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Speed of Sound in Gases Measured by in Situ Generated White Noise

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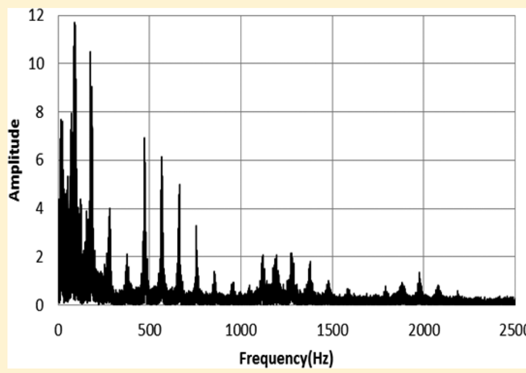
Supporting Information

ABSTRACT: The speed of sound in gases is measured by in situ generated white noise in an acoustic tube. The white noise is generated by the expansion of compressed gas rather than electronically. An acoustic tube acts as a resonant filter. A Fourier transform of the recorded sound pressure can identify the resonant acoustic modes which can be related back to the speed of sound in the gas. The student results with this method were compared to prior student results which measured the wavelength of single frequencies by phase comparison. The Fourier transform method using in situ generated white noise showed better accuracy.



KEYWORDS: *Laboratory Equipment/Apparatus, Laboratory Instruction, Physical Chemistry, Fourier Transform Techniques, Gases, Heat Capacity, Physical Properties, Thermodynamics, High School/Introductory Chemistry, Upper-Division Undergraduate*

Measurement of the speed of sound has been a standard experiment in laboratory courses from introductory physics[1] to physical chemistry. The speed of sound has been used to calculate the heat capacity ratio (γ) of gases in the physical chemistry laboratory courses for many years.[2−4] The speed of sound in a gas is related to the heat capacity ratio by

$$\gamma = \frac{Mc^2}{RT} \tag{1}$$

where M is the molar mass and c is the speed of sound. We refer the reader to nice derivations of this equation in the Halpern and McBane[4] and the Garland et al.[3] physical chemistry laboratory texts. Measurement of the speed of sound has also been used as an acoustic gas analyzer.[5]

The classical method uses a Kundt's tube with a resonant single frequency tone and measures the spacing of the nodes in a standing wave. Originally, this was achieved by light material such as lycopodium powder accumulating at the acoustic nodes.[6] With the availability of audio frequency generation, the method was adapted to measure the nodal spacing via a moveable microphone. The definitive monotone method uses an oscilloscope to compare the phases of the incident and propagated acoustic wave. The resonant frequency of a tube is dependent on the tube length and the speed of sound of the gas filling the tube. The series of resonant frequencies is dependent on the imposed boundary conditions for the tube. Steel et al.[7] and separately Martin[1] realized that the Fourier transform of the resonance tube's response to white-noise excitation could be used to determine the speed of sound in gases. White noise is random noise that has a uniform distribution of frequency components.[8] The resonance tube effectively acts as a filter eliminating the nonresonant frequencies. Both Steel and Martin generated the white-noise excitation through electronic means such as a sound-tone generation program like CoolEdit. This requires an additional computer and possibly amplifier to perform the experiment. We realized that a nonelectronic source of white noise was obtainable from the flow of gas into the resonance tube. This reduces the amount of specialty equipment needed to perform this experiment. The measured frequency spectrum of rushing gas from the laboratory house compressed air line is shown in Figure 1. While it is not a

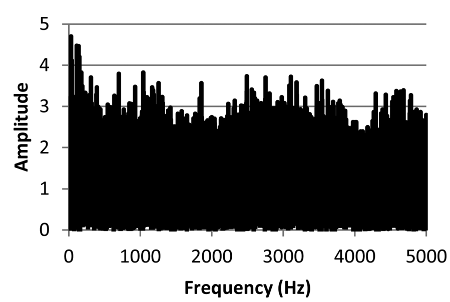


Figure 1. Spectrum of the sound of compressed air from the laboratory house compressed air-line. This is a reasonable approximation of "white noise", even though there is some variation in the amplitude with frequency. The spectrum of ideal "white noise" would have a constant amplitude over the entire frequency range.

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perfect white-noise spectrum with constant power density across all frequencies, it does contain all the frequencies at sufficient amplitude to measure the resonance. The frequency spectra of gases from compressed gas cylinders were comparable.

APPARATUS

The resonance tube was assembled from commonly available 1 inch Schedule 40 PVC plumbing pipe and fittings. The fittings consist of two end-caps and three tee-fittings. One of the end-caps has a small hole drilled to accept a thin thermocouple. Two of the tee-fittings have the perpendicular fitting threaded to accept a hose barb. The third tee-fitting has the perpendicular fitting sized to fit a rubber stopper that has been bored to accept the Vernier microphone. A schematic diagram of the apparatus is shown in Figure 2, with a close detail

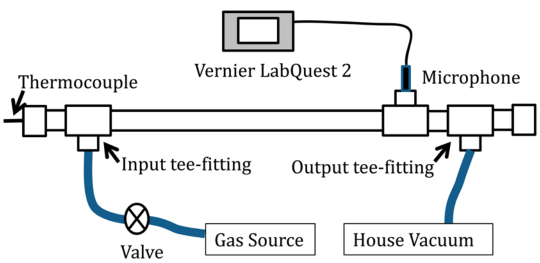

Figure 2. Schematic diagram of resonance tube. The white-noise sound is generated by turbulence caused by the gas expanding as it enters the input tee-fitting.

photograph in Figure 3. The fittings are all slip fit and not glued. The overall length of the tube is measured after assembly.

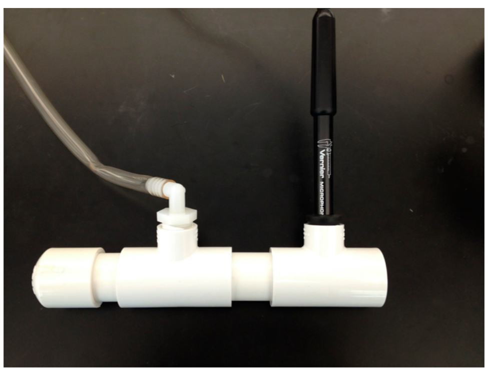

Figure 3. Close up detail of the end-cap, the tee-fitting with hose barb and the tee-fitting used to mount the microphone. This is the output tee-fitting; the input tee-fitting is similarly configured.

Different lengths will move the positions of the acoustic resonances. For this work most data was collected at a 1407 mm tube length, but tube lengths from 346 to 1835 mm were tested. The shorter the tube is, the greater the spacing between resonances, and hence, fewer resonances were measured. The approximately 1.5 m long tube yielded sufficient number of resonances even for the fastest gas, helium.

Sound data was collected on a Vernier LabQuest2. The temperature was measured with a thin wire type K thermocouple with an H800 thermocouple meter both from Omega Engineering. The thin wire thermocouple was used to minimize thermal mass. The use of the house vacuum connection (a low vacuum provided as a utility on our benches building-wide from a central vacuum pump) simplifies the purge process. Purging the apparatus was difficult with our previous Kundt's tube apparatus especially for measuring helium. Additionally, the vacuum line exhausts the gases away from the lab. The measurements also work when venting to atmosphere without the vacuum connection.

EXPERIMENTAL SECTION

Student instructions for the experiment are provided as Supporting Information. Making a measurement with the system is straightforward. The house vacuum is turned on which evacuates the system. The LabQuest2 is set to record the sound wave monitored at the microphone at 10,000 samples/s for five seconds. The gas valve is opened; the rushing gas generates white noise. The data recording is started. Once the recording is complete the gas is shut off. The raw sound pressure data shown in Figure 4 has the resonant frequency components with

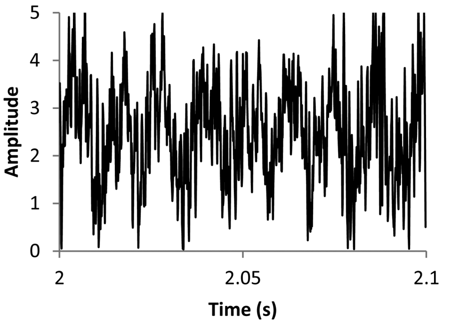

Figure 4. Raw sound pressure data from carbon dioxide in a 1407 mm acoustic tube. This figure shows 0.1 s of a 5 s data collection.

greater amplitude compared to that of the nonresonance frequencies. A Fourier transform of the data as shown in Figure 5

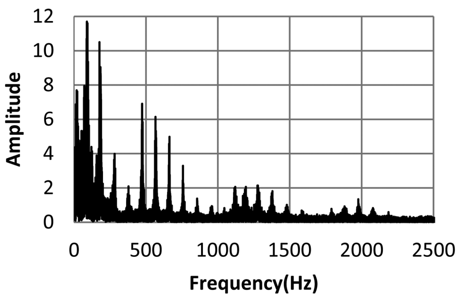

Figure 5. Sound data after application of Fourier transform to convert into frequency domain. Resonant peaks are clearly seen. The envelope of the peaks arises from two contributions: (1) the "white noise" generated not having a uniform power density across the frequencies and (2) the microphone location being close to nodes of certain frequencies standing waves.

identifies the resonant frequencies of the resonance tube. The data can be analyzed on the LabQuest2 using the FFT option, but we found it easier to transfer the data to a PC. FFT analysis is available on the LoggerPro software, but not the LoggerLite software. Students found it easiest to connect a laptop with LoggerPro to the LabQuest2 to perform the analysis.

The envelope of the peaks in the Fourier transform shown in Figure 5 probably arises from several contributions. Martin[1] in prior work attributed the envelope he observed to a combination of wave diffraction and nonlinear responses in the

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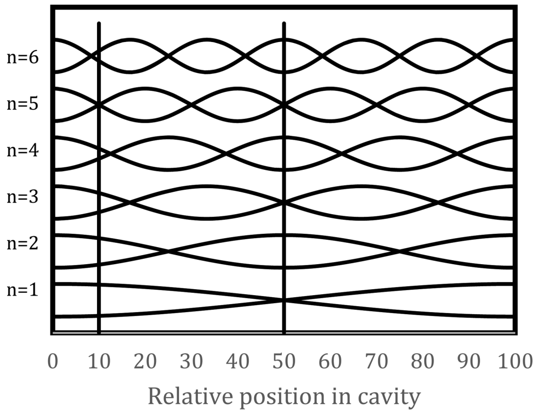

Figure 6. Illustration of standing waves in a tube. Notice that the location of the microphone will determine whether it will be near a node or antinode for a particular harmonic. For example, if the microphone is placed at 10% of the cavity length, the fifth harmonic will be at a node, and the fourth and sixth will be at a lower amplitude. The extreme of this is if the microphone is placed directly at the halfway point of the cavity where all odd harmonics will be at a node.

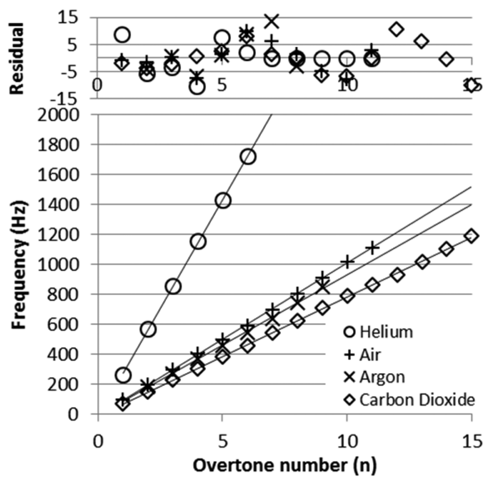

Figure 7. Resonant peaks for helium, air, argon, and carbon dioxide plotted against overtone number for a 1.695 m path length. The residuals of the fit are plotted above.

transducers. We posit a couple of explanations for different elements of the envelope structure: frequency dependence of the microphone sensitivity, greater attenuation of the higher frequency components, nonuniform power density of the generated white noise, and the location of the microphone. Since this apparatus has the microphone positioned approximately 205 mm away from the end of the cavity, it is located at a node for the 3rd, 10th, 17th, etc., overtones of the 1407 mm cavity. The amplitude of the standing wave at a given position (x) in acoustic cavity of a given length (L) can be given by $\cos^2(\pi n x/2L)$ as shown in Figure 6. Simulation of the microphone position reproduces the envelope structure well. If the microphone was located directly in the center of the resonant cavity, every other overtone would be at a node and thus not appear in the spectrum. Ideally, moving the microphones position as close to the end as possible will minimize this envelope structure. The other key factor in the structure of the envelope is increasing attenuation at higher frequencies.

■ DATA ANALYSIS

The peak positions are graphed against an integer position.

$$\nu_n = \frac{nV_S}{2L} \tag{2}$$

Here, ν_n is the nth overtone frequency, V_S is the speed of sound, and L is the cavity length. Thus, plotting the resonant frequencies versus n yields a line with a slope equal to $\frac{V_S}{2L}$, providing an easy pathway to calculate the speed of sound from the fit slope. Figure 7 shows typical data collected for four different gases along with the fit line and residuals. Table 1 compares the speed of sound measured by this method with temperature corrected literature values.[9] The temperature corrections were made by scaling by the square root of the temperature (K). The speed of sound of an ideal gas should be pressure independent, but real gases will display a pressure dependence due to intermolecular interactions.[10] Under the perfect gas condition ($p \rightarrow 0$), the isobaric heat capacity $C^{\circ}_{p,m}$ can be determined by[10]

$$C^{\circ}_{p,m} = \frac{R}{1 - \frac{1}{\gamma}} \tag{3}$$

Table 1. Measured Speed of Sound for a 1.695 m Path Length Resonance Tube

Gas	T, °C	Speed of Sound, m/s: Measured	Speed of Sound, m/s: Literature[a]	Error, %	Calculated γ	Calculated C_p
Air	22.3	344.5 ± 1.8	344.7 (dry air)	0.1	1.381 ± 0.010	30.12 ± 0.22
CO_2	22.2	268.8 ± 1.2	269.3	0.2	1.295 ± 0.008	36.51 ± 0.23
Argon	21.9	318.8 ± 4.5	320.0	0.4	1.655 ± 0.033	21.01 ± 0.42
Helium	21.1	982.7 ± 6.9	1001.6	1.9	1.580 ± 0.016	22.65 ± 0.23

[a]The literature values were corrected to the measurement temperatures.

Table 2. Average Error of Student Measured Speed of Sound Relative to Literature Values

	Phase Method, Fall 2014, n = 4 Groups		FFT Method, Fall 2015, n = 6 Groups	
Gas	Average Error, %	Relative Standard Deviation, %	Average Error, %	Relative Standard Deviation, %
Air	4.1	8.0	0.7	4.1
CO_2	1.3	12.5	1.1	1.5
Argon	6.9	7.7	1.3	4.1
Helium	30.2	19.1	4.7	5.4

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Table 2 compares the average error of student measured speed of sound relative to the temperature corrected literature values. The phase method used a commercial Kundt's tube (35 cm long) measuring the relative phase of the incident sound wave and various positions throughout the tube.[4] The phase of the signal was measured by a Lissajous figure comparing the signal provided to the speaker and the signal detected by the microphone.

The FFT method with in situ generated white noise does show a reduction in average error and relative standard deviation of the results. The most marked improvement was with helium which has been the most difficult gas for students to measure due to the low amplitude signal. Generating the "white noise" by the expansion of gas and measuring the resonances with a low cost Vernier LabQuest2 provides an affordable method to make these measurements.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.6b00407.

Student instructions for the experiment (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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