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The study of temperature measurement for vehicle cabin using ultrasonic transducers

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Abstract *- The optimum temperature control of the Automatic Climate Control (ACC) in the vehicle cabin is dependent on whether or not the thermometer can measure temperatures around occupants. Most in-car temperature sensors are difficult to achieve. To measure the temperature around occupants, this study presents a technique based on ultrasonic temperature sensors using the sampling of the ultrasonic time of flight (TOF). The temperature environment was changed for Measurement. The Kalman filter processed the data for lowering noises and increasing accuracy. The experimental results showed that the ultrasonic temperature sensors could provide accurate temperature measurements, fast response to temperature changes, and non-contact.*

Keywords — *automatic climate control (ACC), thermometer, ultrasonic temperature sensor, time of flight (TOF), Kalman filter, non-contact.*

I. INTRODUCTION

The Automatic Climate Control (ACC) has been servicing passengers for a long time. Even though this system creates a comfortable environment for all the occupants and keeps the passenger compartment free of unpleasant odours and pollutants, it still has a shortcoming. In a cabin, for instance, the ACC cannot measure the air temperature best correlated to thermal comfort, which is within occupant's breathing range, especially in hot weather conditions. For this reason, we use an ultrasonic temperature sensor instead of an in-car temperature sensor aimed at improving temperature sensing.

Because the car window cannot effectively block the sun going through the car [1], this leads to a temperature difference in the driver's seat between the area with sunlight and that with shade. Therefore, the in-car sensor cannot measure temperature accurately. If the temperature sensor can be placed within the driver's breathing range, we can utilize the air conditioning system more effectively. The driver's breathing range is shown in Fig.1. Due to safety and aesthetics, the temperature sensor is put in places outside the driver's breathing range. This is why the temperature sensor cannot get useful and reliable data.

As proposed and conducted in Han's study [2, 3, 4, 5], subjective thermal comfort votes from occupants were compared with temperature readings from an in-car sensor and a thermocouple at the breathing range. The data showed that perceived thermal comfort could be significantly improved if an input to the ACC control system from the in-car sensor was replaced by an input from a sensor that measures the bulk air temperature in front of the occupant.

II. THEORY OF ACOUSTIC TEMPERATURE MEASUREMENT

When a sound wave travels through media, such as solid materials, gas, or water, it follows the rule that the speed of sound varies with temperature and pressure. Therefore, the air temperature can be determined from the measurements of the speed of sound. For a sound wave passing through solid materials, the speed of sound is related to two main material properties and can be expressed as follows.

$$c_s = \sqrt{\frac{k_s}{\rho_s}} \quad (1)$$

Where c_s is the speed of sound in solids, k_s coefficient of stiffness, and ρ_s the material density. The speed of sound increases with the stiffness of the material while it decreases with the material density.

For gas media, the speed of sound is related to three main parameters: temperature, humidity and atmospheric pressure. Referring to [6, 7], the speed of sound can be written as.

$$c_i = \sqrt{\gamma \cdot \frac{p}{\rho}} \quad (2)$$

Where c_i is the speed of sound in the gas, p the pressure, ρ the gas density, and γ is the adiabatic index which is C_p (constant pressure heat capacity) divided by C_v (constant volume heat capacity), as shown in Equation (3).

$$\gamma = \frac{C_p}{C_v} \quad (3)$$

$$p = \frac{n \cdot R \cdot T}{V} \tag{4}$$

$$\rho = \frac{n \cdot M}{V} \tag{5}$$

Using ideal gas law [Equation (4)] and definition of ρ[Equation (5)]. Equation (2) can be rewritten as:

$$c_i = \sqrt{\frac{\gamma \cdot R \cdot T}{M}} \tag{6}$$

Where R is the molar gas constant (also called universal gas constant), M is the molar mass of the gas (the average molecular weight of air is about 0.0288kg/mol.), T is the absolute air temperature. For an ideal gas, the speed of sound can be evaluated by changing the absolute temperature. Fig.2 shows the sound speed variation with the absolute air temperature.

There are two methods of ultrasonic temperature measurements: Mutual-Emit mode, and Echo mode. For the transducer to obtain a more accurate measurement for TOF, the input signal must be processed, including filtering and amplification. Otherwise, there may be too much noise in the input signal resulting in unstable TOF measurements and loss of accuracy. When the signal is amplified, the noise is also amplified. Therefore, the amplification would need to be adjusted to consider the noise effects. The best way to solve this problem is to apply higher energy excitation pulses to the transmitter transducer to increase the amplitude of the signals at the receiver. On the other hand, the measurement accuracy of TOF can be enhanced by boosting the voltage level of the transmitter [8].

Fig. 3 shows the block diagram of the setup used to measure TOF based on the Echo mode. There is no significant difference between Mutual-Emit mode and Echo mode of the block diagram. Both methods for TOF measurements are used to calculate the speed of sound in the fixed distance. The only difference is that for the Echo mode, the sound wave passes to the end of a period, and has a reflection between the transmitter and the receiver. Although both are similar in principles, their applications are quite different. For example, for the Echo mode, the angular dependence of ultrasonic transducer response and the surface of the reflective object is extremely important.

When an ultrasonic wave reflects from surfaces, the angle of incidence equals the angle of reflection. This is called the law of reflection. A transmitter transducer transmits an ultrasonic wave traveling through the air, and it will encounter the front surface of the reflector and reflects through the front surface on its way back to the receiver transducer. If a sound wave hits a reflective object at an angle of 90°, it will be reflected at the same angle (90°). The reflective object must be flat and smooth. Otherwise, TOF measurements will be inaccurate and unstable.

Ultrasonic temperature measurements are based on measurements of the time (TOF) over a known fixed distance. After the TOF time is measured, the speed of sound can be obtained based on Equation (7):

$$c = \frac{d}{\Delta TOF} \tag{7}$$

The speed of sound can then be substituted into Equation (8), and we can obtain the temperature of media over this distance. It should be noted that the temperature obtained from Equation (8) has a unit of Kelvin, and if we want to obtain a unit of Celsius, one needs to subtract 273.15 from it. The TOF measurement with different conditions can be expressed as.

$$\mathrm{T[K]} = \frac{M \cdot C^2}{\gamma \cdot R} \tag{8}$$

As shown in Fig. 4, the Tx pin will transmit, and the Start pin will work automatically after the trigger is initiated. The frequency of square wave signals transmitted by the Tx pin depends on the transducer, and the timer for TOF measurement starts running when the Start pin is transmitted. The timer stops when the Rx pin receives the signals on the receiver. The speed of sound can then be calculated from TOF measurements by using Equation (7). Receiver Processing is shown in Fig. 5. The receiver processing circuit contains two auto-zeroed comparators (a zero-cross detect and a threshold-detect comparator), a threshold setting DAC, and an event manager that we discussed previously. After received signals are filtered and gain amplified from a receiver transducer, the signal must be processed through comparators and event manager for generating a Stop signal. When the signal amplitude exceeds values smaller than the Threshold, the Threshold detect comparator indicates to the event manager to qualify the next zero-cross event as valid. When the zero-cross detect comparator detects the qualified zero-cross, the event manager passes the pulse to the Stop pin until the number of receiver events programmed is reached. Therefore, the TOF completes measurements when the timer stops counting.

III. EXPERIMENT AND RESULTS

In this section, we discuss the experimental instrument that we used, as well as the Kalman filter used to calibrate the measuring TOF for increasing accuracy. Experiment arrangement was separated into two steps. For the first step, we arranged the ultrasonic temperature sensor of Mutual-Emit mode and Echo mode in a changing temperature environment for temperature measurements. For the second step, the results of the original data were filtered and then analyzed.

As the medium of ultrasonic propagation consists of air, there is a temperature difference over the distance. When an ultrasonic wave passes through the air, it may cause reflection or refraction at the boundary. Results in TOF measurements may become inaccurate and unstable.

Especially, this occurs in situations where the temperature changes so fast or there is an airflow disturbance. For instance, as shown in Fig. 6, the temperatures measured by ultrasonic temperature sensors within 3600 seconds have an error of about 0.8 degrees Celsius. These errors are due to the combined interference of various noises in the measurement results. In this study, we present a method for further improvement of the temperature measurements based on a Kalman filter.

The Kalman filter removes noises from measurements of ultrasonic temperature sensors, and the measured values reduce noises significantly, and signals become more stable. As shown in Fig. 7, ultrasonic temperature measurements after filtered are compared with those from PT1000 sensors. The vertical axis is the temperature in degree Celsius, and the horizontal axis is the temperature sampling during 3600 seconds. A temperature difference of about 1 degree is observed between ultrasonic temperature sensors and PT1000 because the speed of sound increases with humidity in the air, resulting in the measurements from ultrasonic temperature sensors higher than those from PT1000. This difference can be ratified by humidity compensation (see next section).

Fig.8 shows a temperature error of ultrasonic temperature sensors after filtered based on temperature measurements of PT1000. The measurement error is about 1 degree Celsius before the humidity parameter calibration. Fig. 9 shows a relative temperature error of ultrasonic temperature sensors after filtered based on temperature measurements of PT1000. The relative error is within 5%. After the humidity calibration, the measurement accuracy of ultrasonic temperature sensors is expected to improve.

The experiment of Mutual-Emit mode temperature measurement simulates the temperature change, such as a passenger compartment environment. The temperature in a passenger compartment has a rapid change due to the sunlight heating up. To simulate this process, we adjusted the temperature of the air conditioner to either hot or cold. Ultrasonic temperature sensors of Mutual-Emit mode were installed under this experimental environment for temperature measuring and were compared with PT1000 sensors. The purpose of simulation for this experiment includes investigation of the accuracy of temperature measurements, the reaction of temperature measurements and accuracy of temperature measurements after humidity compensation. Fig. 10 shows temperature measurements within 3600 seconds using the Mutual-Emit mode and PT1000 sensors. The temperature was adjusted to hot and cold during 800 and 2800 seconds for simulation of the cabin environment. The temperature error for the Mutual-Emit mode is within 1.9 degrees Celsius from the measurements of PT1000 sensors. The relative error is within 6%, as seen from Fig. 10 (c).

IV. CONCLUSIONS

This study investigates a Mutual-Emit mode of ultrasonic temperature sensors in vehicles. Major areas of the study are in response to time, accuracy, and stability, In the Mutual-Emit mode, the sensor responds to temperature changes quickly and accurately, is anti-interference, and provides a longer range of measurements. Although the responsiveness in the Echo mode is not as good as the Mutual-Emit mode, it still can meet our requirements to be used in vehicles. The only potential drawback of the ultrasonic temperature sensors is the effect of driver's unpredictable behaviour on the temperature measurement accuracy. The ultrasonic sensor can be used not only to measure temperatures but also to measure distances. If we take three samples every time, the first sample is used to measure the distance, the second one is used to measure the temperature, and the last one is also to measure the distance. The sensor will display the temperature as long as the distance is within a range that we set.

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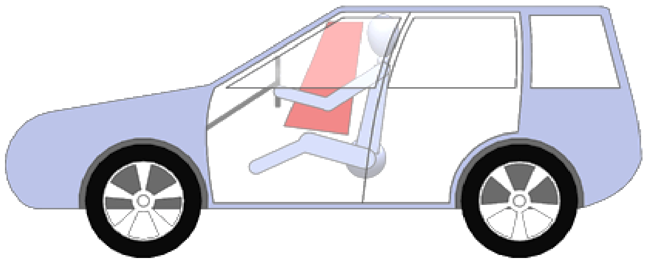


Fig.1 The driver's breathing range.

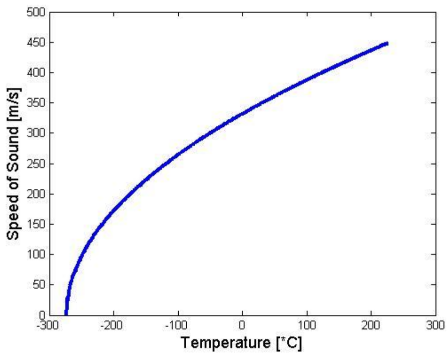


Fig. 2 Sound speed variation affected by absolute temperature.

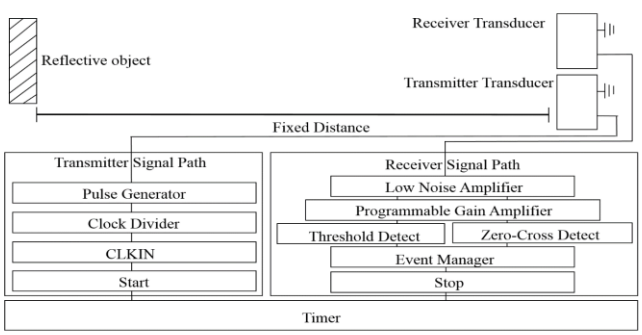


Fig.3 Block diagram of Echo mode

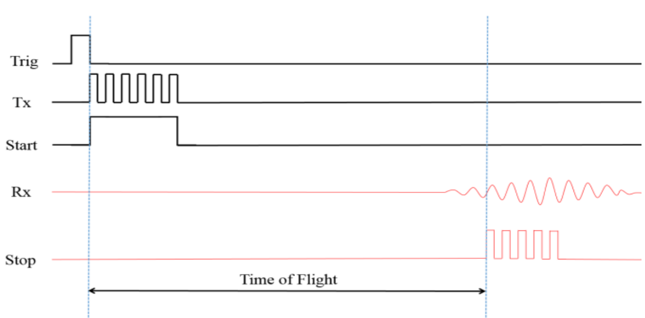


Fig.4 TOF measurement.

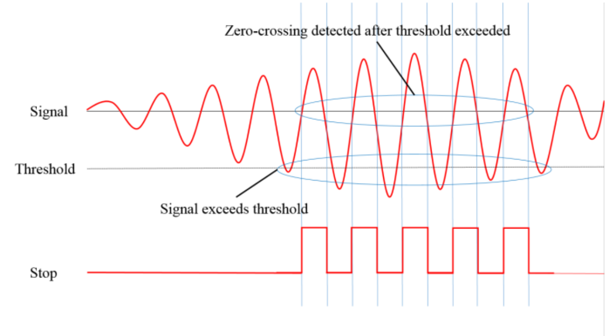


Fig.5 Signals processing.

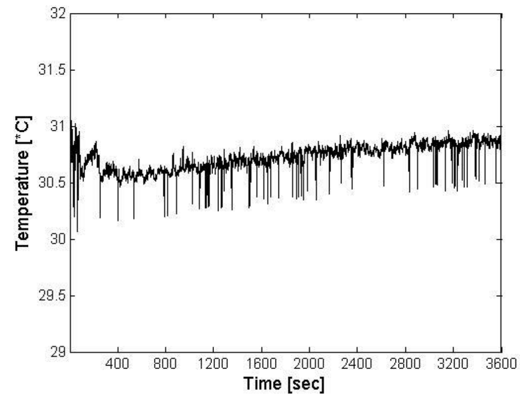


Fig.6 Measurement error of ultrasonic temperature sensor.

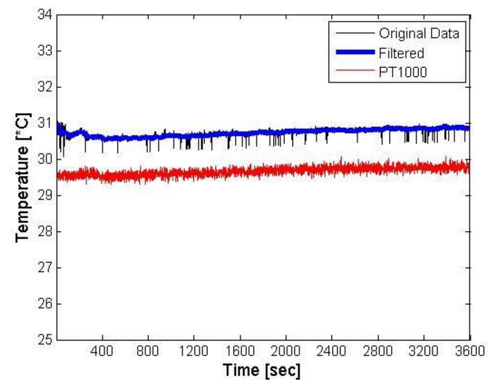


Fig.7 Comparison of filtered values with PT1000 measured values.

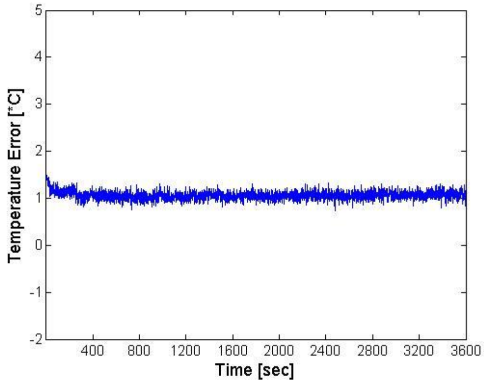


Fig.8 Measurement error after filtered.

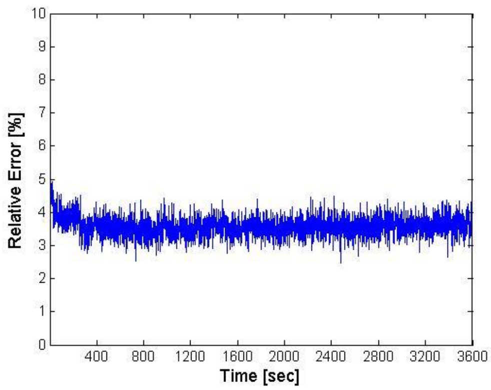
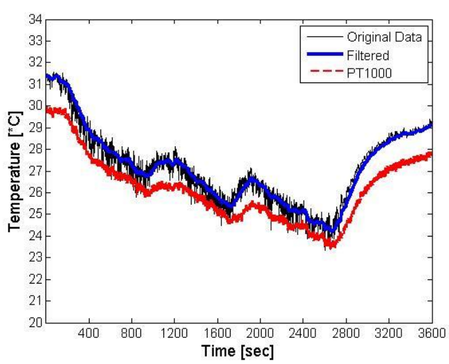
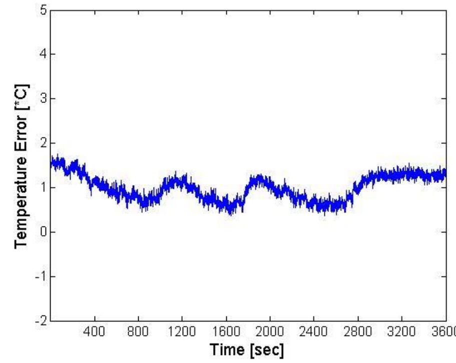


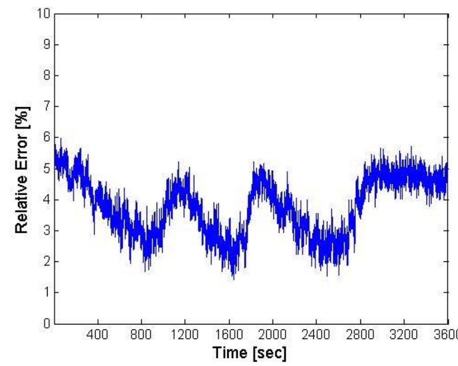
Fig.9 Measurement relative error after filtered.



(a)



(b)



(c)

Fig. 1 The temperature measurement result of Mutual-Emit mode in the experiment of changing temperature environment. (a) Temperature measurement. (b) Temperature error. (c) Relative error.