1 °C within the claimed accuracy. The output of the thermometer is sent to PC used as the standard temperature. Therefore, PC has Δt of the elapsed time of the ultrasound, phase shift data and the temperature measured by thermocouple. From these data, PC can calculate the errors of the temperature measurement and build up a calibration system.

3.2. Software

The algorithm of the software program in the microprocessor can be explicated by the flowchart shown in Fig. 8. First, the 89c51 microprocessor will fetch the actual temperature $T_1$ measured by thermocouple from the PC. Next, it will assign the transmitted signal, adjust the gain-controlled amplifier, wait for the interrupt from either the frequency detector or digital phase meter to calculate the TOF, obtain $\phi_1$, $\phi_2$ and calculate the temperature $T_2$. Then, it will compare $T_1$ with $T_2$. If $|T_2 - T_1| > 1$ °C, it will display $T_2$ on the LCD. Otherwise, PC will re-calculate according to the temperature data and environmental variables from the calibration system. If the waiting time is longer than 50 ms, 89c51 will reassign the transmitted signal. TOF, $\phi_1$ and $\phi_2$ are all sent to the PC via RS232 interface of the 89c51.

4. Ultrasonic experiment

Through the single-pass mode of BFSK signals and continuous waves, we explored the feasibility of measuring air temperature by the speed of sound in our laboratory.
Fig. 1 shows the block diagram of the experiment setup for ultrasonic temperature measurement. We use a chamber with constant air temperature to control the temperature. In this temperature-controlled chamber, a transducer is placed at the right side. This transmitter transducer will generate ultrasonic pulses of BFSK and TFCW that will be received by the transducer located at the left side of the chamber.

To collect data, we first measure the air temperature in the chamber with thermocouple. Secondly, for three times we record the TOF of the BFSK ultrasonic pulse in the chamber, the $\varphi_1$ and $\varphi_2$ from TFCW. Then, we measure the air temperature with the thermocouple for the second time. Finally, we compare the average of the three TOF, $\varphi_1$ and $\varphi_2$ measurements with the average of the two thermocouple measurements. Both can represent the air temperature at the same point of time, i.e. halfway through the measurement cycle. From 0°C to 60°C with 1°C as the interval, we will repeat the measurement and record the data at different temperatures. Using this measurement system and calculating the speed of sound with Eq. (11), we can obtain the average temperature of the air on the propagation path.

5. Results

Fig. 9 shows a logged data graph of the elapsed time and the actual temperature measured by thermocouple, from 0°C to 60°C. From the graph, we know TOF decreases as the temperature rises. That is the speed of sound increases as the temperature rises. Eq. (1) explains this is because air density decreases as the temperature rises. Fig. 10 shows a logged data graph of the differences of two-frequency phase shifts ($\Delta \varphi$) when the temperature rises from 0°C to 60°C. Fig. 11a shows the graph of the actual temperature measured by thermocouple, and logs the temperature data calculated by our ultrasonic system, from 0°C to 60°C. The errors between the actual temperature from thermocouple and the ultrasonic measurement are shown in Fig. 11b. The Standard Error of measurement is calculated as follows:

$$SE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (RP(i) - PP)^2}$$

(13)

where $RP$ is temperature of the ultrasonic measurement, $PP$ is the temperature measured by thermocouple, $n$ is the number of measurements. The average error is 0.19°C and the standard error is 0.23°C. Through repeated experiments, if temperature is under 60°C, the difference of ultrasonic measurement and the actual temperature consistently remains within ±0.3°C.
and the actual temperature from thermocouple is the agreement between the calculated ultrasonic temperature and the average air temperature. At low temperatures, the accuracy and speed of the ultrasonic measurement is more than adequate for average temperature-controlled systems, and the phase shifts are calculated using a counter technique to avoid the limitation by the amplitude of the signal and the finite bits of the A/D converter.

In our experiment, we have demonstrated that an ultrasonic transducer and our hardware system can accurately measure the average air temperature. At low temperatures, the agreement between the calculated ultrasonic temperature and the actual temperature from thermocouple is ±0.3°C with the ultrasonic measurement repeated at 0.1 s intervals. The accuracy and speed of the ultrasonic measurement is more than adequate for average temperature-controlled systems. However, the agreement begins to fail above 60°C. When temperature is higher than 60°C, the error will increase due to the ultrasonic transducers are less efficient at elevated temperatures, so the detected waveform decreases in amplitude as the temperature increases.

6. Conclusions

We have presented a new implementation of high-precision and instant-response air thermometer by ultrasonic sensors. This system successfully combines the techniques of TOF and phase shift. It uses BFSK transmitted signal. Upon receiving the ultrasonic pulse, the approximate value of TOF is calculated by the time when the change between each discrete frequency occurs. Two phase shifts between the transmitting and receiving continuous wave signals are calculated to achieve higher accuracy. The phase shifts are calculated for amplitude of the signal and the finite bits of the A/D converter.

In our experiment, we have demonstrated that an ultrasonic transducer and our hardware system can accurately measure the average air temperature. At low temperatures, the agreement between the calculated ultrasonic temperature and the actual temperature from thermocouple is ±0.3°C with the ultrasonic measurement repeated at 0.1 s intervals. The accuracy and speed of the ultrasonic measurement is more than adequate for average temperature-controlled systems. However, the agreement begins to fail above 60°C. When temperature is higher than 60°C, the error will increase due to the ultrasonic transducers are less efficient at elevated temperatures, so the detected waveform decreases in amplitude as the temperature increases.

References


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