Measuring the Speed of Sound with an Ultrasonic Range Finder

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The speed of sound in an ideal gas depends on the temperature, the average mass of the gas molecules, and the adiabatic index. All three of these variables change during a high-altitude balloon flight. In particular, the drastic temperature changes cause variations of the speed of sound in excess of 10%, which are easily measurable with low-cost ultrasonic range finder. These sensors consist of a speaker that emits short bursts of sound waves, and a microphone that listens for an echo from a reflection off a nearby object. A microcontroller measures the time it takes for the sound waves to return to the sensor. Using this measured travel time and estimations of the speed of sound in air, ultrasonic sensors are commonly used to measure distances in robotics applications. We will present an experiment in which we mount an ultrasonic sensor inside a payload pod to measure the speed of sound during a balloon flight. Because the physics of sound waves is an important part of the introductory physics sequences at most universities, this experiment provides a rich context for integrating high-altitude ballooning into the curriculum.

I. Introduction

Ultrasonic range finders are widely used in robotics and physics lab activities to measure distances. They emit short bursts of ultrasonic sound waves and measure how long it takes for the sound waves to return after they have been reflected by a nearby object. The distance to the object is then calculated by multiplying one half of this round-trip travel time by the known speed of sound in air. Our experiment uses an ultrasonic range finder in reverse. The device is mounted on the inside wall of a polystyrene pod, and the ultrasonic sound waves are reflected off the opposite wall. Thus, the distance travelled by the sound waves is known. As the speed of sound changes under the changing conditions of the atmosphere, the travel time varies, giving an estimate of the changing speed of sound.

II. The Speed of Sound in an Ideal Gas

The speed of mechanical waves is determined by the elastic and the inertial properties of the medium through which the waves travel:

$$c = \sqrt{\frac{\text{elastic property}}{\text{inertial property}}}$$

The harder it is to compress a medium, and the lower its inertia, the faster the mechanical waves travel through this medium. For gases the elastic property in the above equation is given by the bulk modulus B, which is the inverse of the compressibility and quantifies how much the volume of a gas V changes when the pressure P is increased or decreased.

$$B = -\frac{\Delta P}{(\Delta V/V)}$$

The inertial property of a gas is simply its density. The lower the density of a gas, the higher the speed of sound, so the speed of sound in a gas is

$$c = \sqrt{\frac{B}{\rho}}$$

Pressure changes in sound waves occur very quickly, so there is not enough time for heat transfer, and we can assume that the pressure changes adiabatically ($PV^{\gamma} = \text{const.}$). The bulk modulus becomes

$$B = \gamma P$$

where γ is the adiabatic coefficient. For the diatomic gasses O_2 and N_2, which make up 99% of the atmosphere, the adiabatic coefficient is 1.4. For ideal gases the pressure is given by

$$P = \frac{\rho R T}{M}$$

and the speed of sound becomes

$$c = \sqrt{\frac{\gamma R T}{M}} = 20.05\sqrt{T}$$

M = 0.029 kg/mol is the mean molar mass of dry air, R = 8.314 J/K mol is the ideal gas constant, and T is the temperature in Kelvin. Note that because the pressure of an ideal gas is proportional to its density, the speed of sound does not depend on either one of these variables. For moist air some of the O_2 and N_2 molecules are replaced by water molecules, resulting in a slightly lower mean molar mass. Furthermore, the adiabatic index of humid air is slightly smaller because water is a triatomic molecule, not a biatomic molecule like N_2 and O_2. As a result, the speed of sound in moist air is slightly higher than in dry air. However, even for 100% humidity the effect is very small. For example, difference between the speed of sound for 0% and 100% relative humidity at $T = 15°C$ and $P = 101.3$ kPa is only approximately 0.3%. Figure 1 shows the speed of sound calculated for temperature distribution of a standard atmosphere [1].

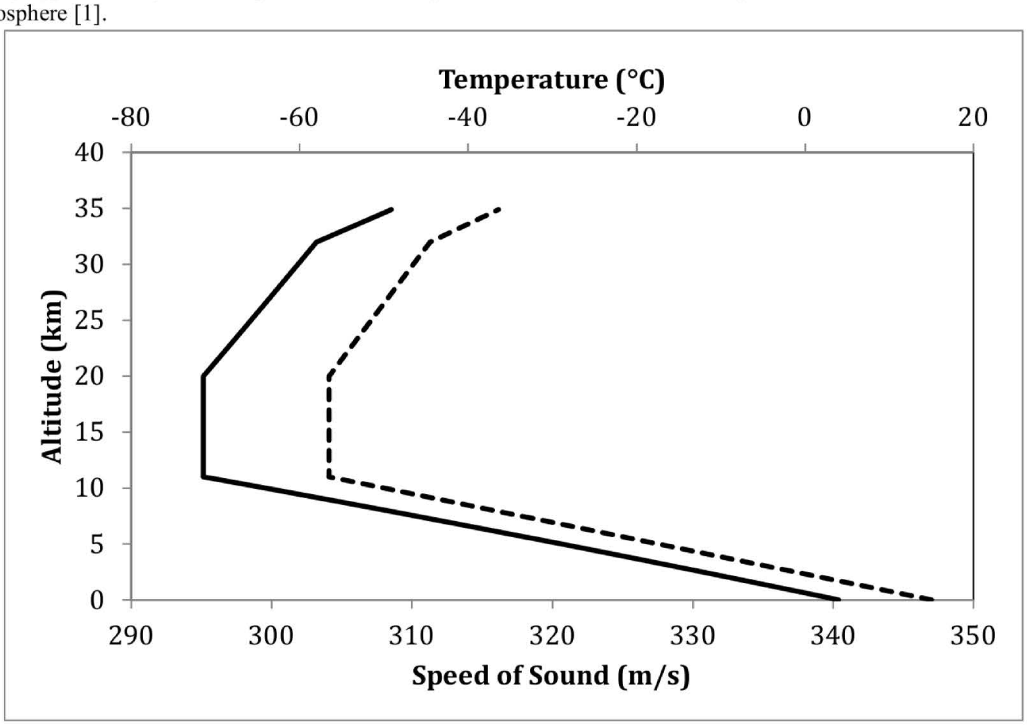

Figure 1: The speed of sound at altitudes between 0 km and 35 km (solid line), which has been calculated based on the temperature distribution of a standard atmosphere (dashed line).

III. Design of the Experiment

Our experiment employs a common and inexpensive ultrasonic range finder to measure the roundtrip travel time of a reflected ultrasonic pulse inside of a pod. We use a "Ping)))™ Ultrasonic Distance Sensor" manufactured by

Parallax Inc. (www.parallax.com) which at the time of purchase cost $29.95. There are similar products available which are priced as low as $9.99 (e.g., VirtuaRobotix LLC).

The Ping))) operates in the following way: First, one sends a small 3.3V or 5V pulse to the unit (2 to 5 microseconds). Then, after a short period of 750 microseconds (called the "holdoff time"), the unit emits an 40kHz ultrasonic pulse that is 200 microseconds long. At this time the Ping))) unit sets the communication pin high. When the reflected pulse is detected the communication pin is set back to low. The time of travel is the period that the communication pin is high:

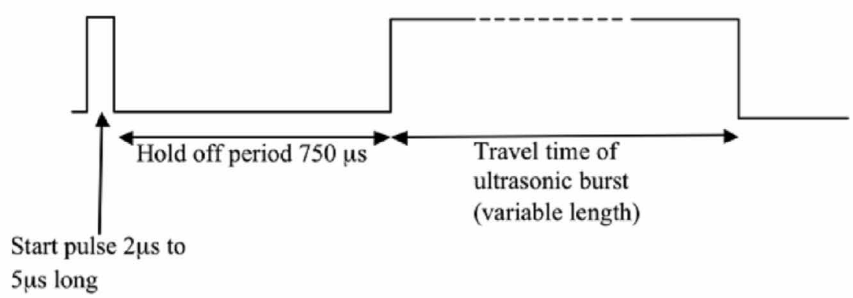

Figure 2

The Ping))) sensor uses a single pin as an input (listening for the start pulse) and as an output (transmitting the travel time pulse). The hold off period allows the microcontroller enough time to switch the mode of communication pin from output to input. Other sensors use separate pins for the input and output, but the concept is identical.

Most commonly used microcontrollers have a built-in function for measuring the length of an incoming pulse. For example, the BasicX microcontroller in our experiment uses the following two lines of code:

```
' Send a 5 x (8/7372800) second long high pulse
Call PulseOut(pingCommunicationPin,5,1)

' Measure travel time of the pulse in (8/7372800) sec. units
PulseWidth = PulseIn(pingCommunicationPin,1)
```

In the case of an Arduino microcontroller, the following code will accomplish the same task:

```
unsigned long duration;

//Send a 5 microsecond pulse

pinMode(pingCommunicationPin, OUTPUT);
digitalWrite(pingCommunicationPin, LOW);
delayMicroseconds(2);
digitalWrite(pingCommunicationPin, HIGH);
delayMicroseconds(5);
digitalWrite(pingCommunicationPin, LOW);

//Change the mode of the communication pin
```

```
pinMode(pingCommunicationPin, INPUT);

//Measure the duration of the travel time in microseconds
duration = pulseIn(pingCommunicationPin, HIGH);
```

Our Ping))) was mounted on one vertical wall of a rectangular polystyrene experiment pod. The sound echoed off a sheet of plastic mounted on the opposite wall approximately 16 cm away. The time and time travel duration was recorded in the memory of the processor and read out after the flight.

IV. Preliminary Results

Figure 3 shows preliminary data collected by Wendy Vergara (Curie High School) during a launch we carried out from Kankakee, IL on July 26, 2011 as part of a high school summer research program. The solid line shows the predicted speed of sound based on the equation derived in section II. Because we do not have the capability to take accurate temperature measurements (see below), we used the temperature data for Central Illinois (ILX) published for the date of our flight on the University of Wyoming web site [2]. Our measured speeds agree reasonably well with the predictions until the balloon reaches the tropopause at an altitude of 17 km. Whereas the predicted speed starts to increase as the balloon enters the warmer air in the stratosphere, the measured speed continues to decrease until the ultrasonic ranger can no longer detect the reflected signal at an altitude of 17.8 km. We currently do not have a good explanation for this discrepancy between predicted and observed speed of sound, but it is consistent with the findings of the McNeese LaACES Group Sound Experiment payload [3].

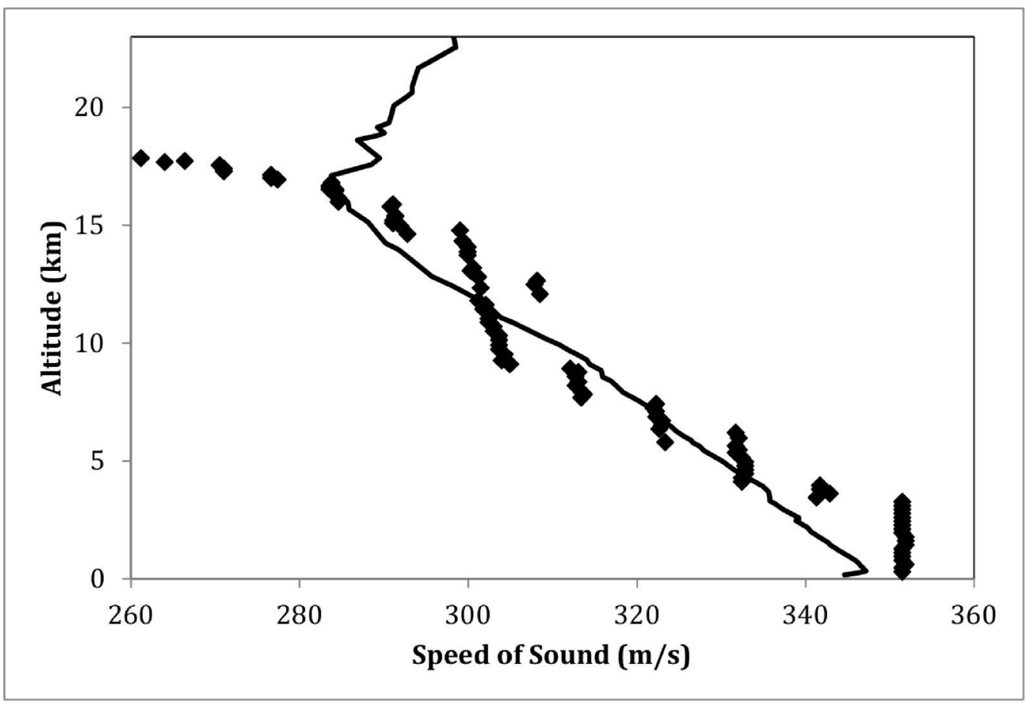

Figure 3: Speed of sound measured with the ultrasonic range finder (solid diamonds) and calculated from the temperature (solid line).

V. Limitations and Challenges

The two most appealing aspects of this experiment may be its simplicity and low cost. The data shown in figure 3 was collected by a high school student with very little experience in programming and experimental design. Overcoming the obvious limitations of the experiment can be an excellent challenge for more advanced students. For example, to generate accurate predictions for the speed of sound at different altitudes one needs to know the temperature. However, accurate temperature measurements are challenging because of the thermal inertia of the pod and the response time of the temperature sensor. Thus, the experiment pod is never in thermal equilibrium with its surroundings, and the measured temperature lags behind the rapidly changing air temperature. We suggest that students first do experiments in a freezer on the ground, where one can wait long enough for the pod and electronics to achieve thermal equilibrium and perhaps model some of the complex thermal effects. Another limitation is that the sound signal becomes undetectable shortly after the balloon enters the stratosphere. In our first test run this occurred at an altitude of 18 km and a pressure of 70 kPa. Students could design ultrasonic sensors (or modify existing ultrasonic sensors) to work at lower pressures; such designs could be first tested on the ground in a vacuum chamber. Another limitation is that the frequency of the processor varies with temperature (primarily due to the crystal); hence timing will change as a function of temperature. This temperature effect should be quantified.

VI. Conclusion

Low-cost ultrasonic range finders commonly used in robotics provide a simple way to measure the speed of sound during balloon flights. Experiments such as the one presented in this paper are appropriate for both high school students and college non-science majors in general education courses. Our preliminary results demonstrate that the speeds measured with these devices in the troposphere agree reasonably well with predictions based on the temperature distribution. Interesting challenges that could be tackled by more advanced students include more accurate temperature measurements to improve modeling of the speed of sound at different altitudes, extension to lower atmospheric pressures, and an investigation of the discrepancy between predicted and observed temperatures above the tropopause.

References

[1] National Oceanic and Atmospheric Administration, National Aeronautics Space Administration, United States Air Force, "U.S. Standard Atmosphere, 1976," U.S. Government Printing Office, Washington, D.C., 1976

[2] University of Wyoming Weather Web, URL: http://weather.uwyo.edu/

[3] M. Stewart, M., Browne, D., Ellison, B., Giammanco, J., Granger, D., Guzik, T. G., Wefel, J. P., "The Louisiana Space Consortium Student Sounding Balloon Program," Proceedings of the 2nd Academic High Altitude Conference, pp. 125-134, 2011