Measuring the Speed of Sound with a Straw Flute

NEHS Eve Wang

1. Objective

This experiment uses the resonance principle of a straw flute to measure the speed of sound in air. By varying the effective length of the straw and measuring the resonance frequencies, we establish the relationship between frequency and length, then apply linear regression to estimate the speed of sound. This allows verification of the standing-wave model and comparison with theoretical predictions.

2. Theory

2.1 Resonance Phenomenon

A physical system vibrates at its natural frequency when disturbed. If the driving frequency matches this natural frequency, resonance occurs, greatly amplifying oscillations. In acoustics, this resonance can efficiently transfer vibrational energy into sound waves at specific frequencies.

2.2 Resonance of a Closed Tube

When sound waves reflect inside a tube, incident and reflected waves superimpose to form standing waves. In a tube closed at one end and open at the other, the closed end is a node and the open end is an antinode. The tube length L and wavelength λ satisfy:

$$L = \frac{(2m-1)\lambda}{4}, \quad m = 1, 2, 3, \ldots$$

Thus the resonance frequency is

$$f_m = \frac{(2m-1)v}{4L}, \quad m = 1, 2, 3, \ldots$$

where v is the speed of sound. For the fundamental mode ($m = 1$):

$$L = \frac{\lambda}{4}, \quad f_1 = \frac{v}{4L}.$$

2.3 End Correction

In reality, the open end does not correspond exactly to an antinode. Air oscillates slightly outside the opening, effectively extending the acoustic length:

$$L_{\text{eff}} = L + \Delta,$$

where Δ is the end correction. By plotting f versus $1/L_{\text{eff}}$ and performing regression, Δ can be determined from the intercept, and the slope used to calculate a corrected value of v.

3. Apparatus

- Straw flute: transparent wide straw (diameter ≈ 1.1 cm)
- Adjustable piston: chopstick wrapped with tissue and tape
- Measuring tools: ruler, marker
- Frequency analysis: smartphone microphone and Phyphox app

4. Procedure

1. **Construction of straw flute**
   (1) Prepare a wide straw as the tube body.
   (2) Wrap a chopstick with tissue and tape to serve as a movable piston; insert into one end ensuring airtight yet movable fit.
   (3) Mark the straw at 1 cm intervals from the open end up to 15 cm.
2. **Measuring frequency**
   (1) Blow across the open end and record the waveform with Phyphox.
   (2) When a stable sinusoidal waveform appears, record the frequency (two significant figures).
   (3) Repeat at least three trials for each length and take the average.
3. **Analysis**
   (1) Calculate $v_i = 4Lf$ for each length and compute the average speed.
   (2) Plot f vs. L and f vs. $1/L$.
   (3) Perform linear regression on f vs. $1/L$ and check whether the intercept is zero.
   (4) Introduce end correction Δ, adjust $L_{\text{eff}} = L + \Delta$ until the intercept approaches zero.
   (5) Estimate v from the regression slope and compare with the average method.

5. Data and Analysis

5.1 Raw Data and Average Method

For each L, $v_i = 4L\bar{f}$ was computed.

Table 1: Resonance frequencies and calculated speeds of sound at different lengths

L (cm)	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)	$\bar{f}$ (Hz)	v (m/s)
2	2850.89	2455.78	2399.50	2568.72	205.50
3	1923.65	1952.48	1946.96	1941.03	232.92
4	1599.67	1630.23	1609.73	1613.21	258.11
5	1341.66	1346.00	1361.06	1349.57	269.91
6	1193.26	1198.45	1203.68	1198.46	287.63
7	1061.95	1067.57	1066.44	1065.32	298.29
8	944.07	943.03	945.10	944.07	302.10
9	862.40	861.49	860.58	861.49	310.14
10	785.86	784.15	785.01	785.01	314.00
11	714.74	717.03	716.27	716.01	315.04
12	669.39	665.11	666.53	667.01	320.16
13	622.57	621.90	623.92	622.80	323.86
14	582.66	583.95	582.87	583.16	326.57
15	554.80	556.08	557.43	556.10	333.66

The average method gives $v \approx 292.71$ m/s. Compared with the theoretical 346.30 m/s at 25°C, the error is about 15.5%.

5.2 Frequency vs. Length

Fig. 1 f vs. L

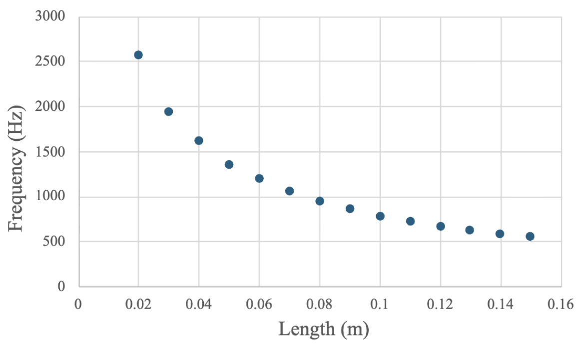
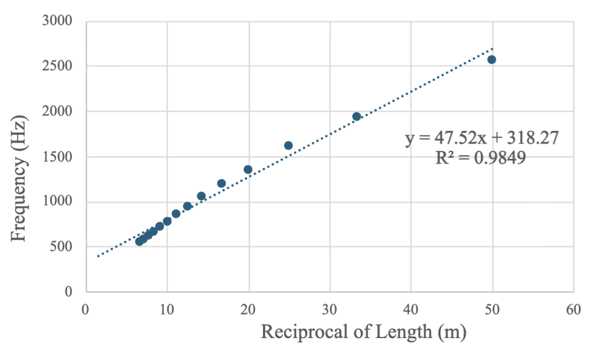


Fig. 2 f vs. $1/L$



The results show $f \propto 1/L$, consistent with theory.

5.3 End Correction and Regression

The regression of f vs. $1/L$ shows a nonzero intercept, indicating an end effect. Adjusting $L_{\text{eff}} = L + \Delta$, the best correction was $\Delta \approx 1.574$ cm, yielding an intercept near zero.

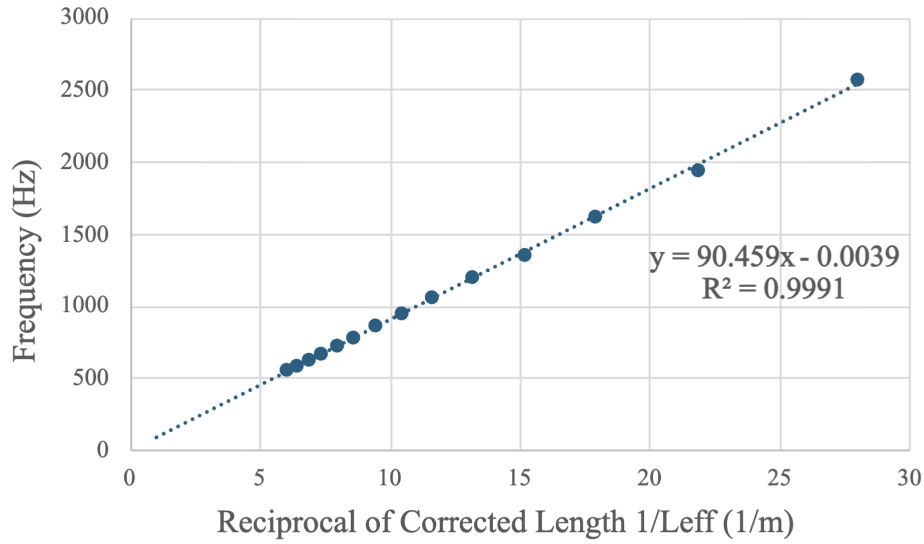


Fig. 3 — f vs. reciprocal of corrected length $1/L_{\text{eff}}$ (m^{-1})

From the regression slope s:

$$f = \frac{v}{4} \cdot \frac{1}{L_{\text{eff}}}, \quad s = \frac{v}{4} \Rightarrow v = 4s.$$

With $s \approx 90.46$, we obtain $v \approx 361.84$ m/s, only +4.5% from theory.

5.4 Uncertainty Analysis

Type A:

- Triple measurements: except $L = 2$ cm ($\approx 5.5\%$), values between $2 \sim 4$ cm give $\approx 0.45\%$, while $L > 5$ cm stay $\leq 0.1\%$.
- Average method (14 points): $\approx 3.5\%$.

Type B:

- Ruler precision: 0.1 cm $\Rightarrow \approx 0.35\%$.
- Phyphox frequency: negligible ($< 10^{-4}$ Hz).
- End correction $\Delta = 1.574 \pm 0.1$ cm: $\approx 0.6\%$.

Combined:

- Average method: $u \approx 3.6\%$, $v = 292.71 \pm 10.54$ m/s.
- Regression method: $u \approx 0.7\%$, $v = 361.84 \pm 2.53$ m/s.

6. Discussion and Reflection

1. **Why is Type A uncertainty lower for longer lengths?**
   Short tubes ($L < 5$ cm) show broader resonance peaks (low Q factor), making readings sensitive to blowing style and noise. Longer tubes yield sharper peaks, giving more stable frequencies.

2. **Why is the measured Δ (1.57 cm) much larger than the theoretical 0.33 cm?**
   Theory predicts $\Delta \approx 0.6r$ for circular pipes ($r = 0.55$ cm). The straw opening was not a clean cut, and the piston end (chopstick+tissue) had gaps, shifting node positions. Blowing and reading errors also inflate Δ.

3. **Why does the average method deviate more from theory?**
   It ignores end correction. Using L_{eff} instead gives $v \approx 362.29$ m/s, closer to theory. Moreover, this method gives equal weight to noisy short-tube data, worsening bias, unlike regression which balances the trend.

4. **Why does v increase with L in the average method?**

$$v_{\text{est}} = 4Lf = 4(L_{\text{eff}} - \Delta)f = v\left(1 - \frac{\Delta}{L_{\text{eff}}}\right).$$

   As L grows, Δ/L_{eff} shrinks, so v_{est} increases monotonically.

5. **How to reduce errors?**

   - Use more data points, especially longer lengths.
   - Replace the tissue piston with a rigid, flat stopper to reduce leakage and damping.
   - Control blowing angle and force for consistency.
   - Measure actual air temperature inside the straw to account for heating and humidity effects.

6. **Reflection**
   This experiment, though simple, vividly demonstrated textbook acoustic theory. I initially followed a video method, but results deviated strongly. Using regression even gave a wrong 190 m/s at first, before realizing the role of end correction. After refining, I better understood short- vs. long-tube differences and damping effects. Resonance still feels mysterious, but this practice deepened my grasp. It was also my first time writing a lab report in LaTeX, and I found it elegant and convenient for equations and layout—a valuable tool for future work.

7. References

- Wikipedia (2024). "Resonance Phenomenon." Retrieved from https://zh.wikipedia.org/zh-tw/%E5%85%B1%E6%8C%AF
- Wikipedia (2024). "Quality Factor." Retrieved from https://zh.wikipedia.org/zh-tw/%E5%93%81%E8%B3%AA%E5%9B%A0%E5%AD%90

- OpenStax (2016). *University Physics, Vol. 1, Ch. 17: Sound.* Rice University. Retrieved from https://reurl.cc/rY0l4x
- The Physics Classroom (2024). "Resonance and Q Factor." Retrieved from https://www.physicsclassroom.com/class/sound/Lesson-5/Resonance
- KYST Education (2023). "Resonance and Standing Waves." Retrieved from https://edu.kyst.com.tw/blog/detail/67
- YouTube (2023). "Straw Flute Sound-Speed Demo." Retrieved from https://www.youtube.com/watch?v=r9HSHdbVrQg
- High School Physics Textbook (2019). Waves and Sound Unit. Taipei: Hanlin Publishing.