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Effects of environment on accuracy of ultrasonic sensor operates in millimetre range☆

Kirtan Gopal Panda*, **Deepak Agrawal**, **Arcade Nshimiyimana**, **Ashraf Hossain**

Department of Electronic and Communication Engineering, National Institute of Technology, Silchar, Assam 788010, India

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Summary The growing use of ultrasonic sensor now demands millimetre range of operation with high accuracy. Ultrasonic sensor uses sound waves for its ranging and the speed of sound is influenced by a number of environmental parameters. The objective of this paper is to discuss on the list of environmental parameters which have the major influence on the accuracy of the ultrasonic sensor and also to formulate a simplified mathematical equation to calculate instantaneous speed of sound by taking these influencing parameters into consideration. Comparison result shows the derived simplified equation for calculating instantaneous speed of sound gives maximum percentage error of 0.33 for the temperature range of 0–50 °C. Here we also focus on the steps to calibrate ultrasonic sensor for millimetres range of operation.

Introduction

Sensors are just like sensing organs of a technical system. From the collection of sensors, the most commonly use sensor for obstacle detection and its distance measurement is ultrasonic sensor. Using this non-contact type sensor Dong et al. (2010) reported human respiration rate measurement system in which movement of the stomach was measured in centimetre range from a distance of 100 cm. Yoannan et al. (2013) reported the use of ultrasonic sensor in the design of security system. Ultrasonic sensor has also used for the aid of physical handicap person. The above systems demand operation of ultrasonic sensor in millimetre range with accuracy. But the main hindrance for high accuracy in millimetre range is its working environment. The ultrasonic sensor uses sound waves which are influenced by a number of medium parameters. So our interest is to figure out the major influencing parameters of the environment and to formulate a simplified equation to calculate instantaneous speed of sound by taking these major influencing parameters. This is an interesting

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* Corresponding author.
E-mail address: kirtangopal.panda@gmail.com (K.G. Panda).

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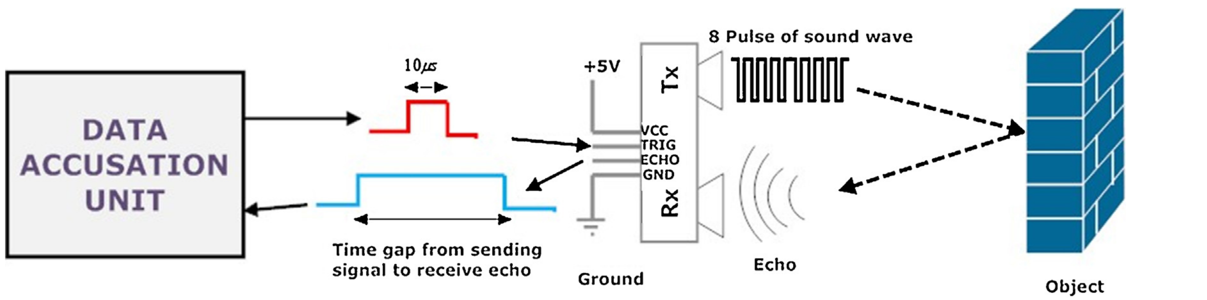

Figure 1 Working principle of an ultrasonic sensor.

problem because the earlier simplified equation considers only medium temperature as input. But when we need to train ultrasonic sensor for millimetre range the effect of humidity is not to be neglected.

Working principle

The commonly available low-cost ultrasonic sensor is Hc-Sr04. Ultrasonic sensor sends sound pulses towards the object and receives echo signals reflect back from it as shown in Fig. 1.

During the time period from transmitting sound waves to receive the echo, ultrasonic sensor gives a high-level signal to Data Acquisition Unit (DAU). Using timer DAU counts the time span signal remains high. By dividing timer output result with two times of exact speed of sound, we will find the object distance. For centimetre range operation of ultrasonic sensor if DAU takes a fixed speed of sound then the output error is accepted up to some extent. But in the case of millimetre range operation, the error due to fixed sound speed will not acceptable. So for millimetre range operation DAU need the instantaneous speed of sound in place of fixed speed. To calculate the speed of sound DAU also need a simplified equation as complicated equation cannot process by microcontroller unit present in it. Before going for a simplified equation, our first intention is to know which medium parameters have major influence on the speed of sound.

Mathematical formulation

The longitudinal sound waves are an isentropic process where the entropy remains constant throughout the process. From Newton—Laplace equation, the speed of sound in ideal gas is

$$C = \sqrt{\frac{\gamma \times R \times 273.15}{M}} \times \sqrt{1 + \frac{\theta}{273.15}} \quad (1)$$

where C is known as the speed of sound, γ is the ratio of specific heat of the gas at constant pressure to that at constant volume, R is molar gas constant (approximately 8.314510 J/(mol K), M is the molar mass of ideal gas, θ is the temperature in°C. Here we consider the ideal gas is dry air.

The molecular mass of dry air (M_D) is 28.969 kg/kmol. But in the practical condition the air medium neither dry nor the concentration of carbon dioxide and Pressure fixed to different geographical area. So the four medium parameters

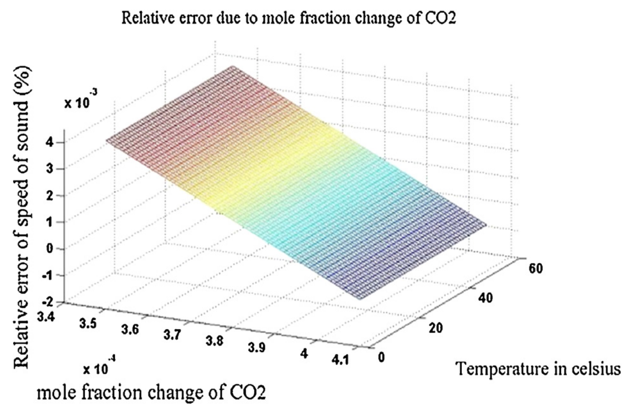

Figure 2 Relative error in speed of sound CO_2.

which can influence the speed of sound are temperature, relative humidity, change in pressure and change in concentration of CO_2 (Nicolau et al., 2009). For a given altitude the pressure variation is very negligible (Dean, 1979). So the influence of change in atmospheric pressure (P) is neglected. Due to change in concentration of carbon dioxide (CO_2) speed of sound also changes. Fig. 2 shows the relative error in speed of sound due to mole fraction change of CO_2 It is clear observed that relative error due to CO_2 is in the range of 10^{-3}. So the effect of CO_2 will be neglected. Now two major parameters left, they are relative humidity and temperature. From Table 1 we can visualize the effect of relative humidity and temperature with respect to dry air speed. We cannot neglect these two parameters for calculating instantaneous speed of sound.

Due to increase in relative humidity some nitrogen and oxygen molecules of air are replaced by lighter molecules of water vapor as a result, molecular weight of air gets decreased (Bohn, 1988). The presence of water molecule affects the specific heat ratio γ which will be modified as

Table 1 Speed of sound in dry and humid air.

θ (°C)	C_D (m/s)	C_E (m/s)		C_S (m/s)	
	RH = 0%	RH = 30%	RH = 100%	RH = 30%	RH = 100%
20	343.210	343.592	344.489	343.800	344.696
30	349.015	349.721	351.392	350.180	351.824
40	354.725	355.977	358.970	356.754	359.596
50	360.344	362.481	367.677	363.581	368.213

$$\gamma_W = \frac{7+h}{5+h} \quad (2)$$

where h is the fraction of water molecules in air medium and it can be calculated from relative humidity (RH), ambient pressure (P) and water vapor pressure ($e(\theta)$).

$$h = \frac{0.01 \times RH \times 133.322 \times e(\theta)}{P} \quad (3)$$

The speed of sound increases with respect to increasing in moisture. The speed of sound in air due to presence of water vapor having molecular weight 18 kg/kmol is given by

$$C_E = \sqrt{\frac{\left(\frac{7+h}{5+h}\right) \times R \times 273.15}{28.969(1-[0.378 \times h])}} \times \sqrt{1+\frac{\theta}{10.15}} \quad (4)$$

Here C_E is the exact speed of sound, depends on relative humidity and temperature. Now our aim is to formulate a simplified equation for the instantaneous speed of sound from exact speed (4). By applying power series expansion with first order approximation we will get

$$C_E = (331.296 + (0.606 \times \theta)) \times (1 + (0.1607 \times h)) \quad (5)$$

In (5) h is input parameter but it depends on RH and $e(\theta)$. Apply series expansion it will be

$$e(\theta) = 10^{\left(A-\frac{B}{C+\theta}\right)} = \frac{10^A}{10^{\frac{B}{C}}}\left[10^{\frac{B}{C}\left(\frac{\theta}{C}-\left(\frac{\theta}{C}\right)^2+\left(\frac{\theta}{C}\right)^3-\cdots\right)}\right] \quad (6)$$

The final simplified equation for instantaneous speed of sound by taking (5) and (6) will be

$$C_S = (331.296 + (0.606 + \theta)) \times \left(1 + \left(RH \times 2.114 \times 10^{-6} \times \frac{10^A}{10^{\frac{B}{C}}}\left[10^{\frac{B}{C}\left(\frac{\theta}{C}-\left(\frac{\theta}{C}\right)^2+\left(\frac{\theta}{C}\right)^3-\cdots\right)}\right]\right)\right) \quad (7)$$

where C_S is the instantaneous speed of sound using simplified equation. Normally the default working temperature range (θ) for an ultrasonic sensor is 0—50 °C. So for the default temperature range (7) will be modified as

$$C_S = (331.296 + [0.606 \times \theta]) \times \left(1 + \left[RH \times 9.604 \times 10^{-6} \times 10^{0.032 \times (\theta - (0.004 \times \theta^2))}\right]\right)$$

The above simplified equation for calculating instantaneous speed of sound depends on two major influencing parameters. These are temperature and relative humidity. We have calculated the speed of sound by using C_E and C_S equation which is shown in Table 1. The maximum error between C_E and C_S is 0.33% which is shown in Fig. 3.

Ultrasonic sensor operation in millimetre range

To improve the accuracy of ultrasonic sensor operates in millimetre range we need to calculate instantaneous speed of sound (C_S) for which temperature and RH sensors are required. Let X be the time for both to and fro motion of the sound, so the object distance (Y) will be

$$Y(\text{mm}) = \frac{X}{2000/C_S}; \quad \text{for } D = 2000/C_S; \quad \text{then } Y(\text{mm}) = \frac{X}{D}$$

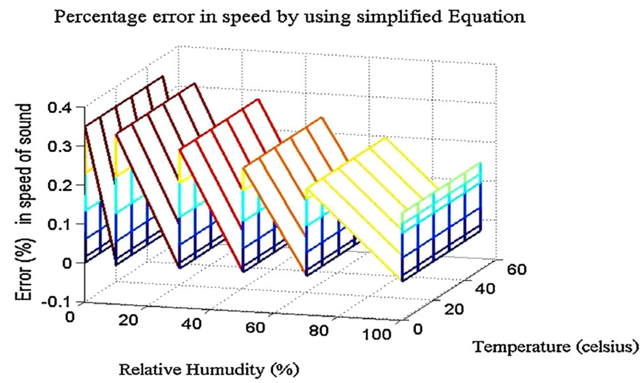

Figure 3 Error in speed of sound due to C_S.

Here D is called as the dividing factor, C_S is the instantaneous speed of sound which is calculated by DAU taking simplified equation into account. Although there is a small error in between exact speed of sound and speed of sound calculated by using simplified equitation but while calculating dividing factor the error again get reduce to 60% to 43%.

Conclusion

To train ultrasonic sensor for high accuracy in millimetre range we need the instantaneous speed of sound which requires two major parameters temperature and relative humidity of the medium. We have framed a simplified equation to get the instantaneous speed of sound which gives maximum percentage error 0.33 for a default working temperature range of 0—50 °C. While calculating dividing factor error due to simplified equation again get reduce to 60% to 43%.

Conflict of interest

None.

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