The Physics Teacher

PAPERS | OCTOBER 01 2022

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Phys. Teach. 60, 597–599 (2022)
https://doi.org/10.1119/10.0014302

Speed of Sound Measurement Using an Ultrasonic Motion Detector

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We propose a method to measure the speed of sound in air using a motion detector. The experiment is based on the principle of a motion detector used to measure distances. This device measures the time of flight of alternating ultrasonic waves between the observer and the target. By assuming a fixed speed of sound, the time of flight can be converted into a distance. The medium, including its temperature through which the sound travels, influences the speed of sound. A motion detector has been used to show the effect of CO_2 concentration on the resulting distance measurement, and to estimate the linear change in speed of sound per degree Celsius.[1] The distance measurement using a motion detector has to be calibrated according to the medium's condition. The Logger Pro 3 features allow adjustment of the temperature setting and addition of an offset value to correct the motion detector reading.[2]

In this experiment the distance measured by using the motion detector is compared to the real distance measured by using a tape measure. Through graphical representation the speed of sound in air can be estimated at various temperatures, hence the speed of sound in air at 0 °C is obtained. This simple experiment can be carried out in the physics laboratory. Students will be able to analyze the data, especially graphical representation, and gain an understanding of the basic principle of a measuring instrument.

Theory

The motion detector emits pulses of ultrasonic waves toward the target and then receives the reflection. The time of flight of the wave Δt is needed to travel the distance from the detector to the target and back to the detector. In order to obtain the distance, the speed of sound v_s has been determined to be a constant value. We use a setup consisting of Vernier's motion detector (MD-BTD) and Logger Pro software. This setup applies the speed of sound of 343 m/s and provides options to account for various temperature settings and offset of the system in motion detector reading. The default temperature and the offset are 20 °C and 0, respectively. This offset varies by interface.[2]

When the detector measures Δt, the distance reported as position p is calculated using the equation

$$p = v_s \times \frac{\Delta t}{2} + \alpha, \qquad (1)$$

where v_s = 343 m/s and α is an offset.

In fact the speed of sound is influenced by the properties of the medium such as its composition and temperature. If under certain conditions the real speed of sound is v, then the real distance d is given by

$$d = v \times \frac{\Delta t}{2}. \qquad (2)$$

By eliminating Δt between Eqs. (1) and (2), we get

$$d = \frac{v}{v_s}(p - \alpha). \qquad (3)$$

The linear regression of the data of d vs. p gives a gradient v/v_s and an intercept $-\alpha v/v_s$.

When we give the obtained value $-\alpha$ as an offset using the menu in Sensor Setup of Logger Pro, the distance is reported as the corrected position p_c and Eq. (3) becomes

$$d = \frac{v}{v_s} p_c. \qquad (4)$$

For temperatures close to room temperature, the speed of sound v depends on the temperature T (in °C) following the equation

$$v = v_0 + bT, \qquad (5)$$

where v_0 is the speed of sound at T_0 = 0 °C and b is a constant value.[3,4] By rewriting Eq. (4) and inserting it into Eq. (5), we get

$$\frac{1}{p_c} = \frac{v_0}{d v_s} + \frac{b}{d v_s} T. \qquad (6)$$

For a constant d, the measured p_c will depend on the temperature T as shown by Eq. (6). The speed of sound at 0 °C v_0 can be obtained by monitoring p_c at various temperatures T.

Experiment

Experiments are carried out in a temperature-regulated air-conditioned room. The motion detector is mounted on the optical bench facing the wall; the distance to the wall can be varied and measured easily. The motion detector is set in such a way that the ultrasound wave is perpendicular to the wall. The real distance d is measured directly from the front housing of the motion detector to the wall using a tape measure attached on the optical bench while the motion detector records its position.

We performed three experiments to estimate the offset of the system α and the speed of sound at 0 °C. Based on Eq. (3) the first experiment was done in a constant room temperature to estimate the speed of sound v and the offset of the system α. The speed of sound at the corresponding temperature was calculated from the gradient, while the offset α was obtained from the ratio of the negative of the intercept to the gradient. The obtained α is then used as an offset in the Sensor Setup for the second and third experiment. The second experiment was carried out at various temperatures to obtain different speeds of sound. The speed of sound at 0 °C and the constant b were estimated using Eq. (5). In the third experiment, we kept the distance constant and varied the temperature continuously. We performed a linear regression based on Eq. (6) to estimate the speed of sound at 0 °C and the constant b.

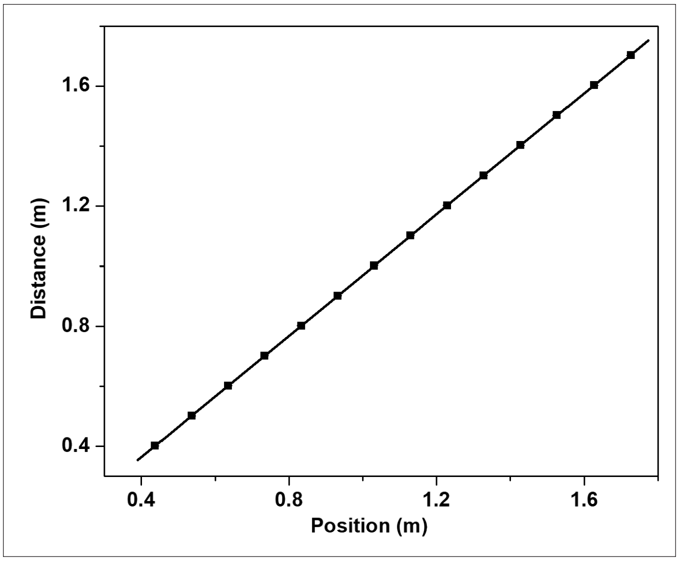

Fig. 1. A plot of the real distance against the position, at temperature (24.9 ± 0.1) °C. The solid line is the corresponding curve fitting to Eq. (3).

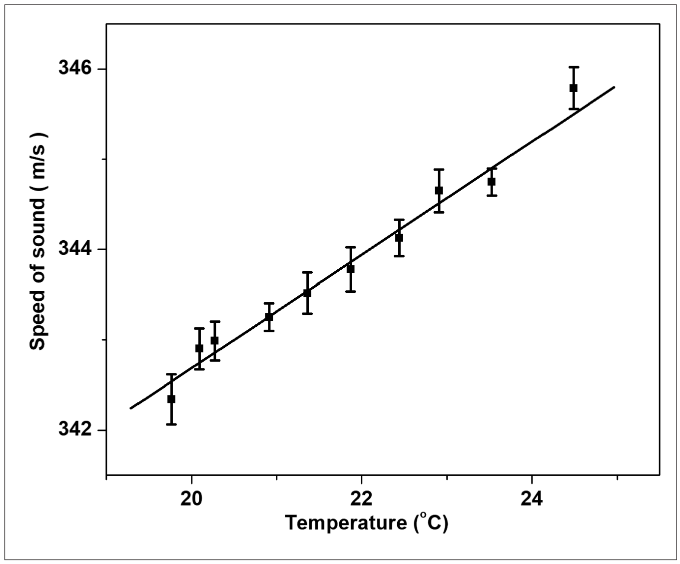

Fig. 2. The speed of sound as a function of the temperature. The solid line is the corresponding curve fitting to Eq. (5).

Estimating speed of sound and the offset of motion detector

We varied the distance from 50 cm to 170 cm with an increment of 10 cm. During the experiment, the temperature was kept constant and was monitored continuously. Three temperature sensors were placed in the area around the motion detector. The experimental result at the average temperature (24.9 ± 0.1) °C is shown in Fig. 1.

Figure 1 shows the linear relationship between the real distance and the position obtained from the motion detector. The individual data points presented here represent an average of seven data points with small standard deviations. The solid line is the best fit corresponding to Eq. (3) that gives a gradient of $(10{,}087 \pm 4) \times 10^{-4}$ and an intercept of $(-385 \pm 5) \times 10^{-4}$ m. The obtained intercept and gradient will give the offset $\alpha = (3.82 \pm 0.05)$ cm. In accordance with Eq. (3), the gradient corresponds to $v/(343\text{ m/s})$. Using the obtained gradient we calculate the speed of sound in air at temperature of (24.9 ± 0.1) °C to be (346.0 ± 0.2) m/s. This value can be compared to the published data; the speed of sound in air is 346.29 m/s at 25 °C.[5] The discrepancy between them is about 0.1%.

Estimating the speed of sound at 0 °C

Using the same setup, we then gave an offset of –3.82 cm in the Sensor Setup. In the same way the speed of sound has been measured at various temperatures. We observed the intercepts were around zero, i.e., ranging from –0.1 mm to 0.6 mm. This fact indicates the offset α is a constant offset of the system and it is independent of the temperature. We performed the experiment in a common laboratory room that was quite large. Due to this situation the temperature can be varied only in the range of 19.8 °C to 24.5 °C. In this small range of temperature, Fig. 2 shows that the measured speed of sound varied from 342.3 m/s to 345.8 m/s.

The linear relation shown in Fig. 2 follows Eq. (5). The

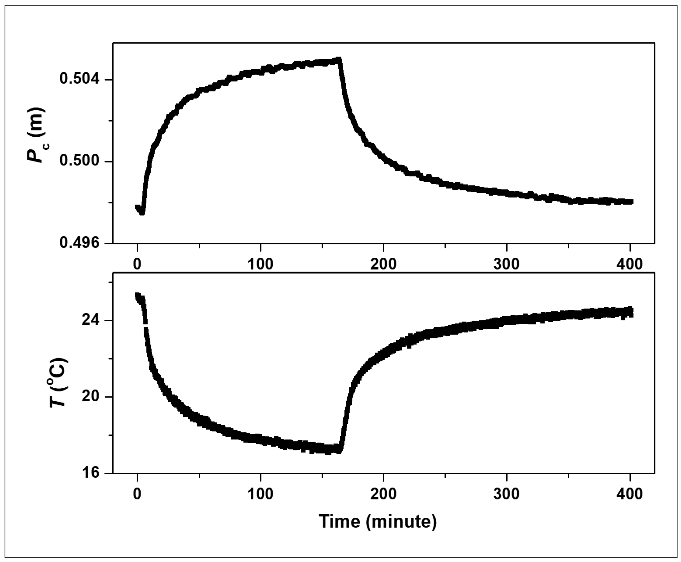

Fig. 3. The recorded position and temperature as a function of the time. The motion detector is placed (0.503 ± 0.002) m from the wall.

best fit gives the intersection of the plot to the vertical axis of (329.9 ± 0.8) m/s, which represents v_0, the speed of sound in air at 0 °C. The constant b is found to be (0.64 ± 0.03) m/s/°C. These values are in agreement with the reported article,[4] e.g., $v_0 = (331 \pm 3)$ m/s and $b = (0.60 \pm 0.06)$ m/s/°C.

We also monitored the output of the motion detector when the temperature was varied continuously. In this measurement the motion detector was stationary at a distance of (0.503 ± 0.002) m from the wall, and we gave an offset of –3.82 cm in the Sensor Setup. The obtained position and temperature were smoothed using the Savitzky-Golay smoothing option in the software Logger Pro and are presented in Fig. 3.

It is clearly shown that the measured position depends on the temperature. There is an inverse relationship between the measured position and the temperature. Based on Eq. (6) this relation is explicitly shown in Fig. 4. By applying Eq. (6) to fit the plot in Fig. 4, we obtain the gradient and the intersection of the plot with the vertical axis as $(3799 \pm 4) \times 10^{-6}\ \text{m}^{-1} \cdot {}^{\circ}\text{C}^{-1}$

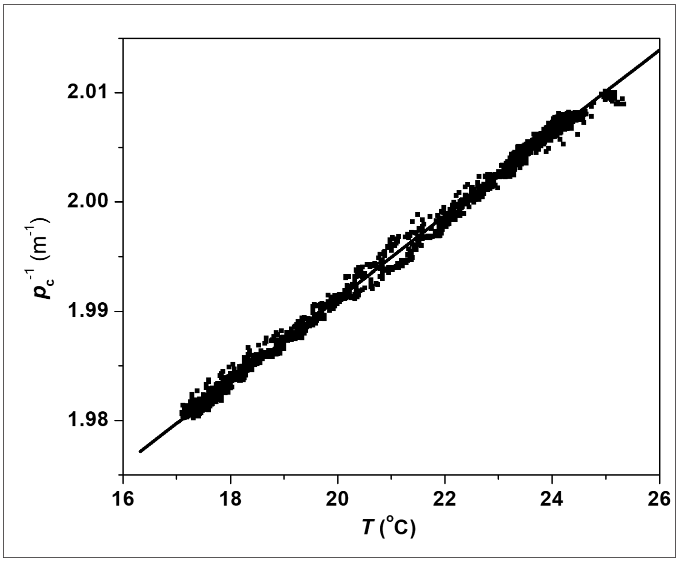

Fig. 4. Plot of p_c^{-1} vs. temperature. The solid line is the corresponding curve fitting to Eq. (6). The motion detector is placed 0.503 m from the wall.

and $(19{,}152 \pm 2) \times 10^{-4}$ m^{-1}, respectively. Using the values $d = (0.503 \pm 0.002)$ m and $v_s = 343$ m/s, the calculation yields $v_0 = (330.2 \pm 1.3)$ m/s and $b = (0.65 \pm 0.03)$ m/s/°C, respectively. The resulting speed of sound v_0 is similar to the value of (331 ± 3) m/s found in Ref. 4. The constant b is about 8% higher than the reported value (0.60 ± 0.06) m/s/°C.[4]

Discussion

The motion detector measures the elapsed time and then converts this time into the distance. The first experiment shows the effect of an offset of the system and a fixed speed of sound to calculate the distance. It causes discrepancy between the real distance and the measured position by the motion detector. By measuring the positions of various distances, we can estimate the speed of sound at certain temperatures and the offset. Here we have a constraint to keep the room temperature constant during experiment. Under the same experiment setup, the effect of the obtained offset can be corrected by giving this offset in the Sensor Setup. The temperature effect on the measured distance is used to calculate the speed of sound. A series of measurements at various temperatures gives a reliable result on the speed of sound at 0 °C.

The other method is also used to estimate v_0. Here we only monitor the distance as well as the temperature. Due to the relatively large size of our experiment room, it takes about seven hours to lower the temperature from 25.4 °C to 17.3 °C, and to rise back from 17.3 °C to 24.7 °C. Figure 3 shows that for a real distance of 0.503 m the obtained position ranges from 0.498 to 0.505 m. This fact demonstrates the effect of the temperature change. The readings vary by temperature due to the actual speed of sound being temperature dependent. In this experiment the temperature change of 8 °C generates a change of 7 mm in position. This change is significantly higher when being compared to the resolution of the motion detector itself, i.e., 1 mm.[2] For a better accuracy this effect should be corrected by taking account of the actual temperature during the experiment.

The resulting speed of sound at 0 °C v_0 and the constant b are in agreement with the other studies.[3,4,6] These results are sufficient for learning purposes. The undergraduate students will benefit from this straightforward experiment.

The method shown in this experiment utilizes the motion detector that provides data on the distance between the detector and the target. For the motion sensor that also provides data on the elapsed time, the speed of sound can be estimated directly.[7]

In summary we have presented a simple method for the pedagogical purposes of measuring the speed of sound. By doing so, one will be able to employ graphical representation to analyze the data. This experiment demonstrates the application of physics concepts, especially the temperature dependence of the speed of sound. In addition, this helps students to understand the limits of any measurement device.

Conclusions

The effect of temperature in measuring distance using a motion detector is significant. The presented experiment shows a reliable method to estimate the speed of sound at room temperature as well as at 0 °C. This method can be implemented in school.

Acknowledgments

The author would like to thank K. Heskett for useful discussions and the reviewer for very helpful comments.

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