

UM-SJTU JOINT INSTITUTE
PHYSICS LABORATORY
(VP141)

LABORATORY REPORT

EXERCISE 4
MEASUREMENT OF THE SPEED OF SOUND

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1 Objectives

In the exercise, I'll learn various methods to measure the speed of sound in air: the resonance method, the phase comparison method and the time difference method. What's more, I'll become familiar with the successive difference method in measurement data processing.

2 Theoretical Background

2.1 Basic Quantitative Characteristics of Sound Waves

Sound is a mechanical wave that propagates through a compressible medium. It is a longitudinal wave because the direction of vibrations of the medium is the same as the direction of propagation. The frequency of sound perceptible to a human ear ranges from about 20 Hz to 20 000 Hz. Sound with the frequency higher than 20000 Hz is called *ultrasound*. In this experiment an ultrasonic wave is chosen as the signal source, because its wavelength is short enough to measure the speed of sound precisely.

The phase speed v , the frequency f and the length λ of a wave are related by the formula

$$v = \lambda f. \quad (1)$$

For motion with constant speed v along a straight line, we have

$$v = \frac{L}{t}, \quad (2)$$

where L is the distance travelled over time t . Hence, if the distance and the time a wave front travels is known, the phase speed may be found.

2.2 Measurement Method

The experimental setup consists of a signal source, two piezoelectric transducers S_1 and S_2 , and oscilloscope arranged as shown in Figure 1.

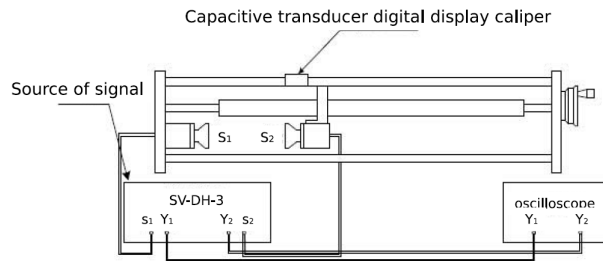


Figure 1: Measurement setup

2.2.1 Resonance Method

The elements S_1 and S_2 are the wave source and the receiver and reactors, respectively, placed a distance L from each other. If they are arranged parallel to each other, the sound wave is reacted. If

$$L = n \frac{\lambda}{2} \quad (3)$$

where $n=1,2,\dots$ the distance is a multiple of half-wavelength, standing waves will form, and maximum speed will be observed in the oscillograph (Figure 2). The distance between two successive maxima ($L_{i+1} - L_i$) is always $\lambda/2$. After the position corresponding to each maximum is measured, it is easy to find the wavelength and then the speed of sound by using Eq. (1). The frequency f is displayed directly on the signal generator.

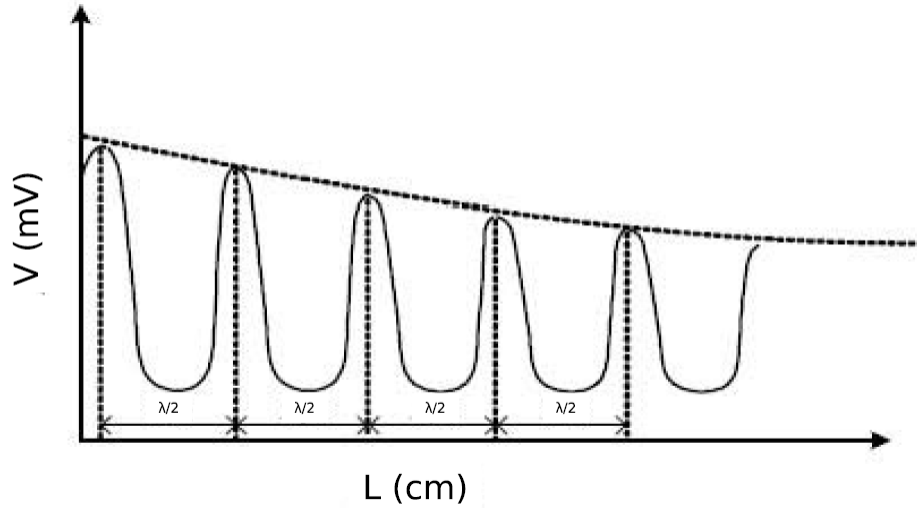


Figure 2: Relationship between the signal voltage and the distance between the transducers.

2.2.2 Phase-comparison Method

If the phase of the wave at two points on the wave propagation direction is equal, then the distance between these points L has to be a multiple of the wavelength, for example:

$$L = n\lambda,$$

where $n=1,2,\dots$. The experimental setup for the phase comparison method is the same as in the previous method (Figure 1). Lissajous figures are used to identify the values of L . Lissajous figures (or Lissajous curves) are trajectories of a particle that moves in a plane so that it moves in a harmonic motion independently along two perpendicular directions (for example the axes x and y of a Cartesian coordinate system), so that $\mathbf{r}(t) = (A_x \cos(\omega_x t + \phi_x), A_y \cos(\omega_y t + \phi_y))$. When the two superimposed harmonic motions have identical frequency $\omega_x = \omega_y$ and phase difference $|\phi_x - \phi_y| = n\pi$, where $n=0,1,2,\dots$ the Lissajous figure will show as a straight line. For other values of the phase difference the figures will have an elliptical shape.

2.2.3 Time-difference Method

The successive difference method is an effective method to increase the accuracy of the average value calculated from a series of measurement data. In this experiment, the usual method of calculating the average value, illustrated by the formula

$$\frac{\bar{\lambda}}{2} = \frac{[(L_1 - L_0) + (L_2 - L_1) + \cdots + (L_n - L_{n-1})]}{n} = \frac{L_n - L_0}{n} \quad (4)$$

will be modified, because as equation (4) shows, the average value of the wavelength is determined only by the first and the last value, L_0 and L_n .

A modification of the formula by rearranging terms as

$$n \frac{\bar{\lambda}}{2} = \frac{\sum_{i=1}^n (L_{n+i} - L_i)}{n}, \quad (5)$$

produces more accurate results, as each value contributes to the final result.

3 Apparatus

1. In the exercise, the most important apparatus I used is Oscilloscope. The oscilloscope can draw the figure of the wave and Lissajous figures for me to calculate the speed and wavelength of sound.

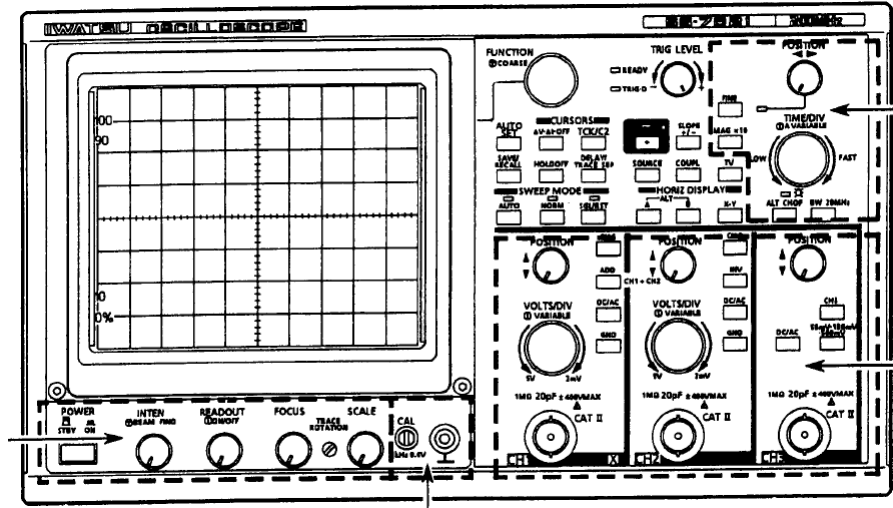


Figure 3: Oscilloscope

2. The second apparatus is the signal sources, which keeps the frequency of sound is 34500 Hz.
3. I also used two piezoelectric transducers in water and air respectively to read and adjust the distance between the transducers.

4. An thermometer with resolution is 1°C is used to measure the temperature in the lab.

4 Measurement Procedure

4.1 Resonance Method

1. Set the initial distance between S_1 and S_2 at about 1 cm.
2. Turn on the signal source and the oscilloscope. Then set the following options on the panel of the signal source
 - (1) Choose *Continuous* wave for *Method*.
 - (2) Adjust *Signal Strength* until a 10 V peak voltage is observed on the oscilloscope.
 - (3) Adjust *Signal Frequency* between 34.5 kHz and 40 kHz until the peak-to-peak voltage reaches its maximum. Record the frequency.
3. Increase L gradually by moving S_2 , and observe the output voltage of S_2 on the oscilloscope. Record the position of S_2 as L_2 when the output voltage reaches an maximum.
4. Repeat step 3 to record 20 values of L_2 and calculate v .

4.2 Phase-comparison Method

1. Use Lissajous figures to observe the phase difference between the transmitted and the received signals. Move S_2 and record the position when the Lissajous figure becomes a straight line with the same slope.
2. Repeat step 1 to collect 12 sets of data. Use the successive difference method to process the data and calculate v .

4.3 Time-difference Method (Air)

Since the pulse wave causes damped oscillations at the receiver, there will be significant interference if S_1 and S_2 resonate. The resonance can be observed on the oscilloscope.

1. Choose *Pulse Wave* for *Method* on the panel of the signal source.
2. Adjust the frequency to 25 Hz and the width to $500\ \mu\text{s}$.
3. Record the distance L_1 and the time t_1 .
4. Move S_2 to another position and repeat step 3. Record L_i and $t_i, i = 2, 3, 4 \dots$

5. Repeat step 4 to collect 12 pairs of L_i and t_i . Plot the $L_i = L_i(t_i)$ graph and use computer software to find a linear fit to the data. The slope of the line is the speed v .

4.4 Time-difference Method in (Liquid)

1. Change the medium to water.
2. Adjust the frequency to 100 Hz and the width to 500 μs .
3. Use the cursor function of the oscilloscope to measure the time and the distance between the the starting points of neighbouring periods. Record 12 pairs of data and calculate v_{water} .

5 Calculation and Results

5.1 Measurement Data

5.1.1 Constant Physical Quantity in Lab

The frequency of the sound wave $f=34500[\text{Hz}]$
 Temperature $T= [29^\circ\text{C}]\pm[1^\circ\text{C}]$

5.1.2 Data for the Resonance Method

$L_i[\text{mm}] \pm 0.01[\text{mm}]$		$L_i[\text{mm}] \pm 0.01[\text{mm}]$		$L_{10+i} - L_i[\text{mm}]$	
1	10.72	11	61.32	1	50.60
2	15.73	12	66.41	2	50.68
3	20.05	13	71.61	3	51.56
4	25.22	14	76.72	4	51.50
5	30.36	15	81.91	5	51.55
6	35.59	16	87.05	6	51.46
7	40.82	17	92.14	7	51.32
8	45.98	18	97.07	8	51.09
9	51.01	19	102.22	9	51.21
10	56.11	20	107.37	10	51.26

Table 1: Data table for the resonance method

5.1.3 Data for the Phase Comparison Method

$L_i[\text{mm}] \pm 0.01[\text{mm}]$		$L_i[\text{mm}] \pm 0.01[\text{mm}]$		$L_{6+i} - L_i[\text{mm}]$	
1	11.44	7	43.80	1	32.36
2	16.90	8	49.64	2	32.74
3	22.32	9	54.75	3	32.43
4	27.85	10	60.20	4	32.35
5	33.34	11	65.51	5	32.17
6	38.61	12	71.05	6	32.44

Table 2: Data table for the phase comparison method

5.1.4 Data for the Time Difference Method (Liquid)

	$t_i[\mu\text{s}] \pm 0.2[\mu\text{s}]$	$L_i[\text{mm}] \pm 0.01[\text{mm}]$
1	82.8	110.00
2	89.4	120.36
3	96.0	130.31
4	102.8	140.25
5	109.2	150.15
6	116.0	160.13
7	122.6	170.13
8	129.4	180.09
9	136.0	190.22
10	142.8	200.05
11	149.2	210.30
12	156.2	220.42

Table 3: Data table for the time difference method (liquid)

5.2 Calculations

5.3 Calculation for Resonance Method

$$\bar{L} = \frac{\sum_{i=1}^{10} L_{10+i} - L_i}{10} = 51.223[\text{mm}]$$

According to equation (3),

$$L = 10 \times \frac{\lambda}{2}$$

$$\lambda = \frac{\bar{L}}{5} = \frac{51.223}{5} = 10.245[\text{mm}]$$

$$v = \lambda f = 10.245 \times 34500 \times 10^{-3} = 353.439[\text{m/s}]$$

5.4 Calculation for the Phase Comparison Method

$$\bar{L} = \frac{\sum_{i=1}^6 L_{10+i} - L_i}{10} = 32.415[mm]$$

According to $L = n\lambda$,

$$\lambda = \frac{L}{3}$$

$$\lambda = \frac{\bar{L}}{3} = \frac{32.415}{3} = 10.805[mm]$$

$$v = \lambda f = 10.805 \times 34500 \times 10^{-3} = 372.77[m/s]$$

5.5 Calculation for the Time Difference Method (Liquid)

According to equation (2), $v = \frac{L}{t}$, I can use origin to draw linear fit diagram to get v_{water} , which is the slope of L vs. t diagram

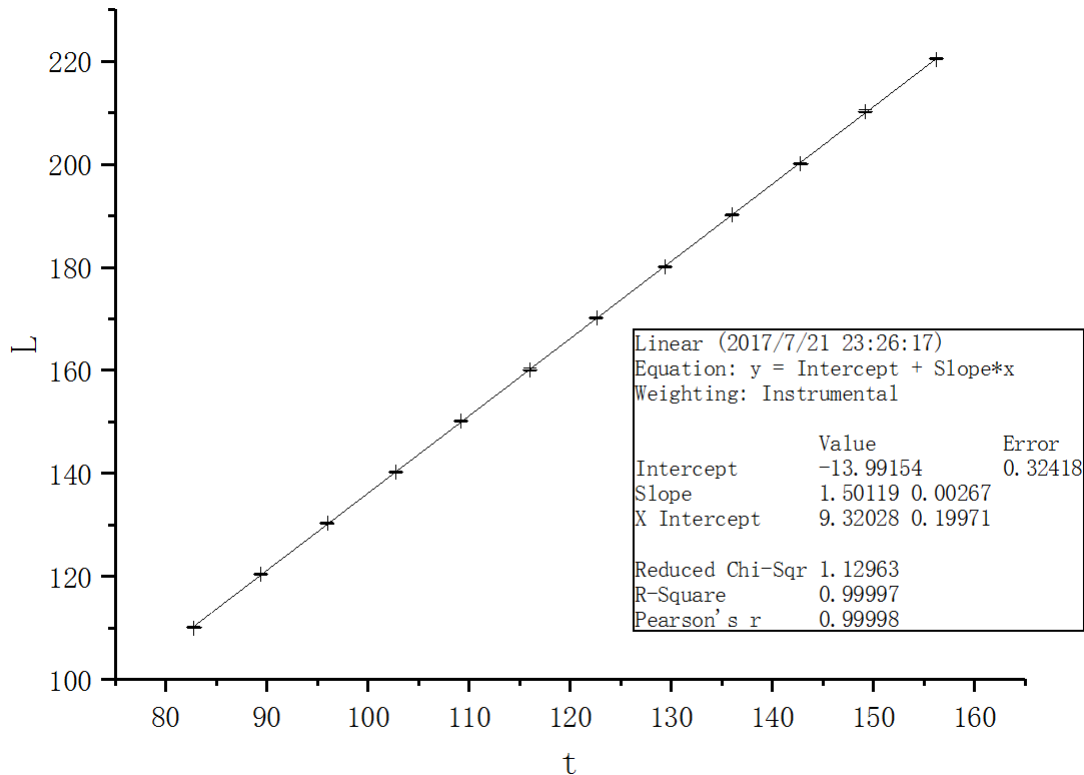


Figure 4: Linear fit diagram for time difference method (liquid)

So $v_{water} = 1.501[mm/\mu s] = 1501[m/s]$

6 Measurement Uncertainty Analysis

6.1 Measurement Uncertainty for Resonance Method

$$\begin{aligned}u_{\Delta L} &= \sqrt{2(u_L)^2} = \sqrt{2 \times (0.01)^2} = 0.0141[mm] \\u_{\bar{L}} &= \sqrt{10 \times (\frac{u_{\Delta L}}{10})^2} = 4.47 \times 10^{-3}[mm] \\u_{\lambda} &= \frac{u_{\bar{L}}}{5} = 8.94 \times 10^{-4}[mm] \\u_v = u_{\lambda}f &= \frac{8.94 \times 10^{-4} \times 34500}{1000} = 3.09 \times 10^{-2}[m/s] \\u_r &= \frac{u_v}{v} \times 100\% = \frac{3.09 \times 10^{-2}}{353.44} \times 100\% = 0.01\%\end{aligned}$$

6.2 Measurement Uncertainty for the Phase Comparison Method

$$\begin{aligned}u_{\Delta L} &= \sqrt{2(u_L)^2} = \sqrt{2 \times (0.01)^2} = 0.0141[mm] \\u_{\bar{L}} &= \sqrt{6 \times (\frac{u_{\Delta L}}{6})^2} = 5.77 \times 10^{-3}[mm] \\u_{\lambda} &= \frac{u_{\bar{L}}}{3} = 1.92 \times 10^{-3}[mm] \\u_v = u_{\lambda}f &= \frac{1.92 \times 10^{-3} \times 34500}{1000} = 6.64 \times 10^{-2}[m/s] \\u_r &= \frac{u_v}{v} \times 100\% = \frac{6.64 \times 10^{-2}}{372.77} \times 100\% = 0.02\%\end{aligned}$$

6.3 Measurement Uncertainty for the Time Difference Method (Liquid)

According to the linear fit diagram, the uncertainty $u_{water} = 2.67[m/s]$

$$u_r = \frac{u_v}{v} \times 100\% = \frac{2.67}{1501} \times 100\% = 0.18\%$$

7 Conclusion and Discussion

7.1 Conclusion

In the exercise, I used three methods to measure the speed of sound in air and water.

	$v[\text{m/s}]$	$u_v[\text{m/s}]$	$u_r[\%]$
$v_{\text{resonance}}$	353.44	3.09×10^{-2}	0.01
v_{phase}	372.77	6.64×10^{-2}	0.02
v_{water}	1501	2.67	0.18

Table 4: Measured speed of sound

Through the exercise, I have a rough idea about what piezoelectric transducers and oscilloscope is and how to use them. The exercise also enrich my knowledge about wave and the speed of sound in different medium. I also know how to use successive difference method in measurement data processing.

7.2 Discussion

7.2.1 Error Analysis

1. The relative uncertainty in the third measurement is much bigger than other two. Although its medium is different from the others, I think it's the time different method that results in the error.
2. In the second measurement, I should have measure $L_{6+i} - L_i$ as 6 times wavelength. However, since I recorded the data as soon as the Lissajous figures becomes a line, the phase difference is actually ϕ while in the procedure its should be 2ϕ , which means I should record the data every two lines. As a result, my $L_{6+i} - L_i$ is 3 times wavelength, and I change n from 6 to 3 in my calculations. Although my uncertainty in this measurement is not very big, but such mistakes may cause errors.

7.3 Questions for Consideration

7.3.1 Why Measure T?

In the air, when the temperature is higher, the speed of sound will be bigger. Since sound wave propagate through the vibration of air molecules, the speed will be bigger when the vibration is more violent, which is caused by higher temperature. This can also affect the speed in liquid/

7.3.2 Why not Use Time Difference Method in Air?

The density of air is not as uniform as in liquid, and the drag force is also not uniformly distributed in air. As a result, the speed of sound may be changeable so the time difference may be not accurate enough.

7.3.3 Why $L_1 > 100mm$ in Time difference Method?

I think the wavelength is bigger than 100mm so the wave can't be formed when $l_1 > 100mm$

8 Data Sheet

Data sheet is attach to the report

9 Reference

- Young, H.D., Freedman R.A. University Physics. Chapter 9,10.
- Qin Tian, Zeng Ming, Zhao Xijian, Krzyzosiak,M. Lab Manual of Exercise 4.
- Qin Tian, Zeng Ming, Zhao Xijian, Krzyzosiak,M. Handbook-Uncertainty Analysis.