Spontaneous and highly accurate ultrasonic temperature measurement system for air conditioner in automobiles

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This paper presents a microprocessor-based, ultrasonic air temperature sensor system whose output controls temperature adjustment of car air conditioner (AC). Perceived thermal comfort correlates better with temperature of bulk air than temperature measured by conventional in-car temperature sensor. It uses ultrasonic measurement of changes in sound speed in air to determine temperature of bulk air. Changes in sound speed are calculated from phase shift of multi-frequency continuous wave. A 89c51 single-chip microprocessor-based signal generator and phase detector was used to record and calculate phase shift and temperature. Advantages of proposed system are high accuracy, instant detection, wider range and low cost.

Keywords: Continuous wave, Microprocessor, Multi-frequency, Phase detector, Ultrasonic measurement

Introduction

In-car temperature sensor of automobile air conditioner (ACs) suffers from response-time lag and drift causing control problem during transient modes and even during steady state conditions. Automatic control of air temperature in a vehicle is made difficult by environmental variables such as radiant heat exchange, distribution of air temperature, velocity around occupants, human clothing and humidity in passenger compartment. Most ultrasonic air temperature measurements utilizing sound speed are based on pulse-echo technique, where distance data are obtained through time-of-flight (TOF) measurement. As sound speed changes with air temperature, one can calculate temperature (°K) of air or other known material on propagation path. Low frequency sound is more often used between 100-1400 m because higher frequency attenuates more quickly with distance.

In air temperature measurement using ultrasound, a phase-shift analysis of single-frequency continuous-wave transmission is used to reduce error. Acoustic wave in sinusoidal signal form is given as

$$ V(t) = A \sin(\omega t + \phi) $$

where $A$ is amplitude of received signal, $\omega$ is resonant angular frequency of transducer, and $\phi$ is phase angle proportional to measured target distance.

Propagated sound waves are very sensitive to air changes. Sound propagates at velocity $c$ as

$$ c = \sqrt{\frac{\gamma RT}{M}} \, , \, \gamma = \frac{C_p}{C_v} $$

where $R$, ideal gas constant; $T$, absolute temperature (°K); $M$, average molecular weight of gas molecules; $C_p$, heat capacity of gas at constant pressure; $C_v$, heat capacity of gas at constant volume, $c \propto \sqrt{T}$.

Techniques measuring air temperature on propagation path by sound speed are widely adopted. Using Eq. (2), a change of air temperature by 1°C (from 20°C to 21°C) increases speed of sound by a factor of 1.00168 (Fig. 1). Thus, to determine $T$ to an accuracy of 1°C in dry air, $c$ must be measured with relative accuracy of about 1.7×10⁻³. According to Eq. (2), $c$ is independent of pressure $p$ at constant temperature. More exact measurements do find a slight pressure dependence, but it is negligible. An increase in humidity (0-100%) increases $c$ by 1.2 m/s while an increase in $T$ (20-21°C) increases $c$ by 0.6 m/s (Fig. 2).
In this paper, an ultrasonic system is developed to measure inner temperature of vehicle in order to improve automobile AC.

**Method**

Changes in sound speed are calculated from phase shift of multi-frequency continuous wave (MFCW), which utilizes three frequencies for air temperature measurement. It is based on two-frequency continuous wave (TFCW) method of ultrasonic distance measurement\textsuperscript{15,16}. Increasing number of frequencies utilized for phase comparison increases maximum range for a given accuracy, at the price of increased time required to measure the range. Initial step of MFCW is identical to TFCW. Specific contribution of MFCW relative to TFCW is dramatic reduction of error contributed by inclusion of second (or higher number of) frequency. MFCW increases number of frequencies utilized for phase comparison to correct range errors and extend the useful range. MFCW system herein utilizes three frequencies, which work conveniently with
inexpensive transducers and circuit components, thereby allowing convenient laboratory verification and testing of general principle. Most commercial ultrasonic transducers are fabricated on the principle of frequency resonance for achieving a high sensitivity at lower operating frequencies (40 ± 2 kHz), which results in narrow-bandwidth devices. MFCW can achieve a narrow bandwidth ultrasonic ranging system, wherein temperature can be measured by following steps: i) Phase shift \( \phi_1 \) is generated by comparing sent and received \( f_1 \) signals (42 kHz); ii) Phase shift \( \phi_2 \) is generated with \( f_2 \) (41.8 kHz) and comparison of \( \phi_2 \) with \( \phi_1 \) yields \( \Delta \phi_1 \), with a frequency difference \((\Delta f_1)\) of 200 Hz; and iii) Phase shift \( \phi_3 \) is generated by comparing sent and received \( f_3 \) signals (40 kHz), and comparison of \( \phi_3 \) to \( \phi_1 \) gives \( \Delta \phi_2 \), resulting in a frequency difference \((\Delta f_2)\) of 2 kHz. Estimate of target distance can be expressed as

\[
L = \text{Int} \left[ \frac{\Delta \phi_1}{2\pi} \times \frac{\Delta f_2}{\Delta f_1} \right] \times \frac{c}{\Delta f_2} + \text{Int} \left[ \frac{\Delta \phi_2}{2\pi} \times \frac{f_1}{\Delta f_2} \right] \times \frac{c}{f_1} + \frac{\phi_1}{2\pi} \times \frac{c}{f_1}, \tag{3}
\]

where \( \text{Int}[\ ] \) is integer operation.

Distance \( L \) [Eq. (3)] is reconstructed in steps. First step yielding largest resolution scale (determined by \( c/\Delta f_2 \)), divides \( \Delta \phi_1 \) data into 10 divisions \((\Delta f_2/\Delta f_1 = 2000/200 = 10)\). In second step, yielding finer resolution (determined by \( c/f_1 \)), divides \( \Delta \phi_2 \) data into 21 divisions \((f_1/\Delta f_2 = 42000/200 = 21)\). In final step, \( \phi_1 \) phase shift data is used to yield highest level of resolution (determined by \( c/f_1 \times 1/360 \text{ mm/degree} \)), 0.0231 mm/degree. From Eq. (3), sound speed can be expressed as

\[
c = \frac{\text{Int} \left[ \frac{\Delta \phi_1}{2\pi} \times \frac{\Delta f_2}{\Delta f_1} \right] \times \frac{1}{\Delta f_2} + \text{Int} \left[ \frac{\Delta \phi_2}{2\pi} \times \frac{f_1}{\Delta f_2} \right] \times \frac{1}{f_1} + \frac{\phi_1}{2\pi} \times \frac{1}{f_1}}{L}, \tag{4}
\]

From Eq. (2), temperature is

\[
T = c^2M/\gamma R \tag{5}
\]

where \( T \) is in \( ^\circ K \), \( T[\circ K] = T[\circ C] + 273.15 \)

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

**System Implementation**

System (Fig. 3) consists of a temperature-controlled chamber, a thermocouple-based thermometer, two acoustic transducers with matching exponential horns, a multi-frequency signal source, power amplifier, preamplifier and gain-controlled system, a digital phase meter. Thermocouple is used to compare measured air temperature with the output of ultrasonic system. A microprocessor controls operation of entire system and a PC examines measurement result and performs calibration.

**Hardware**

**Multi-frequency Ultrasound Source**

Transmitted pulse is made up by three sinusoid waves \((40/41.8/42 \text{ kHz})\). Crystal oscillator (Fig. 4) generates a steady signal with a base frequency of 80 MHz. Divisors of three dividers are set at 2000/1914/1905, which are applied to base frequency. Three frequencies \((40/41.8/42 \text{ kHz})\) are then produced and sent to multiplexer (MUX), which is controlled by an 89c51 microprocessor.

**Preamplifier and Gain-controlled Amplifier**

Bandwidth of ultrasonic transducers is narrow. Amplifier gain must dynamically adjust as frequency of ultrasound changes to reduce error from acoustic attenuation. Therefore, error arisen from acoustic attenuation is minimized in gain-controlled amplifier by keeping amplitude of received signal constant.

**Digital Phase Meter**

Phase shift is transformed into pulse width by two \( D \)-type flip-flops (Fig. 5). An 80 MHz signal is used to count pulse width. Resolution of phase meter is 0.05% for a 40 kHz signal. Finally, counter is cleared by a reset signal generated by microprocessor for counting next phase shift.

**89c51 Single-Chip Microprocessor**

An 89c51 single-chip microprocessor (Atmel, USA) controls measurement system. It controls MFCW signals of ultrasonic, obtains digital phase shift, calculates and displays air temperature.
**Calibration System**

A chamber has an internal fan to maintain inside air temperature uniform (Fig. 3). A thermocouple measures air temperature inside the chamber. Thermocouple voltage is converted into temperature reading with a Testo 946 thermometer (accuracy, $\pm 0.2^\circ C$). Difference from actual temperature at $0^\circ C$ was $+0.1^\circ C$ within claimed accuracy. Output of thermometer is sent to PC with phase shift and temperature measurement data.
**Fig. 5**—Block diagram of digital phasemeter

**Fig. 6**—Software flowchart
From these data, temperature measurement errors are calculated.

**Software**

Microprocessor 89c51 that fetches actual temperature $T_1$ measured by thermocouple assigns transmitted signal, adjusts gain-controlled amplifier, waits for interrupt from digital phase meter, obtains $\phi_1$, $\phi_2$, $\phi_3$ and calculates temperature $T_2$ (Fig. 6). Then, it compares $T_1$ with $T_2$. If $|T_2 - T_1| < 1^\circ C$, it displays $T_2$ on LCD. Otherwise, PC recalculates temperature measurement errors from calibration system. If waiting time is longer than 50 ms, microprocessor 89c51 reassigns transmitted signal and values of $\phi_1$, $\phi_2$, $\phi_3$ and $c$ are sent to PC via RS232 interface of microprocessor.

**System Test**

**Ultrasonic Experiment**

Air temperature in chamber was measured with thermocouple. $\phi_1$, $\phi_2$ and $\phi_3$ were recorded from multi-frequency continuous waves three times. Then, air temperature with thermocouple was measured again. Finally, average of three measurements ($\phi_1$, $\phi_2$ and $\phi_3$) was compared with average of two thermocouple measurements. Both can represent air temperature at the same point of time (halfway through measurement...
cycle). From 0-80 °C with an interval of 1 °C, measurement is repeated and received at different temperatures. Using this measurement system and calculating speed of sound by Eq. (4), average air temperature on propagation path can be obtained.

**Experimental Results**

When temperature increased from 0 °C to 1 °C, there was a decrease in \(\Delta \phi_1\) by 0.396° (Fig. 7a), in \(\Delta \phi_2\) by 3.961° (Fig. 7b) and in \(\phi_1\) by 83.165° (Fig. 8). When temperature increased from 79 °C to 80 °C, there was a decrease in \(\Delta \phi_1\) by 0.271°, in \(\Delta \phi_2\) by 2.708° and in \(\phi_1\) by 56.873°. When temperature increases, sound speed increases, thereby wavelength increases. Thus, changes of phase shift diminished with temperature increase. When distance remains unchanged, increase of wavelength will cause decrease of phase shift. Comparing thermocouple temperature and temperature by proposed ultrasonic system between 0-80 °C, difference of ultrasonic measurement and actual temperature consistently remains within ± 0.3 °C (Fig. 9). Errors between actual temperature from thermocouple and ultrasonic measurement were found as (Fig. 10): average error, 0.138 °C; and standard error, 0.147 °C. Standard error is calculated as:

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

where \(RP\), temperature of ultrasonic measurement; \(PP\), temperature measured by thermocouple; \(n\), number of measurements.

**Conclusions**

A newly developed highly accurate ultrasonic temperature system for an automobile AC is based on detection of phase difference, and hence traditional acoustic attenuation problems are avoided. High frequency 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. This results in transmitting transducer mechanical spring coefficients producing audio signals with slow-onset envelopes. The slow onset makes exact signal start time unclear to the receiver. Continuous wave transmission has similar start/stop envelope problems. But during continuous operation, these problems are no longer present. Error between actual temperature measured by thermocouple and temperature measured by proposed
system is only $\pm 0.4^\circ C$, with measurement for every 0.1 sec. This level of accuracy with speed of ultrasonic system detection is more than adequate for average temperature control systems. Ultrasonic pulse can efficiently be used to measure bulk air temperature without any visual concern.

References
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