An Arduino Investigation of Humidity and Temperature on Speed of Sound across Air and Water

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Abstract

Speed of sound as a mechanical wave is a property of the medium it is travelling through, however, the value of speed of sound is sometimes considered constant regardless of the physical condition. This study investigates the effect of temperature and humidity on speed of sound across air and water using an Arduino ultrasonic sensor coupled with a humidity and temperature sensor. The equation for the independent effect of temperature on speed of sound in air was found to be \(v = -0.27 * temperature + 349.39\) with a spearman correlation coefficient of 0.03. The speed of sound in air with humidity was found to follow the relationship of \(v = 0.34 * humidity + 324.78\) with a spearman correlation coefficient of 0.48. The compound effect of temperature and humidity of speed of sound was fit by \(v = 1.10 * temperature(^{\circ}C) + 0.95 * humidity + 270.77\) with a spearman correlation coefficient of 0.48. When studying the speed of sound through water, we observe that the speed of sound decreases and then increases as ice melts to water. Overall, the results are inconclusive and do not replicate current literature values [2]. This is likely due to the presence of errors in measurement and in the design of the study. Future experiments could be done by measuring the speed of sound using one distance and by collecting data over a continuous period of time.

1. Introduction

Sound as perceived by the human ears is the result of the propagation of a small disturbance in the air being transmitted to the inner ear, energy of which is eventually translated via the vibration of hair cells into electrical impulses that leads to the perceptual sensation of sound by the brain. Sound relies on particle interactions to transport its energy, which explains why no sound exists in the vacuum such as outer space. As a disturbance is initiated in a medium such as air, molecules create a series of compression and refraction, which can be modeled as a longitudinal pressure wave. The derivation of speed of sound therefore depends on the elastic property of the medium and state of the medium, which can be expressed as [x]:

$$\nu = \sqrt{\frac{\beta}{\rho}} \qquad [1]$$

where
$v = speed\ of\ sound,\ bulk\ modulus,\ \rho = density$

The speed of sound is a property of the medium. Thus, it is logical to assume that factors influencing particle interactions in air, such as temperature and humidity, would affect the speed of sound. While some traditional ways of finding speed of sound require complicated setup of digital storage oscilloscopes in combinations with microphones, ultrasonic sensors can achieve this by calculating the time lapse between emitted ultrasound waves and reflected sound waves. By controlling the target distance, the experimental speed of sound can be found with following:

Distance = ½ Time x Speed of sound [2]

In this study, we used an Arduino with an ultrasonic sensor in conjunction with humidity and temperature sensor to investigate and quantify the humidity and temperature effect on speed of sound in air and water.

Air over the range of temperature we investigate (5℃ to 28 ℃) at atmospheric pressure may be treated as ideal gas due to the system at low pressures and relatively high temperature, which follows the Ideal Gas Law [x]:

$$PV = nRT \qquad [2]$$

where P= pressure, V= volume, n=amount of substance, R=ideal gas constant, T=absolute temperature.

Using the gas law we can rewrite density as follows:

$$\rho = \frac{nM}{V} = \frac{nM}{\frac{nRT}{P}} = \frac{MP}{RT}$$

Laplace shows that the compression and refraction of sound waves follow adiabatic processes in which changes in temperature leads to higher elastic properties of air molecules, which can be expressed by [x] :

$$PV^{\gamma} = constant \qquad [3]$$

where $\gamma = C_p / C_V$ is the specific heats ratio of gas at its constant pressure to its constant volume. For diatomic molecules, γ= 1.40.

Taking the first derivative of Equation 3 we get (dP/dV) V^{γ} + gammaP$V^{\gamma-1}$ = 0, which can be rearranged to yield

$$(dP/dV) = -\ \gamma P/V$$

Using the definition of bulk modulus ($B = \ -V\frac{dP}{dV}$) along with equation [3], we get:

$$B = -V\frac{dP}{dV} = -\ V\ *\ \ -\gamma P/V\ =\ \gamma P$$

Finally, we can substitute B and density into Equation 1 to get::

$$v = \sqrt{\frac{\gamma RT}{M}} \qquad [4]$$

where M=molecular mass of gas.

Eq. 4 shows the temperature and humidity dependence of speed of sound. As temperature increases, speed of sound increases. As humidity increases, due to the decrease in molecular weight caused by water vapor present in air compared to dry air (18 g/mole for water versus 28.96 g/mole for dry air), speed of sound increases. Although there is a decrease in the specific heat ratio of humid air, the increased molecular weight dominates.

Thus, we hypothesize that through analysis of speed of sound over a seven day period with natural and forced environmental changes of humidity and temperature, we would expect to observe a trend that as humidity and temperature increases, the speed of sound in air would increase. We also hypothesize that there would exist a similar effect of temperature on the speed of sound in water, that the speed of sound in water increases as temperature increases. However, due to higher intermolecular forces in liquid compared to gas, we expect to observe an increase in the speed of sound in water as compared to air.

2. Methods

The experimental data were collected in a seven-day period at three different locations, using three different Arduino devices.

2.1 Effect of Temperature and Humidity on Speed of Sound in Air

In order to calculate the speed of sound at different temperatures and humidities we used an Arduino Uno R3 Controller Board, a HC-SR04 ultrasonic sensor, and a DHT11 Temperature Humidity module. The circuit diagram (FIG. \ref{fig:circuit}) shows how we connected the sensors to collect the temperature and humidity data, and FIG. \ref{fig:setup_air} shows our experimental setup for calculating the speed of sound in air at a particular temperature and humidity. The Arduino was programmed to send a sound wave for 10 μs then take a 2 μs break. The sound waves were pointed at a large flat object that would reflect the sound wave and the Arduino ultrasonic sensor recorded how long it took for the sound wave it emitted to be reflected off of the object and return. The distance between the object and the sensor was recorded. For each temperature and humidity, we measured the time at five different distances. The distances selected were in the range 10 - 30 cm at intervals of 5 cm +/- 0.1cm. This range was chosen because it was within the range of detection for our ultrasonic sensor and provided consistent results. For each distance, 100 time measurements were taken to reduce error. In order to obtain speed of sound data for a variety of temperatures and humidities, three members of the group collected data in indoor and outdoor settings and at different times of the day over a seven day period. Temperature and humidity variations are thus due to both natural causes (weather change) and man made reason (heating systems). Since all three data collectors are located in different continents (Asia, Europe, and North America), we were able to get a fairly diverse set of data with respect to temperature and humidity.

We also set up an experiment to see if the changes in the speed of sound from temperature were consistent across liquid medium, such as water. To do this we used a cup of tap water that was frozen and then let it sit at room temperature. We measured the depth of the iced water, which was 5.5 cm. We also measured the distance from the ultrasonic sensor to the top of the ice. The ultrasonic sensor measures the time it takes for ultrasound to travel to the bottom of the cup and back simultaneously as the temperature of the iced tap water rises to the temperature of the room, which was 26C. We took 500 time measurements at every 5 minute interval. The sensor and the reflecting surface were kept motionless to ensure accurate results.

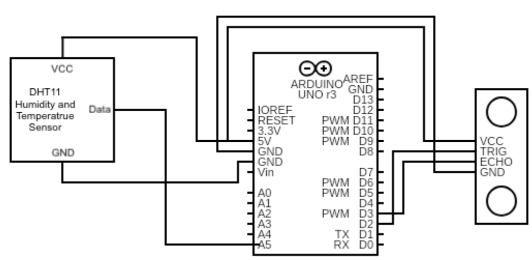

Figure 1: Arduino Setup
Diagram outlining the circuit setup used in the experiment to determine the speed of sound.

Figure 2: Ultrasonic Sensor Experimental Setup
The experimental setup used to determine the time taken by sound to travel a predetermined distance.

2.2

3. Analysis and Results

3.1 Effect of Temperature and Humidity on Speed of Sound in Air

After collecting the ultrasonic sensor data at five different distances for each temperature and humidity combination, we calculated the average time taken for sound to travel each of the distances. We then plotted the time against distance and obtained the best fit line for the plot. The best fit speed was obtained from the equation for the best fit line as indicated in Equation 1. We computed the best fit speed for each temperature and humidity.

$$Speed = \frac{distance}{time} = \frac{1}{\frac{time}{distance}} = \frac{1}{slope\ of\ time\ vs\ distance\ best\ fit\ line}$$

Equation 1

We first observed the independent effects of temperature and humidity on speed of sound. We plotted the speed of sound in air against humidity (Fig). The humidity range was from 41 - 80%. Using least square regression we obtained a best fit line. Additionally, we obtained a spearman correlation of 0.48 between the experimental and predicted speed values based on humidity. No strong trend is observed.

Similarly, we plotted the speed of sound in air against temperature (Fig). The temperature range was from 5 - 28℃. We obtained a best fit line using least square regression. Additionally, we obtained a spearman correlation of 0.03 between the experimental and predicted speed values based on temperature. We observe no strong trend.

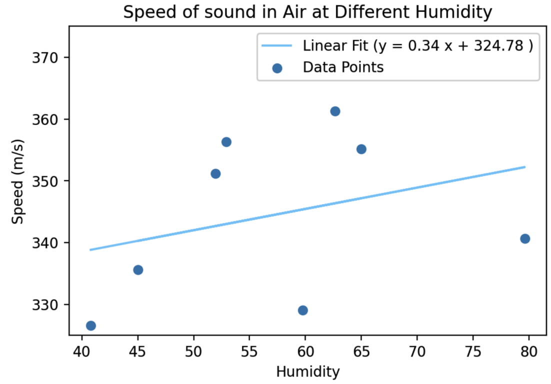

Figure 3: Speed of sound in air at varying humidities
The best fit line was y=0.34x+324.78. However, it did not fit the data well.

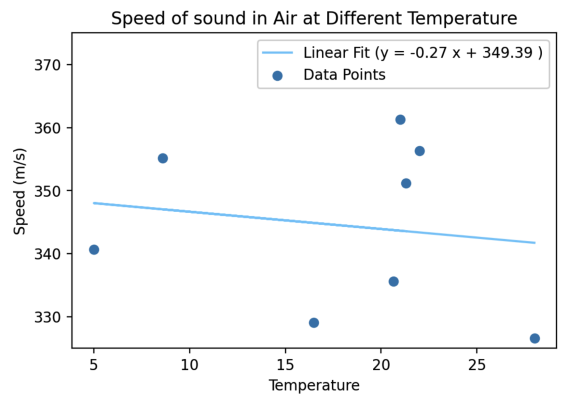

Figure 4: Speed of sound in air at varying temperatures
The best fit line was y = -0.27 x + 349.39. However, it did not fit the data well.

Additionally, we observed the combined effect of temperature and humidity on speed of sound in air. We use least square regression to model the relation between temperature, humidity, and speed of sound in air as seen in Equation 2. We obtained a spearman correlation coefficient of 0.48 between the experimental and predicted values of speed (Fig) indicating an absence of a definitive relationship between the variables.

$$v_{air} = 1.10 * temperature(\circ C) + 0.95 * humidity + 270.77$$

Equation 2

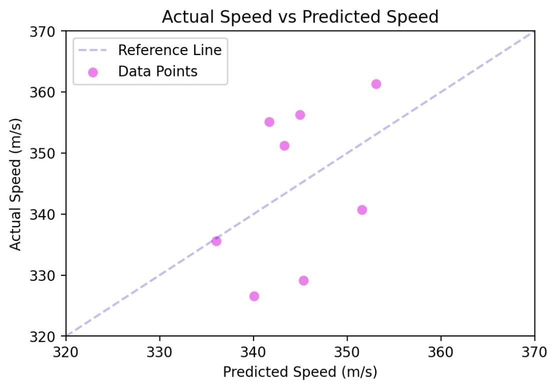

Figure 5: Experimental speed of sound in air vs predicted speed of sound in air using temperature and humidity

3.2 Effect of temperature on speed of sound in water

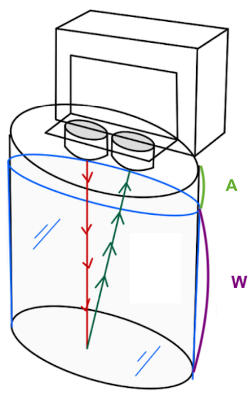

Figure 6: Experimental setup
A is the distance travelled by sound in air, while **W** is the distance travelled by sound in water

Prior to collecting the data, we made a few measurements at t = 0, when the container contained only ice. The distance between the ultrasonic sensor and the top of the ice was 1.0 cm (**A** in Fig), while the distance between the top and bottom of the ice was 5.5 cm (**W** in Fig). Assuming the speed of sound in air to be 343 m/s, we know that the time taken by sound to travel 2 * 1 cm would be:

$$time\ in\ air\ = \frac{distance}{speed} = \frac{2*10^{-2}m}{343\ m/s} = 58.31\ \mu s$$

To obtain the time travelled by sound through water, we subtract time sound travels in air from the total time taken. We then compute the speed of sound in water knowing that the distance travelled by sound in water is 11.0 cm. We then compute the speed of sound in water from the ultrasonic measurement taken at every five minutes. We plot the speed of sound in water at a five minute interval for a duration of 50 minutes against the time stamp. At t=0 minute, everything is pure ice. At t=50 minutes, the ice has fully melted and has been raised to the room temperature.

$$Speed\ of\ sound\ in\ water\ = \frac{distance\ in\ water}{time\ in\ water}$$
$$= \frac{distance\ in\ water}{total\ time - time\ in\ air} = \frac{11*10^{-2}}{(total\ time\ - 58.31)*10^{-6}}$$

Equation 3

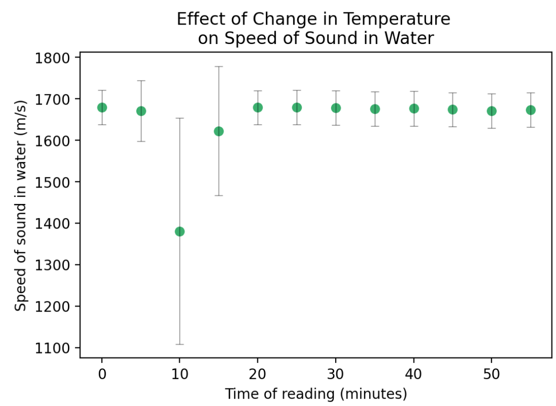

Figure 7: Effect of water temperature on speed of sound in water

We observe an initial decrease in speed followed by an increase in speed. At t = 20 minutes all the ice has melted and the speed of sound in water does not fluctuate anymore. This could be due to the fact that the water is at room temperature and there is no more change in state or temperature of the medium.

4. Discussion and Conclusion

4.1 Effect of Temperature and Humidity on Speed of Sound in Air

Figs. 3 and 4, which show the graph of humidity and temperature independently plotted against the speed of sound in air, gave no conclusive evidence to suggest there was a correlation between the speed of sound in air and humidity or temperature. The spearman correlation between the actual and best fit speeds was 0.48 with varying humidities and 0.03 with varying temperatures, which indicate no clear trend.

The lack of data points is one of the greatest factors in our failure to produce meaningful results. The methodology we adopted relies on manually changing the target distance from the ultrasonic sensor to find the speed of sound via the best fit line. This process results in errors in at least two ways. One is that the process needs to be repeated over at least five distances to find the speed of sound, which greatly limits the amount of data we can possibly obtain in a short amount of time. Secondly, since we are required to measure the distance between the sensor and the target object, this leads to human error in measurement of +/- 0.05cm. In comparison, we found that other studies were successful in replicating the literature speed of sound at 0 ℃ (V_0 = 331.45 m/s [2]) by obtaining data in real time with an Arduino ultrasonic sensor and a temperature sensor, during a long interval of 14 hours [3] with the sensor placed at a single distance. This method could be adopted for future experiments, as it is a more efficient way of obtaining large datasets across various temperatures and humidities, as well as making sure the conclusions drawn from the data is more reliable due to the higher number of data points.

Another source of error could be due to the fact that the temperature humidity sensor of our choice is not fit to capture the temperature fluctuation of the environment. DHT11 sensor gets new data every 2 seconds [4], thus the temperature and humidity readings we obtain are 2 seconds old. In one study of temperature effect on speed of sound, it is found that fans and heaters generate great fluctuation in temperature and increase the errors[3]. In our study, location of measurements were not taken into consideration and some data are indeed recorded in an indoor setting near the heater. One way to circumvent this issue is to conduct speed of sound measurement in a room away from the heat source. Also, more temperature sensors can be used simultaneously to make it possible to obtain average temperature measurement throughout the experiment to minimize temperature deviation, as we have found that this has been done in one study [3].

Additional errors in our study may have also arisen from different ultrasonic sensors emitting sound waves of slightly different frequencies, leading to a shift in the measured speeds of sound when measured with different Arduino ultrasounds. Since the humidity and temperature probe operates within a humidity range of 20%-80% (+/- 5%) and a temperature range of 0-50 ℃ (+/- 2℃) [4], the probe may have measured data inaccurately, contributing to even more errors. To ensure that the results are less affected by fluctuations in data, future studies should remove outliers in the raw data before proceeding with analysis.

4.2 Travel time of sound in ice through time

We observe a much higher average speed of sound in water, 1647 m/s, as compared to the average speed of sound in air, 345 m/s. This was in accordance with our expectations since water is much denser than air and allows for faster propagation of sound.\\

While we do not see the expected trend of increasing speed with increasing temperature in our data, there are some features worth discussing. Figure 7 shows that there is an initial decrease in the speed of sound in the medium as the ice melts, peaking at 1381 m/s at t = 10 minutes into the experiment. This could be attributed to the volume of water decreasing as the ice melts. As the volume of water decreases, sound spends more time in air. Since the speed of sound is lower in air, not accounting for the change in volume can lead to a measured decrease in the speed of sound in the water. We also observe that the standard deviation of the time also increased during this period, as the medium became partially solid and partially liquid. This could be due to sound waves bouncing off of ice pieces in water, causing inaccuracies in the measured speed of sound.

Later, the speed of sound increased, possibly due to the increasing temperature. We also observe that the speed becomes constant after the ice completely melts at t = 20 minutes. This could be due to the water approaching the room temperature, which is approximately constant.

However, lack of data also presents as a challenge in this experiment. More data needs to be taken at shorter intervals in order to establish a more reliable dataset and thus a more reliable conclusion. In the future, a waterproof ultrasonic sensor might be a better option, since it would ensure that the time-measurement was only in water, and that the sound is not travelling across two different mediums through the air-water barrier. Additionally, we may have found more accurate results for the speed of sound in water over a range of temperatures if the water did not have any ice that would alter the speed of sound. One such example is by cooling the water through lowering the pressure of the environment to cool the water.

5. References

Need to update this later

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6. Appendix

Arduino Code