Environment Temperature Monitoring System

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***Abstract*—In this article, an environment temperature monitoring system with binary frequency shift-keyed (BFSK) ultrasound is proposed. It uses the ultrasonic measurement of the changes in speed of sound in the air to determine the temperature of bulk air. The changes in speed of sound are calculated by combining time-of-flight (TOF) and phase shift techniques. This method can work in a wider range than using phase shift alone and is more accurate than TOF scheme. The system consists of a micro-computer, two-frequency ultrasound generator, power amplifier, pre-amplifier, gain-controlled amplifier, digital phase meter, and phase shift converter.**

***Keywords*—Time-of-flight, Phase Shift, Binary Frequency Shift-keyed**

1. INTRODUCTION

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

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

where P is the ambient pressure , ρ the gas density , and γ the ration of the specific heat of gas at constant pressure to that at constant volume. Moreover, the term γ 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 γ 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

$$c = \sqrt{\frac{1.4P}{\rho}} \quad (2)$$

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

$c = 331.45 \pm 0.05$ m/s

at $0^{\circ}C$ and 1 atm(760 mm Hg) 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 $\rho = \frac{M}{V}$ (mass per unit volume), Eq. (2) may be rewritten as

$$c = \sqrt{\frac{1.4RT}{M}} \quad (3)$$

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:

$$c = C_0 \sqrt{\frac{T}{273.15}} \quad (4)$$

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

$$c = 331.45\sqrt{1+\frac{T_c}{273.15}} \qquad (5)$$

where T_c is the temperature in degrees Celsius. This is why using the speed of sound to calculate the average air temperature on the propagation path is a widely adopted measurement technique [3, 4].

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 combing the calculations of the TOF and phase shift [5-7].

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.

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

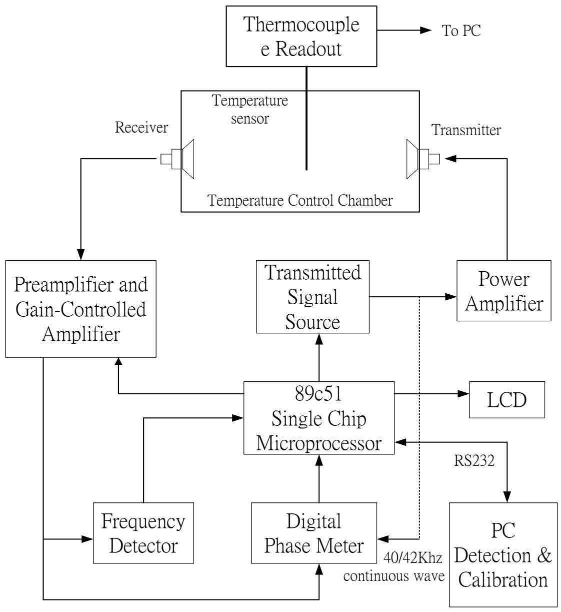

Fig. 1. Block diagram of the ultrasonic temperature measurement system.

two frequencies f_1 and f_2 as shown in Fig. 2. T_r is the period of S_T. S_R is the received signal corresponding to the transmitted signal in Fig. 2.

2.2. TOF Calculation

In Fig. 2 , the elapsed time Δt , 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 and 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 this increases being constant ($1p$), 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 (np) can be divide by ($1p$), 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.

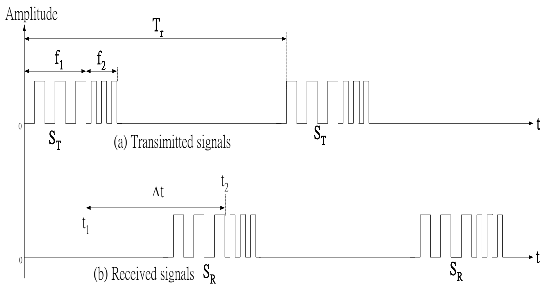

Fig. 2. Transmitted signals and received signals.

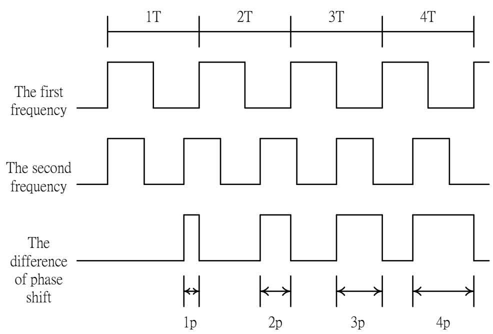

Fig. 3. The description of the TFCW waveforms .

The detection of the phase shift is based on TFCW [8,9]. The method underlying TFCW is as follows. The first frequency (f_1) continuous wave is transmitted from an ultrasonic transducer. The first phase shift (ϕ_1), transmitted signal relative to received signal, is calculated by digitized phase information. The second frequency (f_2) continuous wave is transmitted, yielding the second phase shift (ϕ_2).

$$d = \left(n_1 + \frac{\phi_1}{2\pi} \right) \times \lambda_1 \qquad (6)$$

and

$$d = \left(n_2 + \frac{\phi_2}{2\pi} \right) \times \lambda_2 \qquad (7)$$

Here d is the distance between the receiver and the transmitter, λ is the wavelength of the ultrasound, n is an integer, and ϕ 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:

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

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 $\phi_1 < \phi_2$, $\Delta\phi = \phi_1 + 2\pi - \phi_2$,

From Eq. (8), the ranging distance can be expressed as

$$d = \frac{\Delta\phi}{2\pi} \times \frac{c}{\Delta f} \ (\Delta f = f_1 - f_2). \ (9)$$

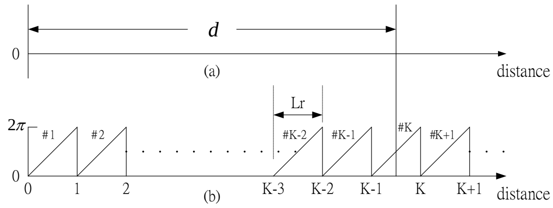

Fig.4. Relation between $d = c * \Delta t$ and $d = (k-1) * Lr + (\Delta\phi / 2\pi) * Lr$.

Equation (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 (Δf). 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 Δt is TOF. In Fig. 4(b), distance d is divided into regions $[(k-1)Lr, kLr]$ ($k = 1,2,3,\ldots$), Lr is the wavelength of Δf . The distance d can be expressed as $d = \left[(k-1) + \frac{\Delta\phi}{2\pi} \right] \times \frac{c}{\Delta f}$ where k is an integer. The region defined by $[(k-1)Lr, kLr]$ is called #k region. The $k-1$ integer can be obtained by an integer operation Int($\Delta t \times \Delta f$). The distance can then be expressed as

$$d = \left[Int(\Delta t \times \Delta f) + \frac{\Delta\phi}{2\pi} \right] \times \frac{c}{\Delta f} \qquad (10)$$

and the speed of sound is then

$$c = \frac{d}{\left[Int(\Delta t \times \Delta f) + \frac{\Delta \phi}{2\pi} \right] \times \frac{1}{\Delta f}} \qquad (11)$$

From Eq. (5) we know the temperature is

$$T = 273.15 \times \left(\left(\frac{c}{331.45} \right)^2 - 1 \right) \qquad (12) \ .$$

3. EXPERIMENTAL RESULTS

Figure 5(a) shows the graph of the actual temperature measured by thermocouple, and logs the temperature data calculated by our ultrasonic system, from $0\,^\circ C$ to $60\,^\circ C$. The errors between the actual temperature from thermocouple and the ultrasonic measurement are shown in Fig. 5(b). The Standard Error of measurement is calculated as follows:

$$SE = \sqrt{\sum_{i}^{n} \frac{[RP(i) - PP]^2}{n}} \qquad (13)$$

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 $^\circ C$ and the standard error is $0.23\,^\circ C$. Through repeated experiments, if temperature is under 60 $^\circ C$, the difference of ultrasonic measurement and the actual temperature consistently remains within $\pm 0.3\ ^\circ C$.

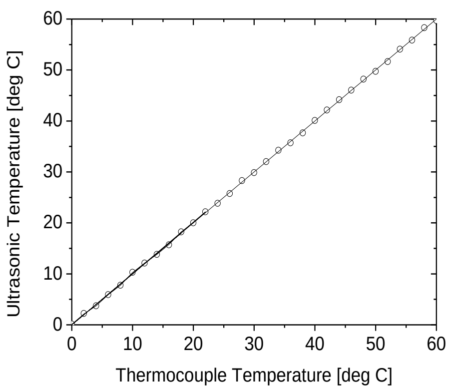

Fig.5(a) .A logged data graph of the actual thermocouple temperature vs. calculated ultrasonic temperature.

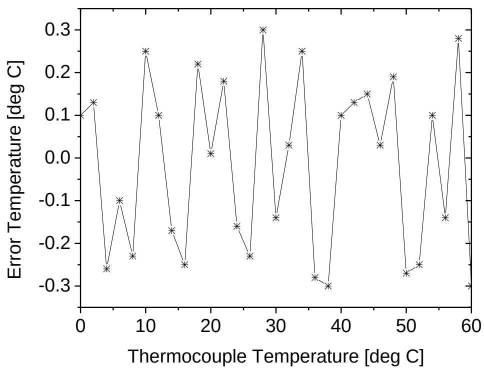

Fig. 5(b). The plot of error temperature.

4. CONCLUSIONS

We have presented an environment temperature monitoring system using a binary frequency shift-keyed (BFSK) ultrasound. 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 transmiting and receiving continuous wave signals are calculated to achieve higher accuracy. 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 $\pm$ 0.3 $^\circ C$ with the ultrasonic measurement repeated at 0.1 sec intervals. The accuracy and speed of the ultrasonic measurement is more than adequate for average temperature-controlled system. However, the agreement begins to fail above $60\,^\circ C$. When temperature is higher than 60 $^\circ C$, 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.

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