Instruction Book of University Physics Experiment A

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Experiment I: Michelson Interferometer

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1. What is the principle and function of each part of the Michelson interferometer?

2. What are the similarities and differences between localized interference and non-localized interference and what are the conditions for producing bright or dark fringes?

3. What is the principle of measuring the wavelength of He-Ne laser?

4. What is the method for measuring the refractive index of air?

II. Objectives and Tasks

1. Understand the structure, principle and adjustment method of the Michelson interferometer;

2. Observe the non-localized and localized interference phenomena of light, including equal inclination and equal thickness interference;

3. Measure the wavelength of He-Ne laser by the difference method;

4. Calculate the refractive index of air by the drawing method.

III. Principle

1. Working Principle of Michelson Interferometer

Michelson interferometer is an instrument that obtains double-beam interference by amplitude division method. Its structure is shown in Figure 1-1.

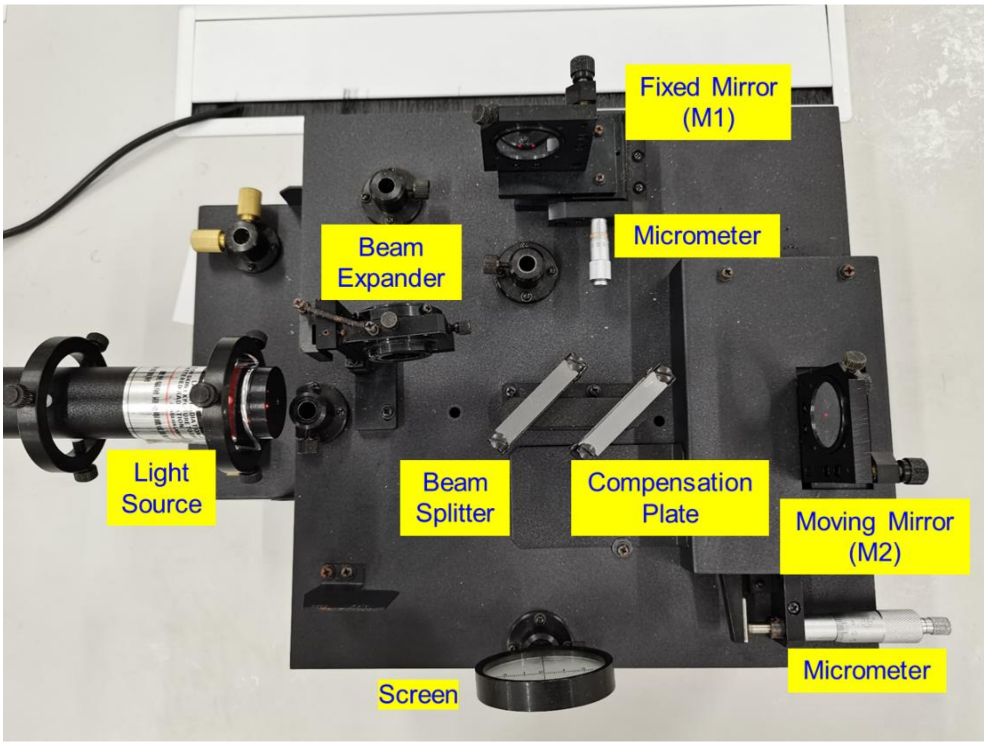


Figure 1-1 Structure of Michelson Interferometer

Mirrors M1 and M2 are plane mirrors perpendicular to each other. Their angles can be adjusted by two screws at the back of the adjustment frame, and their positions can be adjusted by the micrometers. The moving distance of M2 is 1/20 of the change in the corresponding micrometer reading, while the moving distance of M1 is the same as the change in the corresponding micrometer reading. Therefore, the position adjustment accuracy of M2 is higher. During measurement, M1 is usually fixed and only the position of M2 is adjusted, so M1 and M2 are called fixed mirror and moving mirror respectively. The beam splitter and compensation plate are two glass plates of the same material and thickness, and are placed in parallel, so that the optical path of the two light beams in the glass is exactly the same.

The working principle of the Michelson interferometer is shown in Figure 1-2.

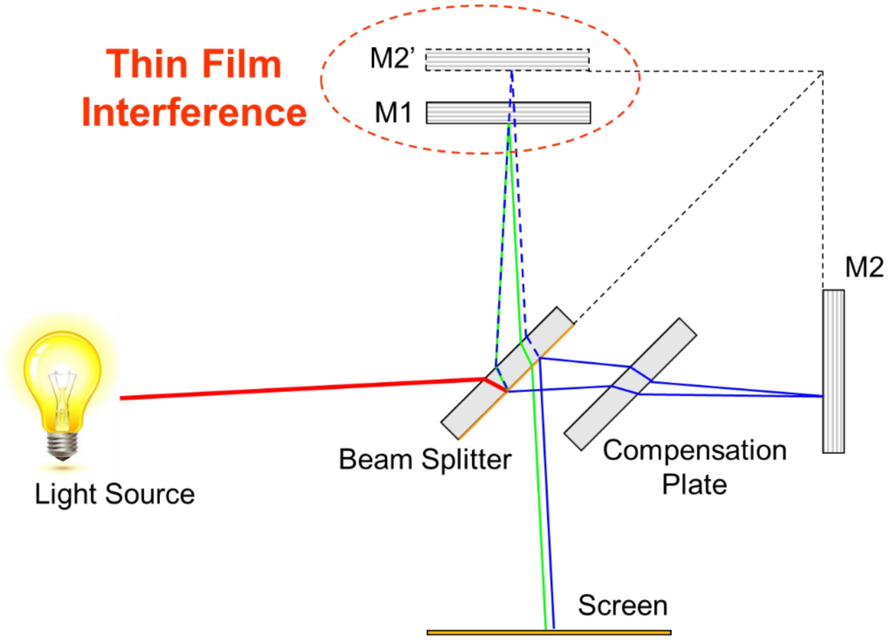


Figure 1-2 Working Principle of the Michelson Interferometer

The light beam emitted by the light source is incident on the beam splitter, and the back surface of the beam splitter is coated with a semi-transparent film. The light beam is reflected and transmitted on the semi-transparent film and is divided into two beams with nearly equal light intensity. The two beams are respectively directed to the two plane mirrors M1 and M2, and after being reflected by them, they converge on the beam splitter and then are incident on the screen, as shown by the green line and the blue solid line in Figure 1-2. The two light waves interfere at the screen, and a clear interference pattern can be obtained. The interference pattern is related to the optical path difference of the two light waves. By adjusting the angle and position of the mirrors, the optical path difference can be changed, thereby changing the interference pattern. Using this principle, many measurement and inspection functions can be realized, such as the Optical

Coherence Tomography (OCT) equipment used in medicine, the Laser Interferometer Gravitational-Wave Observatory (LIGO) for detecting gravitational waves, etc., as shown in Figures 1-3 and 1-4. In this experiment, we will use a Michelson interferometer to measure the wavelength of the light emitted by a He-Ne laser and the refractive index of air.

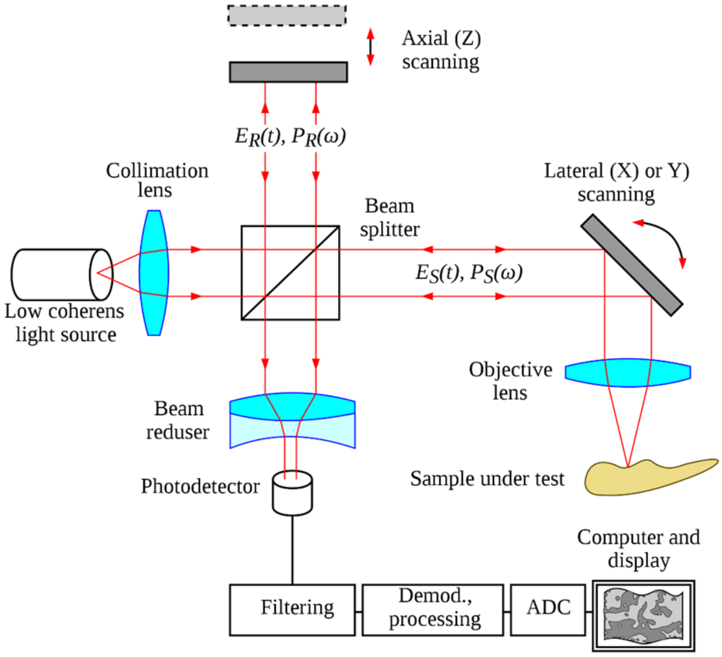


Figure 1-3 Working Principle of the Optical Coherence Tomography (OCT)

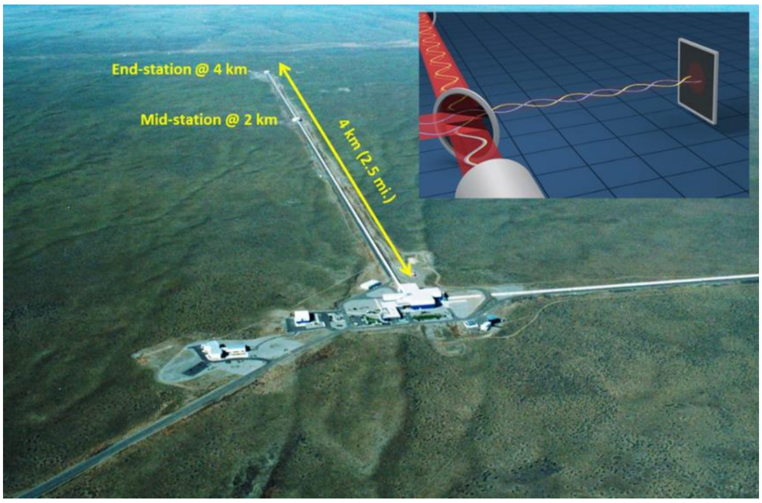
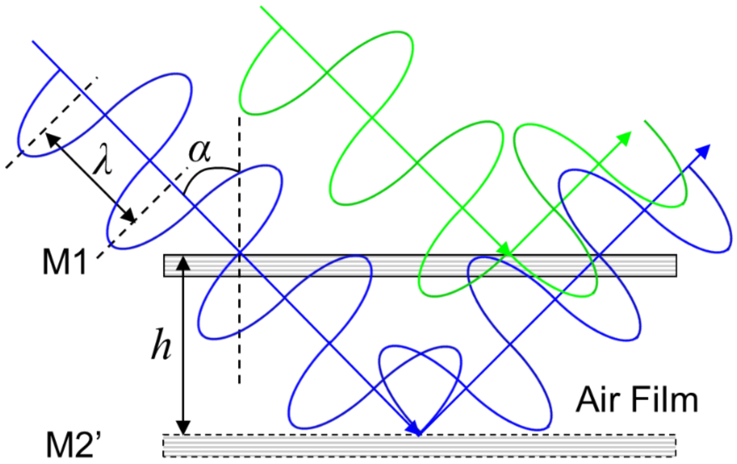


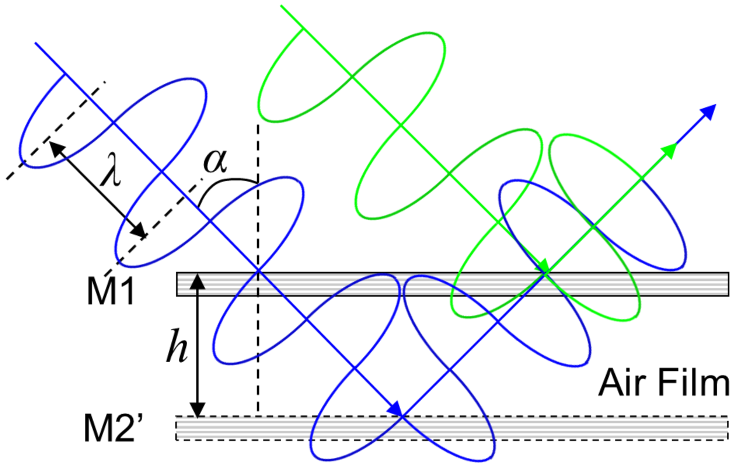
Figure 1-4 Laser Interferometer Gravitational-Wave Observatory (LIGO)

In order to quantitatively analyze the changes in the interference pattern, it is necessary to calculate the optical path difference. In order to simplify the calculation, the optical path in Figure 1-2 can be simplified. In fact, the light reflected by the moving mirror M2 is equivalent to the light reflected by its image M2' formed on the rear surface of the beam splitter, as shown by the blue dotted line in Figure 1-2. Therefore, the Michelson interferometer is actually equivalent to the air film interference formed between the two reflectors M1 and M2'. Adjusting the angle or position of M1 and M2 is actually changing the thickness of the air film. From this equivalent optical path, the reason for setting the compensation plate can be analyzed by yourself.

Therefore, the working principle of the Michelson interferometer can be simplified to the thin film interference as shown in Figure 1-5.



（a） Constructive Interference



（b） Destructive Interference

Figure 1-5 Thin Film Interference

Assume that the thickness of the air film is h, and two beams of light with a wavelength λ are incident on the upper and lower surfaces of the film at an incident angle α and then are reflected. Through simple geometric calculations, we can get that the optical path difference is

$$\Delta L = 2h\cos\alpha \tag{1-1}$$

According to the interference conditions, when the optical path difference satisfies equation (1-2), the two waves interfere constructively, as shown in Figure 1-5 (a), producing bright fringes; when the optical path difference satisfies equation (1-3), the two waves interfere destructively, as shown in Figure 1-5 (b), producing dark fringes. m in the equation is a natural number, representing the order of interference.

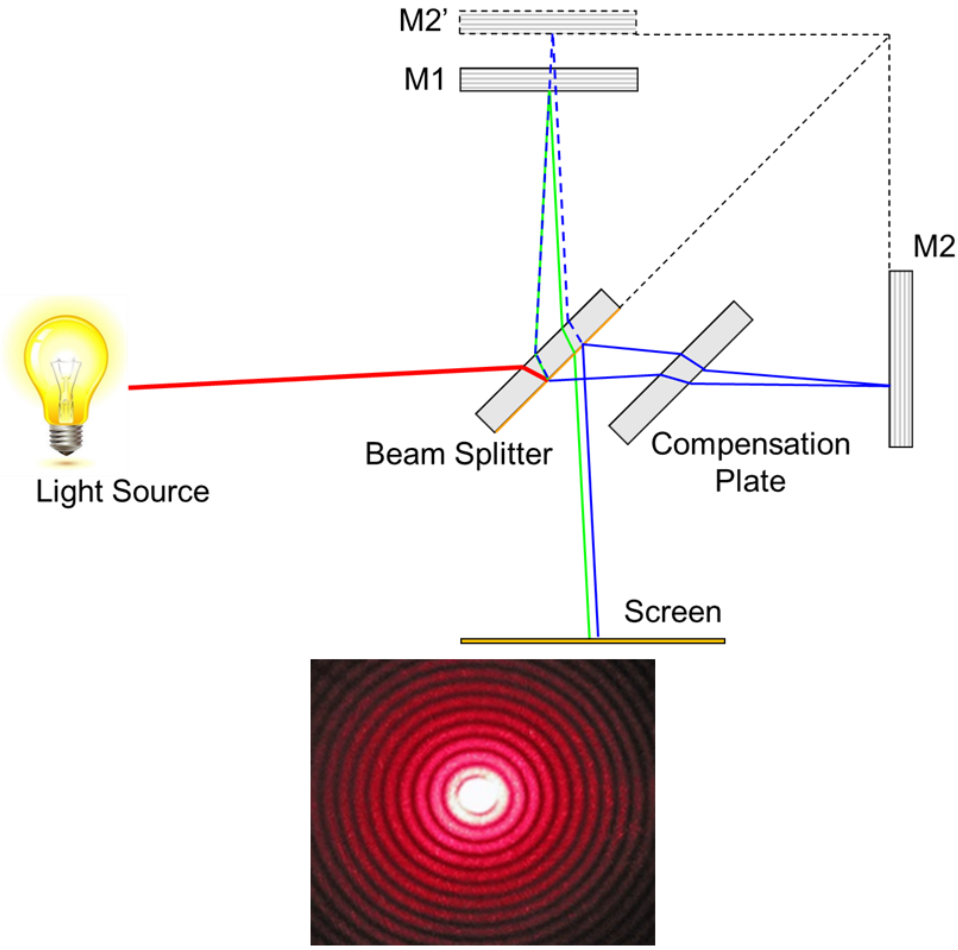
$$\Delta L = 2hcos\alpha = m\lambda \tag{1-2}$$

$$\Delta L = 2hcos\alpha = (2m+1)\lambda/2 \tag{1-3}$$

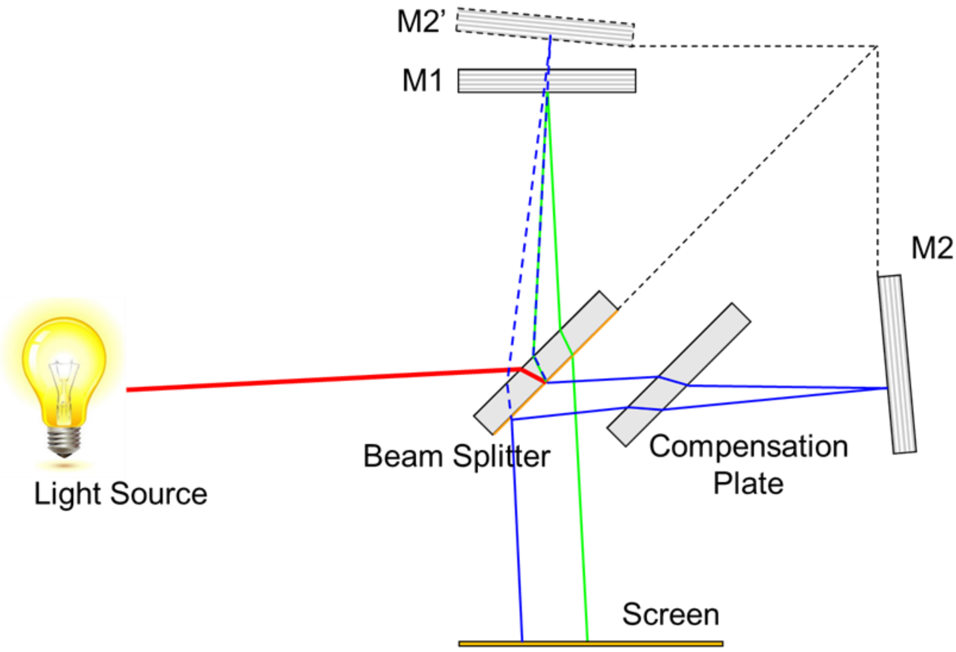
2. Equal-inclination Interference and Equal-thickness Interference

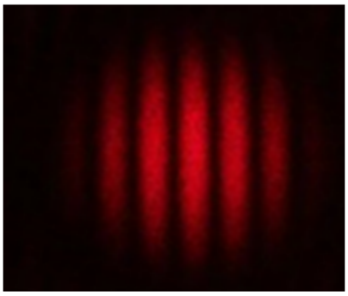
It is not difficult to see from the expression (1-1) of the optical path difference that it depends on two parameters: the incident angle α and the film thickness h. If M1 and M2' are parallel to each other, as shown in Figure 1-6, the film thickness h is uniform, so the optical path difference is only related to the incident angle (inclination angle). The same incident angle (inclination angle) α corresponds to the same interference order, referred to as "equal-inclination interference", and the interference pattern is a series of rings with bright and dark alternating. If M1 and M2' are not parallel, but form a small wedge angle, as shown in Figure 1-7, the film thickness h is uneven. For light incident from the same incident angle, the optical path difference is only related to the film thickness. The same film thickness h corresponds to the same interference order, referred to as "equal-thickness interference", and the interference pattern is a series of parallel straight stripes with bright and dark alternating.

Combined with the optical paths of Figures 1-6 and 1-7, analyze why different interference patterns are generated.



Figures 1-6 Equal-inclination Interference





Figures 1-7 Equal-thickness Interference

3. Characteristics of the Equal-inclination Interference Rings

In this experiment, you are required to observe the characteristics of the equal-inclination interference rings, such as the " swallow or spit ", the thickness of the rings, and the spacing between the rings. You can analyze the following questions by yourself based on the expression of the optical path difference in formula (1-1) and Figure 1-8, and compare them with the phenomena observed in the experiment.

（1） Interference order (*m*): Is it higher at the center or at the edge? (Tips: The integer *m* in equations (1-2) and (1-3) is the interference order of the bright and dark fringes, respectively. By comparing the optical path difference corresponding to the interference rings at the center and the edge, the interference order can be qualitatively analyzed.)

（2） Spacing between the rings (described by $\Delta\alpha_m$): Is it denser in the center or at the edge? (Tips: Taking bright fringes as an example, combined with equation (1-2), we can calculate the difference in inclination angles between the mth-order ring and the (m+1)th-order ring, $\Delta\alpha_m=\alpha_m-\alpha_{m+1}$, to qualitatively analyze the variation of the spacing between the bright rings. We need to introduce the approximate condition that the light is close to normal incidence, that is, $\alpha_m\approx\alpha_{m+1}\approx 0$. The analysis method for dark fringes is the same.)

（3） Thickness of the rings (described by $\delta_{\alpha m}$): Is it thicker in the center or at the edge? (Tips: Similar to the analysis of the spacing between the rings, combine equations (1-2) and (1-3) to calculate the difference in inclination angle $\delta_{\alpha m}$ between the m[th] bright ring and the adjacent dark ring. $\delta_{\alpha m}$ can be used to characterize the thickness of the rings. Similarly, the approximate condition that the light is close to normal incidence needs to be introduced.)

(4) "Swallow or spit": When the moving mirror approaches (or moves away from) the fixed mirror, will the number of rings increase or decrease? Will they become thicker or thinner? Will they become denser or sparser? (Tips: Taking the bright fringe as an example, combined with the analysis of formula (1-2), when the moving mirror is moved, the thickness of the air film h is actually changed. For any bright ring, the corresponding optical path difference is unchanged. Therefore, in this process, the corresponding inclination angle α will change accordingly. By qualitatively analyzing whether the inclination angle α increases or decreases with the thickness h, we can understand the changing rules of the rings, such as "swallow or spit ", density, thickness, etc.)

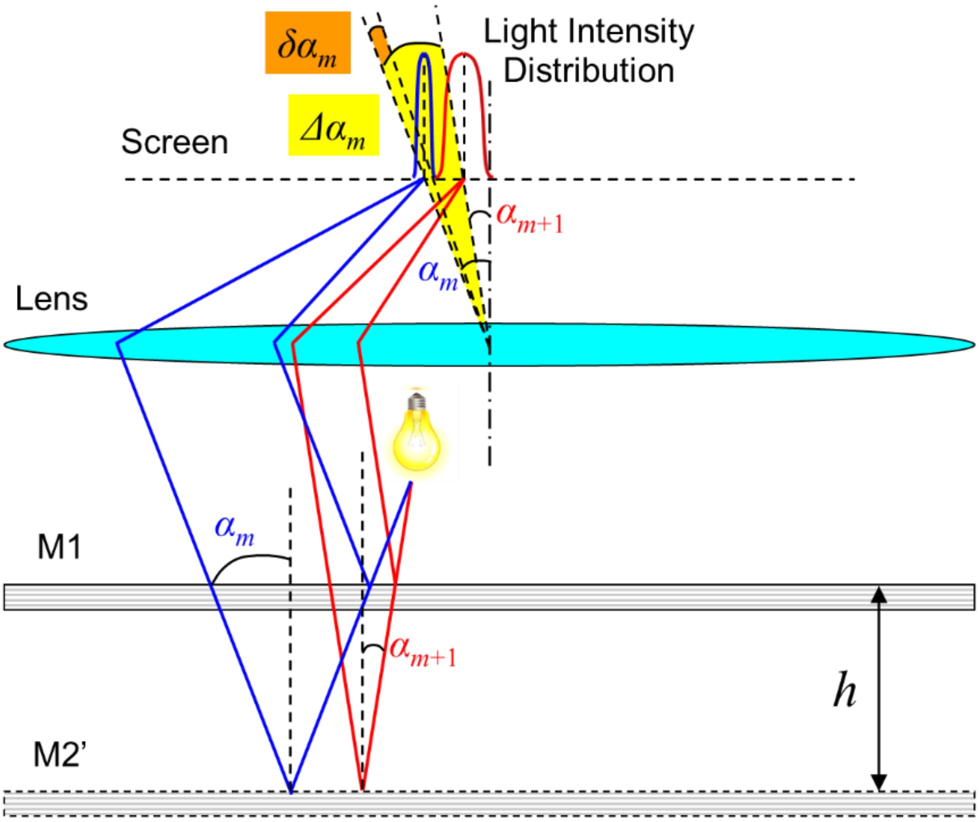


Figure 1-8 Light Path Diagram for Analyzing the Characteristics of Equal-inclination Interference Pattern

4. The "Bending" Characteristics of Equal-thickness Interference Fringes

According to the previous analysis, in theory, the equal-thickness interference pattern produced by a parallel light beam passing through the Michelson interferometer should be parallel straight stripes with bright and dark alternating. However, in actual experiments, we will observe curved equal-thickness interference stripes, which is particularly obvious when using sodium lamps for experiments, as shown in Figure 1-9.

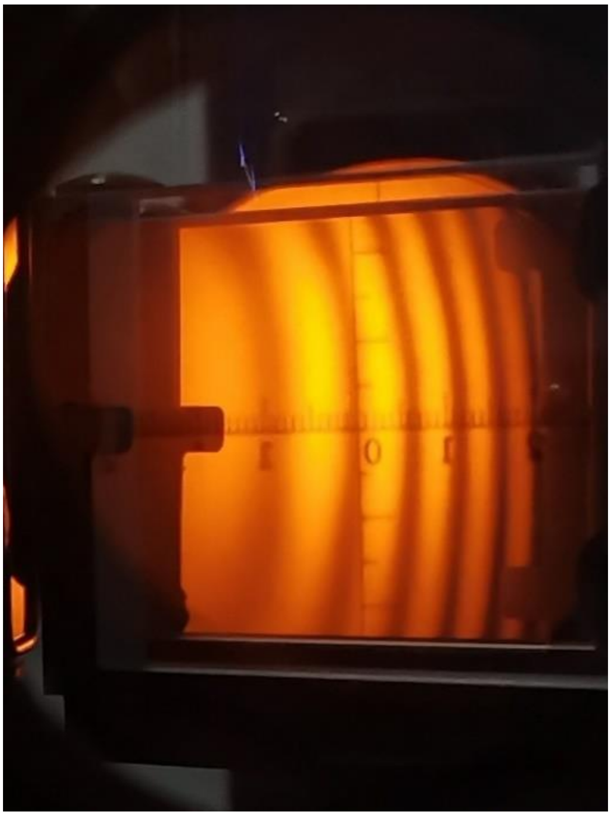


Figure 1-9 Interference Fringes of Equal Thickness Produced by Sodium Light Passing through a Michelson Interferometer

In addition, in the experiment, we will observe that the curvature of the interference fringes of equal thickness will change when the spacing between M1 and M2' is changed, as shown in Figure 1-10. Please analyze why this happens by combining the expression of optical path difference in formula (1-1) and Figure 1-11, and compare it with the phenomenon observed in the experiment. (Tips: The curvature of the fringes can be mathematically characterized by the differential of the thickness h with respect to the inclination angle α.)

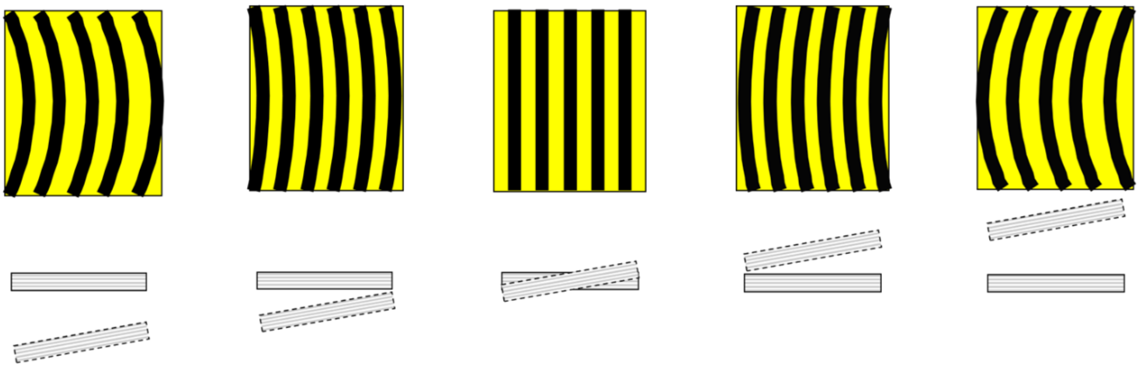


Figure 1-10 The "Bending" Characteristics of Equal-thickness Interference Fringes

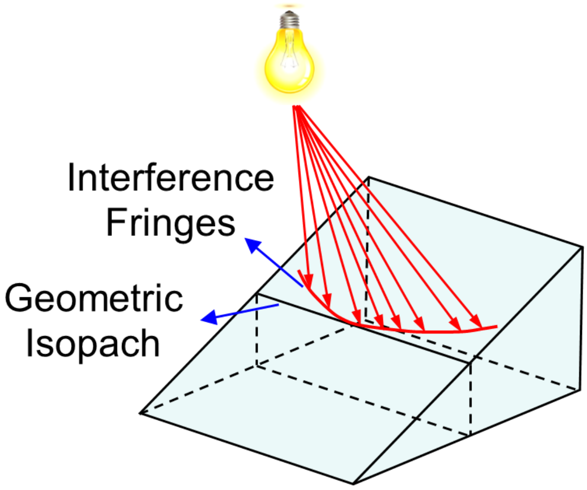


Figure 1-11 Light Path Diagram for Analyzing the "Bending" Characteristics of Equal-thickness Interference Fringes

5. Localized and Non-localized Interference

In this experiment, two light sources will be used: helium-neon laser (He-Ne laser) and sodium lamp. Sodium light is not easy to produce interference due to its poor monochromaticity (i.e. poor coherence), and the interference fringes are limited to a small specific area (a few centimeters), i.e. localized interference.

Laser is easy to produce interference due to its good monochromaticity (i.e. good coherence), and the interference area is very large (a few meters to tens of meters), i.e. non-localized interference.

IV. Operation

1. Familiarity with Michelson Interferometer and Tuning the He-Ne laser

(1) Be familiar with the structure and function of each part of the Michelson interferometer;

(2) Be familiar with the "moving mirror" system. Note that the actual moving distance of the mirror is 1/20 of the change in the corresponding micrometer reading. Rotate the knob to make it in the middle;

(3) Adjust the height and direction of the He-Ne laser so that the laser beam it emits can pass through the small hole of the beam expander.

2. Observe the Non-local Interference Phenomenon Formed by Monochromatic Point Light Source

(1) Move the beam expander out of the optical path and place the screen on it. You can see two columns of reflected light spots from the fixed mirror and the moving mirror. Carefully adjust the screws behind the moving mirror or the fixed mirror so that the two columns of light spots overlap.

(2) Add the beam expander into the optical path. Circular stripes will appear on the screen. Slowly adjust the screws behind the moving mirror so that the center of the stripes is in the center of the screen. If the stripes are too dense or too sparse, adjust the fixed mirror micrometer knob to make the stripes clear and of appropriate density;

(3) Move the moving mirror and observe the changes in the stripes. Note whether the stripes "grow" or "retract", become sparse or dense, and whether the diameter increases or decreases. Record the observed phenomena and compare them with the results of theoretical analysis.

3. Measure the Wavelength of He-Ne Laser

Rotate the moving mirror micrometer knob, and the fringes will be “swallowed” or “spit out”. Record the initial position (0 ring) and the position reading every 50 rings until 250 fringes change. The format is shown in Table 1-1. According to the expression of optical path difference, optical path difference $\Delta L=2h\cos\alpha$, since the inclination angle α corresponding to the central ring is very small, $\cos\alpha\approx1$, so $\Delta L\approx2h$. Based on this, the expression of wavelength is derived, and the data in Table 1-1 are processed by the difference method to obtain the measured value of wavelength, which is compared with the nominal value (632.8nm).

Note: The actual moving distance of M2 is 1/20 of the moving distance of the micrometer. Analyze why it is designed in this way.

4. Measure the Refractive Index of Air

(1) Place the air chamber with a length of l=80mm in front of the fixed mirror and adjust the interferometer to make the interference fringes clear;

(2) Fill the air chamber with ΔP=50, 100, 150, 200 and 250mmHg respectively;

(3) Release the valve and slowly release the air until the pressure gauge pointer returns to the starting position, count the number of interference ring changes N (accurate to 0.5), measure 3 times and take the average value, record the data in Table 1-2;

(4) Draw the N-ΔP relationship curve, calculate the slope and the refractive index of air under ambient pressure (P_{amb}=760mmHg).

Note: When the air chamber pressure changes by ΔP, the refractive index of air changes by Δn, the optical path difference changes by $2\Delta nl$, and the number of interference rings changes by N, then $N\lambda=2\Delta nl$, and the refractive index of air under ambient pressure (P_{amb}=760mmHg) is $n=1+\Delta n\cdot\frac{P_{amb}}{\Delta P}=1+\frac{\lambda\cdot P_{amb}}{2l}\cdot\frac{N}{\Delta P}$.

5. Using Sodium Lamp to Observe Localized Interference Phenomenon (Optional)

(1) Localized equal-inclination interference: Move the beam expander out of the light path, insert the screen (a piece of frosted glass) between the sodium lamp and the beam splitter, and observe the interference fringes directly with your eyes. Finely adjust the moving mirror screw until the fringes are not “swallowed” or “spit out” when the line of sight moves horizontally, and only move horizontally with the direction of the line of sight. Then rotate the moving mirror micrometer knob, observe the changes in the fringes, and record the observed phenomena.

(2) Localized equal-thickness interference:

a. Use a point light source to adjust non-localized circular interference fringes;

b. Adjust the fixed mirror fine-tuning screw to make the fringes shrink and thicken continuously until there are very few fringes in the field of view, then slightly change the moving mirror angle, and parallel straight fringes will appear;

c. Adjust the angle or position of the moving mirror, observe the changes in the fringes, and compare them with the previous theoretical analysis and Figures 1-10.

V. Precautions

1. Do not look directly at the He-Ne laser beam that has not been expanded or scattered to avoid

damaging the retina;

2. The operation must be gentle and the optical surfaces must be protected. It is forbidden to touch the translucent and reflective surfaces of optical parts with your hands.

VI. Requirements for Experimental Reports

1. Calculate the wavelength of He-Ne laser using the difference method.

Table 1-1 Data for Measuring the Wavelength of He-Ne Laser

Number of Ring Changes	**0**	**50**	**100**	**150**	**200**	**250**
M2 Micrometer Position（mm）						

2. Draw a curve of the number of ring changes *N* versus the pressure change Δp, calculate the slope using a graphical method (think about other suitable methods, which can also be used), and find the refractive index of air. (Record three sets of data for each pressure.)

Table 1-2 Data for Measuring the Refractive Index of Air

Number of Measurements	ΔP **（mm Hg）**	**50**	**100**	**150**	**200**	**250**
1	N					
2	N					
3	N					
Average Value of N						

3. **(Optional)** Take photos to record the adjusted equal-inclination interference and equal-thickness interference phenomena, attach them to the experimental report, and analyze their characteristics.

VII. Questions

1. Summarize the characteristics of non-local interference and local interference.

2. What factors determine the density of interference fringes produced by the Michelson interferometer? What is the law of change?

3. Explain why the instrument needs a compensation plate.

Experiment II: Young's Modulus of a Metallic Wire

I. Preparation Guide

1. What is the physical significance of Young's modulus and what is its International System of Units?
2. What is the principle of the optical lever method, and how does it amplify small displacement? (Draw the optical path diagram of the measurement principle).
3. Which physical parameters must be measured to indirectly obtain the Young's modulus in this experiment?

II. Objectives and Tasks

1. Learn the principle of measuring small displacement with optical levers
2. Learn the measurement of Young's modulus of metallic wire by the tensile method.
3. Master the use of the difference-by-difference method to analyze experimental data.

III. Principle

1. Young's Modulus

Taking the simplest example of deformation, consider a cylindrical object with an original length L. When a force is applied along its length, the change in length of the rod is ΔL, and $\Delta L/L$ is defined as the strain. If the cross-sectional area of the rod is S, and the tensile force increases from F to F', resulting in an elongation of ΔL, according to Hooke's law, we have:

$$\frac{F'-F}{S}=E\frac{\Delta L}{L} \tag{2-1}$$

where $(F'-F)/S$ is the change of stress, and the coefficient E is the Young's modulus or the elastic modulus. In the International System of Units, the unit of E is N/m^2.

For a steel wire with a diameter d, the Young's modulus is expressed as:

$$E=\frac{4\left(F'-F\right)}{\pi d^2}\frac{L}{\Delta L} \tag{2-2}$$

Typically, the ΔL is small, and how to accurately measure the small displacement in length is the key. In this experiment, we will use an optical lever to measure the tiny elongation of the length.

2. The Principle of Optical Leverage

The structure of the optical lever is shown in Figure 2-1(a). It consists of a bracket equipped with a rotatable plane mirror. The lower part of the bracket features three legs. The line connecting the two front legs is parallel to the mirror surface, while the rear leg is in contact with the steel wire clamp. The steel wire clamp is designed to move vertically as the wire experiences elongation or contraction. When the rear leg moves upward or downward by a small distance ΔL due to the change in the length of the metal wire, the normal of the mirror rotates through an angle θ, as shown in Figure 2-1(b). When the angle θ is very small, we can use the following approximation:

$$\tan\theta\approx\theta\approx\frac{\Delta L}{D} \tag{2-3}$$

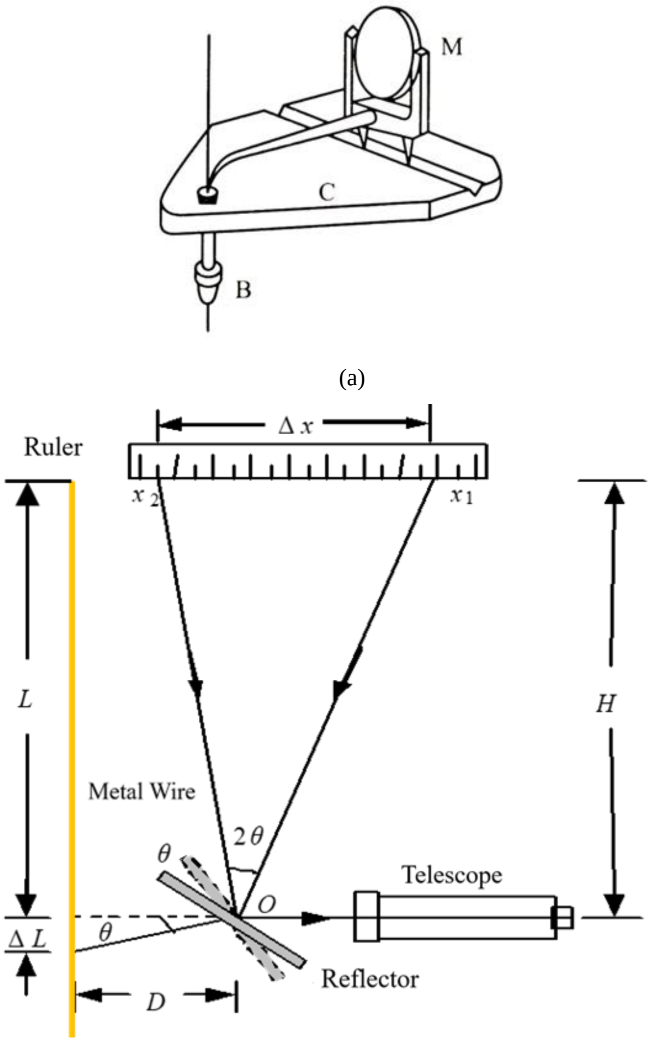
where D is the arm length of the light lever, defined as the vertical distance from the rear leg to the two front legs. When the mirror rotates by an angle θ, the reflected light beam rotates by 2θ. Therefore:

$$\tan 2\theta \approx 2\theta \approx \frac{\Delta x}{H} \tag{2-4}$$

In the equation, Δx is the change in the ruler reading, and H is the distance from the mirror to the ruler. Combining the equation (2-3) and (2-4) together, then we can get:

$$\Delta x = \frac{2H}{D} \cdot \Delta L \tag{2-5}$$

Therefore, the magnification principle of the optical lever is to utilize the rotation of the plane mirror to convert small angular displacements into large linear displacements, and then enable the measurement of small length changes. This process converts the small elongation ΔL, which is difficult to measure directly, into a more easily measurable scale difference Δx. $\frac{2H}{D}$ is the magnification factor.



(a)

(b)

Figure 2-1. Magnification principle of the optical lever

IV. Operation

1. Adjust the Experimental Stand

Before the experiment, it is crucial to ensure that the upper and lower clamps tightly grip on the wire to prevent the wire from slipping relative to the clamps during the application of force, and to ensure that the reflector can rotate freely.

(1) Wiring: Connect the signal line of the force sensor to the signal interface of the digital force gauge, and use a DC cable to connect the power output port of the digital force gauge to the power socket of the backlight source.

(2) Power On: Turn on the power switch of the digital force gauge and allow it to warm up for 10 minutes. The backlight source should illuminate, and the scale markings should be clearly visible. The panel of the digital force gauge will display the force currently applied to the metal wire.

(3) Initialization: Rotate the force application nut to apply a predefined load f_0 (3.00±0.02 *kg*) to the metallic wire, straightening any initial bends in the wire.

2. Adjust the Telescope:

(1) Position Adjustment: Move the telescope closer and align it directly with the platform base, ensuring that the distance between the front of the telescope and the platform board edge is within the range of 0 to 30 cm. Adjusting the telescope to ensure that the rotation axis of the mirror is approximately along the centerline of the telescope tube when viewed from the side of the experimental setup. Simultaneously, adjust the three screws on the bracket until a bright light from the backlight source is clearly visible through the eyepiece.

(2) Fine Adjustment: Adjust the eyepiece knob to make the crosshair lines clearly visible. Then, use the focusing wheel to ensure that the image of the scale within the field of view is also distinctly visible.

(3) Initialization: Adjust the screws on the bracket (this can also be combined with adjustments to the angle of the plane mirror) to align the horizontal crosshair with the scale lines, ensuring they are parallel and aligned with the scale line ≤ 2.0 cm to avoid exceeding the range of the scale during the experiment. Finally, move the bracket horizontally to align the vertical crosshair with the center of the scale.

3. Data Measurement

(1) Select Appropriate Measuring Instruments to Measure L, H, D, and d, respectively.

Use a tape measure to determine the original length L of the metallic wire. Place the starting end of the tape measure on the lower surface of the wire clamp, which corresponds to the upper surface of the crossbeam, and align the other end with the upper surface of the platform base.

Use a tape measure to measure the vertical distance H from the rotation axis of the mirror to the scale. Place the starting end of the steel tape measure on the upper surface of the scale board, and align the other end with the upper surface of the vertical holder, which is at the same height as the rotation axis.

Loosen the locking screw on the movable foot of the optical lever, and adjust the movable foot to an appropriate length to ensure that the tip of the movable foot is as close as possible to, but not touching, the metal wire, and the two front feet are placed in the same groove on the platform base. Use the three-foot tips to press shallow marks on a sheet of paper on, and draw fine lines connecting the two front foot marks to determine the height of the connecting line, which represents the optical lever constant. Then, measure the length of the optical lever constant D using a vernier caliper. Place the optical lever on the platform base with the tip of the movable foot close to the metal wire, ensuring the tip is directly in front of the wire.

The above-mentioned physical parameters are single measurement values and should be recorded in the experimental data.

Measure the diameter d_j of the metallic wire at various positions and directions using a micrometer screw gauge (at least six positions). Prior to measurement, take note of the zero error d_0 of the micrometer screw gauge. Record the experimental data in the table and calculate the arithmetic mean of the measured diameters $\overline{d_j}$. Subsequently, calculate the average diameter of the metallic wire using $\overline{d} = \overline{d_j} \pm d_0$.

(2) Measurement of Scale *x* and Force *f*.

Initially, press the "Zero" button on the digital force gauge and record the corresponding scale value x_1 when the horizontal line of the crosshair is aligned with the scale.

Slowly rotate the loading nut to gradually increase the tensile force in the metallic wire. Record the scale readings x^+ every 1.00 (±0.02) *kg* increment until the predetermined maximum force is reached. Then, record one additional data under an increment of approximately 0.5 kg (not exceeding 1.0 kg) of applied force.

Subsequently, reverse the rotation of the loading nut to the set maximum value and record the data. Similarly, gradually decrease the tensile force in the metal wire, recording the scale reading x_i^- every 1.00 (±0.02) *kg*, until the force reaches 0.00 (±0.02) *kg*.

Record the experimental data.

(3) Upon the completion of the experiment, loosen the force loading nut to allow the metallic wire to freely extend, and then turn off the digital force gauge.

V. Precautions

1. Following the initial adjustment of the telescope, no further adjustment should be made during subsequent experimental steps. To ensure stability, avoid any vibrations on the experimental table.
2. The experimental apparatus has a maximum force restriction mechanism, and the maximum actual force applied during the experiment should not exceed 13.00 *kg*.
3. The position of the limit nut must not be changed under any condition to prevent the maximum force restriction mechanism from failing.
4. During both the force applications and force release processes, the force loading nut must not be rotated in reverse.
5. **Upon the completion of the experiment, the force loading nut should be loosened** to allow the metallic wire to freely elongate, and the digital force gauge should be turned off.

VI. Report Requirements

1. Analyze the data using the difference-by-difference method.
2. Calculate Young's modulus and its uncertainty, and present the complete expression of the measurement results.
3. Answer the following discussion questions.

VII. Questions

1. For two metal wires made of the same material but with different diameters and lengths, are their Young's modulus values the same?
2. From the perspective of error analysis, why is it necessary to use different measuring instruments for length measurements?
3. During the experiment, why is it prohibited for the loading nut to undergo reverse rotation during the processes of loading force and releasing force?
4. What are the advantages of using the difference-by-difference method for data analysis? What issues should be considered while employing this method?

Measurement tools and their related parameters required for the experiment

Instrument Name	Measuring Range	Resolution	Error Limit
Ruler (*mm*)	80.0	1	0.5
Micrometer (*mm*)	10.0	0.1	--
Tape Measure (*mm*)	3000.0	1	0.8
Vernier Caliper (*mm*)	150.00	0.02	0.02
Micrometer Screw Gauge (*mm*)	25.000	0.01	0.004
Digital Force Gauge (*kg*)	20.00	0.01	0.005

Experiment III: Collision and Targeting Experiment

I. Preparation Guide

1. Classification of collisions (by energy transfer and by angle of collision).
2. Conditions for conservation of momentum and mechanical energy.
3. Derivation of the relationship between the ideal drop height h_0 of the pendulum ball and the height y of the ball support, the preset target center x_0, the mass m_1 of the pendulum ball, the mass m_2 of the target ball, and the radius r of the target ball.

II. Objectives and Tasks

1. Investigate the phenomena and laws of two-body collision problems.
2. Apply kinematic principles, conservation and transformation laws of mechanical energy to solve practical target-hitting problems, and study energy loss during collisions.
3. Master the use of general instruments such as vernier calipers.

III. Principle

1. **Collision**: A phenomenon where two moving objects come into contact and rapidly change their states of motion. A "head-on collision" occurs when the velocities of the two colliding objects are along the line connecting their centers of mass; other collisions are "oblique collisions." An "elastic collision" is one where there is no loss of mechanical energy during the collision; an "inelastic collision" is one where mechanical energy is not conserved, with some of it being converted into non-mechanical energy (e.g., heat).
2. **Conservation of Momentum during Collision**: In the absence of external forces or when the sum of external forces is zero, the total momentum of the two objects before and after the collision remains unchanged.
3. **Conservation of Mechanical Energy**: In any physical system where potential and kinetic energy are interconverted, if the net work done by external forces on the system is zero and all internal forces are conservative (non-dissipative), the total mechanical energy (the sum of potential and kinetic energy) of the system remains constant.
4. **Projectile Motion**: When an object of mass m is thrown with an initial velocity v_0 in the horizontal direction, the motion of the object is called projectile motion (ignoring air resistance). The kinematic

equations are: $x = v_0 t$, $y = \frac{1}{2} g t^2$, The initial kinetic energy is: $E_k = \frac{1}{2} m {v_0}^2$ ..

IV. Experiment Principles

The experimental setup is shown in Figure 3-1. The potential-energy column is equipped with an electromagnet whose magnetic field direction is parallel to the rod. The rod has a scale. The slider on the potential energy column is equipped with an electromagnet component, allowing the slider to move up and down the column to adjust the height of the main striking ball and change its potential energy. The center of the electromagnet, the center of mass of the pendulum ball (steel ball), and the center of mass of the target ball are aligned in a plane perpendicular to the base plate and passing through the centers of the two columns. Since the centers of mass of the two balls are adjusted to the same height beforehand, once the electromagnet's power is cut off, the pendulum ball will swing freely and collide head-on with the target ball, causing the target ball to undergo projectile motion and eventually land on the base plate with the target.

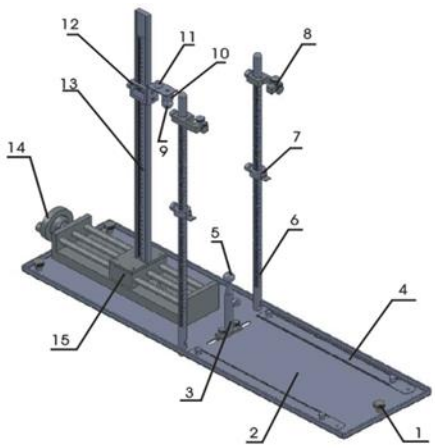


Figure 3-1: The experiment instrument

1. Leveling feet; 2. Base plate; 3. Ball support column; 4. Paper clamp; 5. Target ball; 6. Column; 7. Wire length adjustment slider; 8. Wire fixing seat; 9. Pendulum ball; 10. Electromagnet; 11. Electromagnet control input socket; 12. Potential energy column slider; 13. Potential energy column; 14. Drum wheel; 15. Horizontal slider.

The collision process is shown in Figure 3-2. The target ball of mass m_2 is placed on the ball support column at height y. The pendulum ball of mass m_1 falls from height h_0 and collides head-on with the target ball in the horizontal direction. The target ball undergoes projectile motion with a horizontal displacement of x_0 (pre-set, recommended to be 20 cm). Before starting the experiment, the relationship between h_0 and y, the preset x_0 (recommended to be 20 cm), m_1, m_2, and r should be derived under ideal conditions, and the preset height $h = h_0 + r + y$ of the pendulum ball should be calculated.

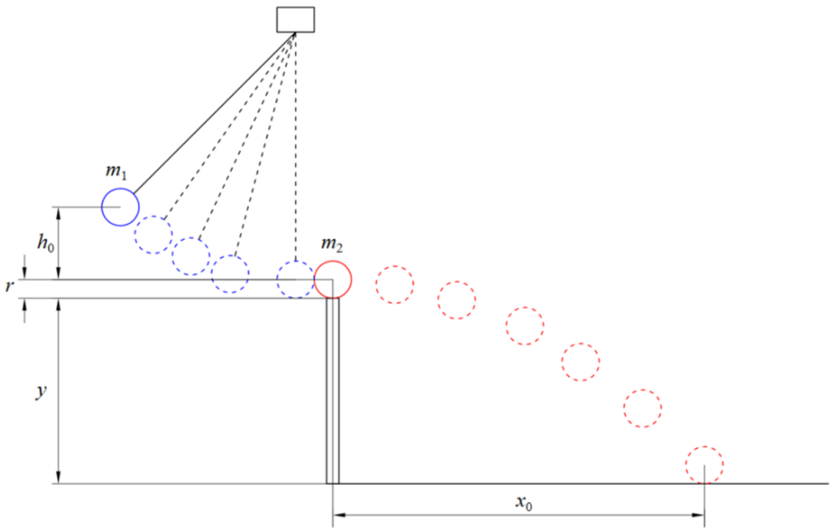


Figure 3-2: Collision Process

V. Operation

1. Adjust the screws on the instrument base to level the base and the guide rail.
2. Use a steel ball as the target ball. Measure the mass of the steel ball using an electronic scale and use this as the mass of the pendulum ball. Measure the diameter of the target ball using a vernier caliper.
3. Move the ball support column to center it left and right. Adjust the two pairs of locking screws to make them equal in height.
4. Take a sheet of white paper to record the landing points of the target ball. Fold the paper to create a crease, and use the pair of steel rulers on the base to secure the paper, aligning the crease, the ball support column, and the scale plate in a straight line.
5. Place the target ball on the ball support column. Adjust the upper locking screws to set the height and position of the pendulum ball, and adjust the height of the ball support column so that the pendulum ball can collide head-on with the target ball at the lowest point of its swing.
6. Measure the height y of the ball support column using a vernier caliper. Based on the preset target center x0, calculate the ideal height difference h0 between the pendulum ball and the center of the target ball.
7. Cover the recording paper with carbon paper. Power the electromagnet coil to hold the pendulum ball on the electromagnet core. Determine the height of the slider on the potential energy column (i.e., the preset height of the pendulum ball) based on the potential energy difference (i.e., h_0) as $h = h_0 + r + y$. Move the translation frame to adjust the tension of the wire.
8. Turn off the power, and the pendulum ball will automatically fall and collide with the target ball.

9. Measure the distance x the steel ball is ejected (collide 10 times, measure the positions of 10 landing points, and take the average). Record the data.
10. Observe the motion states of the two balls before and after the collision. Adjust the height of the pendulum ball and repeat the experiment several times to determine the height h' that allows the target ball to hit the target center x_0. Record the h' value when the target ball hits the target paper.
11. Repeat the experiment with two other target balls, observe the similarities and differences in the experimental phenomena, and analyze and discuss the results.

VI. Precautions

1. This experiment requires a self-prepared A4 sheet of paper for target practice.

2. The landing point of the target ball should not deviate from the crease on the white paper by more than 1 cm.

3. After each collision, immediately measure and record the landing point position before proceeding to the next collision.

4. Pay special attention to the calculation and setting of the initial position of the pendulum ball.

VII. Report Requirements

The data to be measured and recorded in this experiment include the mass and diameter of the target ball, the preset position x_0, and the height y of the ball support column. Derive the ideal height difference h_0 (include the derivation process). In the three sets of experiments, the values of x_0 and y should remain unchanged. In each set of experiments, record the positions of 10 landing points and the height h' that allows the target ball to hit the preset position x_0. Calculate the percentage of mechanical energy loss based on the average value $\overline{x}$ of the 10 landing points: $\Delta E = \dfrac{h'-h}{h_0+h'-h}$.

Experiment IV: The Hall Effect

I. Preparation Guide

1. What is the principle behind the Hall effect?

2. How can the Hall effect be used to measure magnetic fields?

3. What systematic errors exist in Hall voltage measurements, and how can these errors be eliminated?

II. Objectives and Tasks

1. Measure the UH-IH curve using the "symmetric measurement method" and calculate the sensitivity of the Hall sensor;

2. Measure the UH-IM curve using the "symmetric measurement method" and calculate the sensitivity of the Hall sensor;

3. Measure the magnitude and distribution of the magnetic induction B in the air gap of the electromagnet.

III. Principle and Operation

1. Electrode Equipotential Error

When current I_H flows through the Hall plate, the plane perpendicular to I_H is called the equipotential surface. If the two electrodes measuring U_H are not on the same equipotential surface, an additional voltage will exist. The error voltage is $U_0 = I_H\ r$, where r is the resistance between the equipotential surfaces corresponding to the two electrodes. The direction of U_0 depends on I_H and is independent of B. This error can be eliminated using the symmetric measurement method. Other effects also need to be taken into consideration which are explained below.

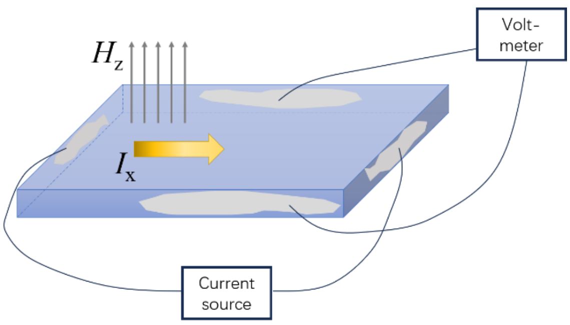


Figure 4-1: Hall Effect: Suppose an electric current flows along the *x*-axis of a conducting plate (blue) while an applied magnetic field *H* is applied along the z-axis, then a voltage potential appears along the *y*-axis direction.

2. The Ettingshausen Effect

The velocity of charge carriers has a statistical distribution. The Hall electric field E_H depends on the average velocity v of the carriers. If carriers with velocity v are balanced, carriers with velocities greater or less than v will deflect to opposite sides, creating a temperature gradient in the y-axis direction and generating a thermoelectric potential U_E. The direction of I_H depends on I_H and B, so it cannot be eliminated by the symmetric measurement method.

3. The Righi-Leduc Effect

If there is a temperature gradient in the x-axis direction of the Hall plate, a diffusion current I_d will be generated in the x-axis direction. This will cause a thermoelectric potential U_{RL} in the y-axis direction, similar to the Ettingshausen effect. The direction of U_{RL} depends on B but is independent of I_H.

4. The Nernst Effect

The diffusion current under the Lorentz force will directly generate an additional potential U_N whose direction depends on B but is independent of I_H.

U_{RL} and U_N can be eliminated by changing the direction of I_H using the symmetric measurement method. Under small electric currents and weak magnetic field conditions, U_E can be neglected. By changing the directions of I_H and B, four Hall voltage values can be measured, and their absolute values can be averaged to eliminate the errors from secondary effects.

V. Operation

1. Pre-experiment Operations

Understand the functions of each part of the instrument and connect the circuit properly.

Before turning the power switch on or off, rotate the working current and excitation current adjustment knobs counterclockwise to minimize the current.

To improve the accuracy of the Hall sensor measurement, pre-heat the Hall sensor for 5 minutes before the experiment. The specific operation is as follows: close the working current switch, disconnect the excitation current switch, and pass a working current of 5 mA. Wait for 5 minutes before starting the experiment.

The dimensions of the Hall sensor are ($l*b*d$) 300 μm×300 μm×260 μm.

2. Measuring the Sensitivity K_H of the Hall Sensor

Move the two-dimensional moving scale to position the Hall sensor at the center of the electromagnet air gap.

Set the excitation current I_M = 300 mA, and calculate and record the magnetic induction B in the electromagnet air gap using the formula $B = C \cdot I_M$ (where C is the coil constant of the electromagnet, which can be read directly from the instrument panel).

Design the working current I_H values to be adjusted at equal intervals, with I_H ranging from 1.0 to 10.0 mA. For each I_H value, change the directions of I_H and I_M to measure the U_H value. Record at least 5 sets of data as shown in Table 4-1.

Table 4-1: Relationship between the Hall Voltage U_H and Working Current I_H

I_M = ___ mA, C = ___ mT/A, d (Hall element thickness) = ___ mm

I_H (mA)	U_1 (mV)	U_2 (mV)	U_3 (mV)	U_4 (mV)	$U_H = (\|U_1\| + \|U_2\| + \|U_3\| + \|U_4\|)/4$ (mV)
	$+I_M$, $+I_H$	$-I_M$, $+I_H$	$+I_M$, $-I_H$	$-I_M$, $-I_H$	

3. Measuring the U_H - I_M Curve

Move the two-dimensional moving scale to position the Hall sensor at the center of the electromagnet air gap. Set the working current $I_H = 3.00$ mA.

Adjust the excitation current I_M values (at equal intervals) ranging from 100 to 1,000 mA. For each I_M value, change the directions of I_H and I_M to measure the U_H value. Record at least 5 sets of data as shown in Table 4-2.

Table 4-2: Relationship between Hall voltage U_H and excitation current I_M

I_H = ___ mA, C = ___ mT/A, d (Hall element thickness) = ___ mm

I_M (mA)	U_1 (mV)	U_2 (mV)	U_3 (mV)	U_4 (mV)	$U_H = (\|U_1\| + \|U_2\| + \|U_3\| + \|U_4\|)/4$ (mV)	B (mT)
	$+I_M$, $+I_H$	$-I_M$, $+I_H$	$+I_M$, $-I_H$	$-I_M$, $-I_H$		

4. Measuring the Magnitude and Distribution of Magnetic Induction B in the Electromagnet Air Gap

Set $I_M = 600$ mA, $I_H = 5.00$ mA. Adjust the vertical scale of the two-dimensional moving scale to position the Hall sensor at the center of the electromagnet air gap in the vertical direction.

Adjust the horizontal scale, starting from the 0 mark, change the directions of I_H and I_M to measure the U_H value; and calculate the magnetic induction intensity based on K_{H2}; the horizontal position x should cover the range [0, 50 mm], and at least 15 points should be measured so the profile distribution of the magnetic induction B can be represented in more detail.

Table 4-3: Distribution of the magnetic induction B in the electromagnet air gap

I_H = ___ mA， I_M = ___ mA， C = ___ mT/A

x (mm)	U_1 (mV)	U_2 (mV)	U_3 (mV)	U_4 (mV)	$U_H = (\|U_1\| + \|U_2\| + \|U_3\| + \|U_4\|)/4$ (mV)	B (mT)
	$+I_M$, $+I_H$	$-I_M$, $+I_H$	$+I_M$, $-I_H$	$-I_M$, $-I_H$		

V. Questions

1. How can the conductive type of the Hall plate (N or P type semiconductor) be determined based

on the directions of B, I_H, and U_H? Illustrations are also required. (Note: In N type semiconductors, the carriers are electrons; in P type semiconductors, the carriers are holes or positive ions).

2. Estimate the carrier concentration of the Hall plate used in this experiment.

Experiment V: Measurement of the Surface-tension Coefficient of a Liquid

I. Preparation Guide

1. What is surface tension? What factors are related to the liquid surface tension coefficient?

2. What is the experimental principle of measuring the surface tension coefficient of liquids using the pull-off method?

II. Objectives and Tasks

1. Understand the basic structure of the surface tension coefficient measuring instrument, master the method of calibrating the measuring instrument with standard weights, and calculate the sensitivity of the sensor.

2.Observe the physical process and physical phenomena used to measure the surface tension of liquids using the pull-off method, and conduct analysis and research using basic concepts and laws of physics to deepen the understanding of physical laws.

3. Master the use of pull-off method to measure the surface tension coefficient of pure water and use the difference-by-difference method to process data.

III. Principle

If you observe carefully, you will find that many phenomena in life are related to the surface tension of liquids. For example, raindrops on lotus leaves do not spread out, but form nearly spherical water droplets. This phenomenon occurs because the molecules at the liquid interface or surface are subject to an additional stress - surface tension. Macroscopically speaking, liquids have a tendency to reduce their surface area as much as possible, and the liquid surface is like a stretched rubber film. In industrial production and scientific research, the unique properties and phenomena of liquids are often involved, such as the transmission process of liquids in chemical production, the drug preparation process, and the movement and balance of liquids in animals and plants in the field of bioengineering research. Therefore, it is of great practical significance to understand the properties and phenomena of liquid surfaces and master the method of measuring the surface tension coefficient of liquids. Methods for measuring the surface tension coefficient of liquids usually include: pull-off method, capillary rise method and droplet gravimetric method. This experiment mainly introduces the liquid film pull-off method.

If a clean cylindrical lifting ring is immersed in a liquid, and then the lifting ring is slowly lifted, the cylindrical lifting ring will bring up a liquid film, as shown in Figure 5-1.

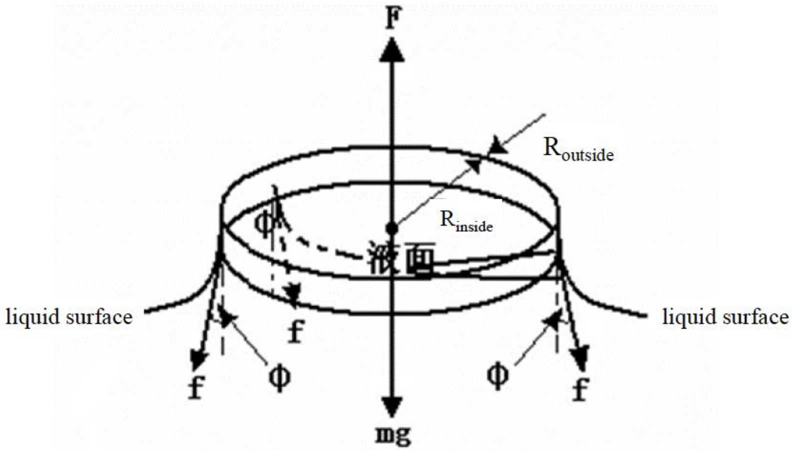


Figure 5-1 Schematic diagram of the force exerted on a circular lifting ring slowly pulled up from the liquid surface

The surface tension ***f*** that causes the liquid surface to shrink is along the tangent direction of the liquid surface, and the angle φ is called the wetting angle (or contact angle). When the cylindrical ring is continued to be lifted, φ gradually becomes smaller and approaches zero. At this time, the tension ***f*** on the inner and outer surfaces of the pulled out liquid film is vertically downward. Assume that the pulling force when the liquid film ruptures is ***F***, then

$$F=(m+m_0)g+2f \tag{5-1}$$

In this formula, *m* is the mass of the liquid adhering to the lifting ring, m0 is the mass of the lifting ring. Because the surface tension is proportional to the length of the perimeter of the contact surface, therefore,

$$2f=L\alpha=\pi(D_{\text{inside}}+D_{\text{outside}})\alpha \tag{5-2}$$

The coefficient α is called the surface tension coefficient, and its unit is N/m. α is numerically equal to the surface tension per unit length. *L* is the sum of the circumferences of the inner and outer rings of the cylindrical ring.

$$\alpha=\frac{F-(m+m_0)g}{\pi(D_{\text{inside}}+D_{\text{outside}})} \tag{5-3}$$

Since the metal film is very thin and the liquid film being pulled up is also very thin, m is very small and can be ignored, so the formula can be simplified to:

$$\alpha=\frac{F-m_0g}{\pi(D_{\text{inside}}+D_{\text{outside}})} \tag{5-4}$$

The surface tension coefficient α is related to the type, purity, temperature of the liquid and the composition of the gas above it. Experiments show that the higher the temperature of the liquid, the smaller the α value, the more impurities it contains, and the smaller the α value. As long as the above conditions remain constant, the α value is a constant. The core part of this experiment is to accurately determine $F\text{-}m_0g$, that is, the downward surface tension exerted by the cylindrical lifting ring. It can be measured with a surface tension coefficient measuring instrument.

IV. Experimental Instruments

Figure 5-2 Surface Tension Coefficient Measuring Instrument

As shown in Figure 5-2, the main components of the surface tension coefficient measuring instrument include: base, column, sensor fixed bracket, pressure resistance sensor, digital millivolt meter, organic glass vessel (connector), standard weight (weight plate), and cylindrical lifting ring.

V. Operation

1. After connecting the cable, turn on the instrument and preheat for 15 minutes (do not heat the liquid to be measured yet).

2. Clean plexiglass vessels and hanging rings.

3. Put the liquid to be measured into the organic glass vessel (ethanol and other solvents that are harmful to the organic glass vessel cannot be used).

4. Hang the weight plate on the hook of the force sensor.

5. If the whole machine has been preheated for more than 15 minutes, you can calibrate the force-sensitive sensor. Press the button switch on the panel to pop it up (the button indicator light is on). Before adding weight, you should first read the initial reading V_0 of the electronic scale (this reading includes the

weight of the weight pan). (Note: For instruments with a zero-adjustment device, you can adjust the zero-adjustment knob on the back of the chassis so that the initial reading is zero). Then each time a 500mg weight is added, a corresponding data (unit: mV) is read and recorded in the table. Note that the movements should be as light as possible when placing the weight. Use the difference-in-differences method to find the conversion coefficient of the force-sensitive sensor *K*=________(N/mV).

6. Before changing the lifting ring, you should first measure the inner and outer diameter of the lifting ring, then hang the lifting ring and read a corresponding data (unit: mV). During the process of measuring the surface tension coefficient of the liquid, you can observe the buoyancy and tension generated by the liquid. Turn the piston adjustment knob counterclockwise to make the liquid level rise. When the lower edge of the ring is close to the liquid level, carefully adjust the suspension line of the lifting ring to make the lifting ring horizontal, and then immerse the lifting ring partially in the liquid. At this time, press the button switch on the panel (i.e., the peak measurement position, the button indicator light goes out), the instrument function switches to peak measurement, and then slowly turn the piston adjustment knob clockwise. At this time, the liquid level gradually drops (relatively speaking, the lifting ring is pulled upward). Observe the physical processes and phenomena when the ring is immersed in the liquid and pulled up from the liquid. When the lifting ring pulls off the liquid column, the moment can be captured by the digital voltmeter, and the pulling force peak value V_1 will be displayed and the data will be automatically maintained. After pulling it off, press the button switch and the voltmeter will resume its measurement function. After it stops, its reading value is V_2. Write down this value. Do this 5 times in a row and find the average value, then the surface tension is $2f=(\overline{V_1}-\overline{V_2})\cdot\overline{K}$ and the surface tension coefficient is

$$\alpha=\frac{2f}{L}=\frac{(\overline{V_1}-\overline{V_2})\cdot\overline{K}}{\pi(D_{\text{inside}}+D_{\text{outside}})}.$$

7. Heating the liquid to be measured, repeat the above-mentioned measurement steps 6 every time the temperature rises about 5°C (**Note: before measuring, turn the piston adjustment knob to move the piston up and down several times to make the liquid flow and the temperature uniform, and then wait for the liquid level to calm down before measuring**).

VI. Precautions

1. Lifting rings must be handled strictly and clean. After using the solution to remove oil stains or impurities, rinse with clean water and dry with hot air.

2. The level of the lifting ring must be adjusted well and pay attention to the deviation.

3． The instrument needs to warm up for 15 minutes when it is turned on.

4. When adjusting the liquid level lifting piston, the speed should be slow to minimize the fluctuation of the liquid;

5. The working environment should be protected from wind to prevent the swing of the lifting ring from causing the zero point to fluctuate, resulting in inaccurate measured coefficients;

6. If the liquid is pure water, prevent dust, oil and other impurities from contaminating it during use. Pay special attention not to touch the liquid being measured with your fingers;

7． When using the force-sensitive sensor, the force should not be greater than 4.9N. Excessive tension sensor is easily damaged (the instrument will automatically alarm if the force is too large or deviates too much from the normal value).

8. After the experiment, the hanging ring must be dried with clean paper, wrapped in clean paper, and placed in a drying cylinder.

VII. Data Records

1．Use the difference-in-differences method to find the conversion coefficient of the instrument K：

Record the weight as initial reading first V_{0}=________mV， then add a weight of 500mg each time (the standard weight complies with the national standard, and the relative error is 0.05%)

Weight 10^{-6}Kg	Record after adding $V_i'(\mathrm{mV})$	Record after reducing $V_i''(\mathrm{mV})$	$V_i = \dfrac{V_i' + V_i''}{2}(\mathrm{mV})$
0			
500.00			
1000.00			
1500.00			
2000.00			
2500.00			
3000.00			
3500.00			

Use the difference-in-differences method to find the reading of the electronic scale corresponding to every 500 mg ΔV, then $\overline{K}=\frac{mg}{\Delta V}$ =_______N/mV.

2. Use the pull-off method to find the electronic scale reading corresponding to the pulling force:

Water temperature (room temperature) _______________ºC,

Electronic scale initial reading V_{0}=________mV

Number of measurements	Maximum reading when pulling off V_1 (mV)	Lifting ring reading V_2 (mV)	Surface tension corresponding reading $V=V_1-V_2$ (mV)
1			
2			
3			
4			
5			
Mean value			$\overline{V}$ =_______________

3. The inner and outer diameter of the lifting ring (unit: mm)

Number of measurements	1	2	3	4	5	mean
inner diameter D_{inside}						
outer diameter $D_{outside}$						

4. Calculate α and the uncertainty:

$$\overline{L}=\pi(\overline{D_{内}}+\overline{D_{外}})$$

$$\overline{\alpha}=\frac{\overline{K}\cdot\overline{V}}{\overline{L}}$$

$$\left(\frac{\Delta\alpha}{L}\right)^2=\left(\frac{\Delta K}{K}\right)^2+\left(\frac{\Delta V}{V}\right)^2+\left(\frac{\Delta L}{L}\right)^2$$

$$\alpha=\alpha\pm\Delta\alpha$$

5. Find the theoretical value of the surface tension coefficient α of water at room temperature from the

appendix, compare the experimental results with this value, find the relative error, and analyze it.

6. Measure the surface tension coefficient at different temperatures and analyze and compare it with the theoretical value of the surface tension coefficient of water at room temperature.

VIII. Questions

1. What approximations were made in deriving the formula for measuring the liquid surface tension coefficient? What is the physical meaning of each quantity in the formula?
2. If the weight of pulling up the liquid film is taken into account, how should the experimental results be corrected?

Appendix:

Experimental instrument technical indices:

1． Silicon piezoresistive sensor

（1）Force bearing range: 0-4.9N

（2）Nonlinear error: ≤0.2%

（3）Supply voltage: Adjustable DC constant current source 5-10V

2． Display instrument

（1）Reading display：0-500.999 mV 6-digit high-precision digital voltmeter

（2）Zero adjustment：One-click zero adjustment

（3）Connection method：5-core aviation plug

3． 500mgweight, 0.025mg Accuracy.

Surface Tension Coefficient Value of Pure Water (Under Standard Atmospheric Pressure)

Water Temperature (℃)	10	15	20	25	30
α ($\times10^{-2}$N/m)	7.422	7.349	7.275	7.197	7.118
Water Temperature (℃)	35	40	45	50	55
α ($\times10^{-2}$N/m)	7.038	6.956	6.874	6.791	6.705

Experiment VI: Characteristics of RLC circuits

I. Preparation Guide

1. What are the voltage expression for the transient process of the series RC and RL circuits, and the expression for the time constant τ?
2. What are the voltage expressions for the transient process (three types of damping processes) of the series RLC circuit, and the expression for the time constant τ?

II. Objectives and Tasks

1. Use a digital oscilloscope and a signal generator to observe the voltage changes during the transient process of the series RC, RL, and RLC circuits.
2. Measure the time constant τ and understand the physical meaning of τ.

III. Principle

1. Series *RC* Circuits

In a DC series circuit composed of a resistor *R* and a capacitor *C*, the transient process refers to the charging and discharging process of the capacitor. As shown in Figure 6-1, when the switch is switched to position 1, the power supply *E* charges the capacitor *C* until the voltage across the capacitor *C* is equal to that of the power supply *E*.

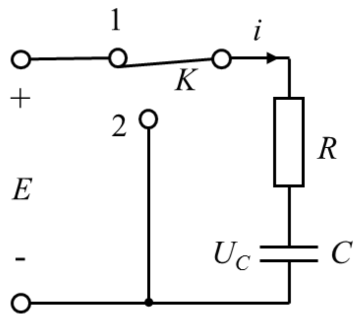


Figure 6-1 A series *RC* circuit

During the charging process, the equation is:

$$RC\frac{dU_C}{dt}+U_C=E \tag{6-1}$$

Considering the initial conditions t=0 and U_C=0, we can obtain the solution to Equation 6-1 as

$$U_C(t)=E\left(1-e^{-\frac{t}{RC}}\right)=E\left(1-e^{-\frac{t}{\tau}}\right) \tag{6-2}$$

Equation (6-2) represents the growth of the capacitor voltage from zero during the charging process, where $\tau = RC$ is the time interval when the charging voltage of capacitor increases from 0 to 0.63E. τ is an important physical quantity that characterizes the speed of the transient process, and is called the time constant of the series RC circuit.

In Figure 6-1, when the switch is switched to position 2, the capacitor *C* discharges through the resistor R, and the equation is:

$$RC\frac{dU_C}{dt}+U_C=0 \tag{6-3}$$

Considering the initial conditions t=0 and U_C=E, the solution to Equation (6-3) can be obtained as:

$$U_C(t)=Ee^{-\frac{t}{RC}}=Ee^{-\frac{t}{\tau}} \tag{6-4}$$

Equation (6-4) represents the exponential decay of the voltage $U_C(t)$ across the capacitor during the discharge process, and the time constant τ represents the time interval when the voltage decays from E to 0.37E. Figure 6-2 shows the charging and discharging curves of the series RC circuit.

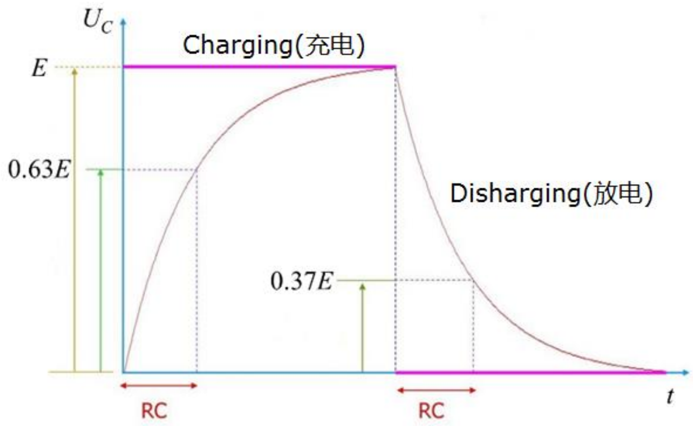


Figure 6-2 charging and discharging curves of the series RC circuit

2. Series *RL* circuits

In a DC series circuit composed of a resistor R and an inductor L (Figure 6-3), when the switch is in position 1, the equation of the loop is:

$$L\frac{di}{dt}+Ri=E \tag{6-5}$$

From the initial condition: i(0) =0, the solution to Equation (6-5) can be obtained as:

$$i(t)=\frac{E}{R}\left(1-e^{-\frac{tR}{L}}\right)=\frac{E}{R}\left(1-e^{-\frac{t}{\tau}}\right) \tag{6-6}$$

$\tau = L/R$ is called the time constant of the RL circuit, which is an important physical quantity that characterizes the rate of growth of the current i(t).

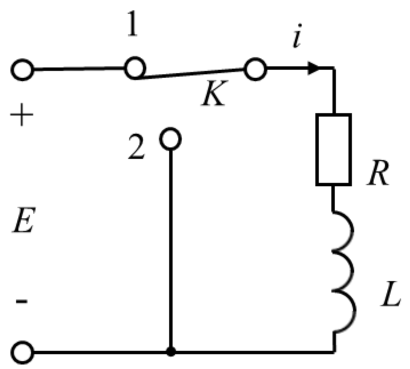


Figure 6-3 Series RL circuit

When the switch is switched to position 2, the equation of the circuit is:

$$L\frac{di}{dt}+Ri=0 \tag{6-7}$$

Considering the initial condition $i(0)=E/R$, the solution to Equation (6-7) can be obtained as:

$$i(t)=\frac{E}{R}e^{-\frac{tR}{L}}=\frac{E}{R}e^{-\frac{t}{\tau}} \tag{6-8}$$

The process of the loop current change in the series RL circuit is shown in Figure 6-4.

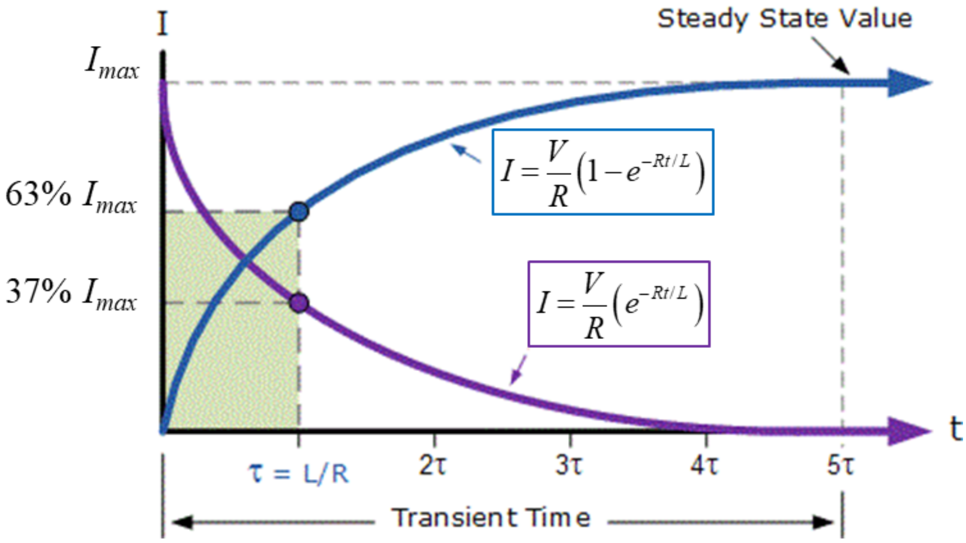


Figure 6-4 Variation of the current in the series RL circuit

3. Series *RLC* circuits

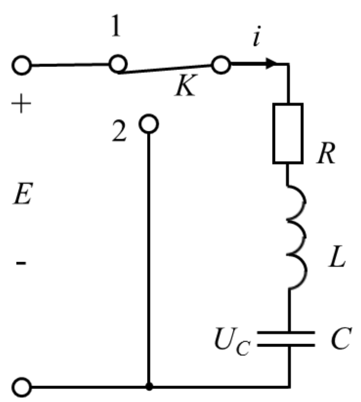


Figure 6-5 Series RLC circuit

In a DC series circuit composed of a capacitor *C*, an inductor *L*, and a resistor *R* (note that the capacitor, inductor, and the power have resistance), when the switch is in position 1（Figure 6-5）, the power source charges the capacitor, and the equation is:

$$LC\frac{d^2U_C}{dt^2}+RC\frac{dU_C}{dt}+U_C=E \tag{6-9}$$

Considering the initial conditions t=0，U_C=0，and $\frac{dU_C}{dt}=0$, the solution can be obtained in three cases: (1) underdamped state, (2) critically damped state, (3) overdamped state.

（1）Underdamped state：When $R<\sqrt{\frac{4L}{C}}$,

$$U_C(t)=E\left(1-\sqrt{\frac{4L}{4L-R^2C}}e^{-\frac{t}{\tau}}\cos(\omega t+\varphi)\right) \tag{6-10}$$

Where $\tau=\frac{2L}{R}$ is the time constant of the *RLC* circuit and $\omega=\frac{1}{\sqrt{LC}}\sqrt{1-\frac{R^2C}{4L}}$.

（2）Critically damped state：When $R=\sqrt{\frac{4L}{C}}$,

$$U_C(t)=E\left(1\text{-}\left(1+\frac{t}{\tau}\right)e^{-\frac{t}{\tau}}\right) \tag{6-11}$$

（3）Overdamped state：When $R>\sqrt{\frac{4L}{C}}$,

$$U_C(t)=E\left(1-\sqrt{\frac{4L}{R^2C-4L}}e^{-\frac{t}{\tau}}\right)\sinh(\beta t+\varphi) \tag{6-12}$$

where $\beta=\frac{1}{\sqrt{LC}}\sqrt{\frac{R^2C}{4L}-1}$.

When the switch is switched to position 2, the capacitor *C* discharges through the closed RLC circuit, and the equation is:

$$LC\frac{d^2U_C}{dt^2}+RC\frac{dU_C}{dt}+U_C=0 \tag{6-13}$$

The equation solution has three cases.

(1) Underdamped state. When $R<\sqrt{\frac{4L}{C}}$,

$$U_C(t)=E\sqrt{\frac{4L}{4L-R^2C}}e^{-\frac{t}{\tau}}\cos(\omega t+\varphi) \tag{6-14}$$

(2) Critically damped state. When $R=\sqrt{\frac{4L}{C}}$,

$$U_C(t)=E\left(1+\frac{t}{\tau}\right)e^{-\frac{t}{\tau}} \tag{6-15}$$

(3) Overdamped state. When $R>\sqrt{\frac{4L}{C}}$,

$$U_C(t)=E\sqrt{\frac{4L}{R^2C-4L}}e^{-\frac{t}{\tau}}\sinh(\beta t+\varphi) \tag{6-16}$$

Figure 6-6 shows the variation of U_C during the charging and discharging processes of the series RLC circuit.

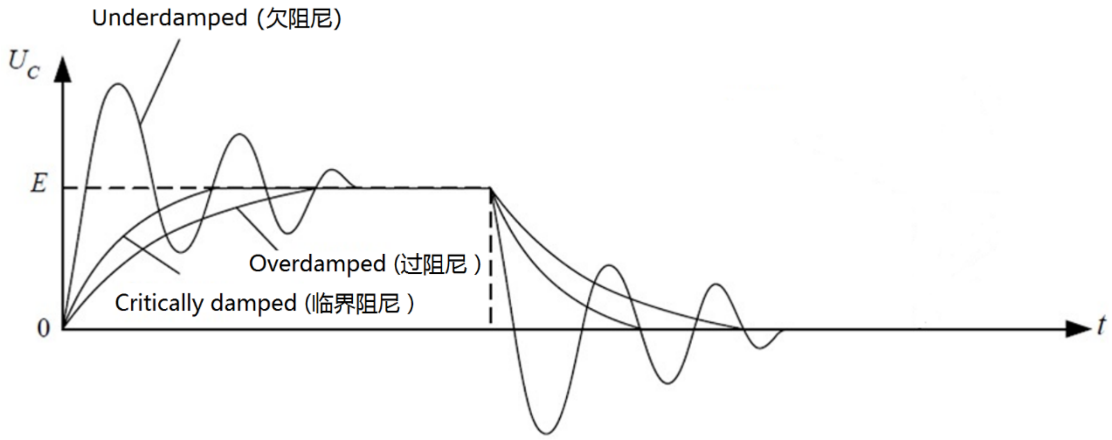


Figure 6-6 The chargind and discharging curves of the series RLC circuit under three different damping cases

IV. Operation

1. Transient characteristics of the series RC circuit (Use square-wave pulses with amplitude V_{pp}=10V)

If the signal source is a DC voltage, a storage oscilloscope should be used to observe the single charging process. In this experiment, we choose square-wave pulses as the signal source to conduct the experiment, so that a regular oscilloscope can be used for observation. Since a power signal output is used, electrical short-circuits should be prevented.

(1) Select appropriate R and C values, for example: R=100 Ω, C=10 μF. According to the time constant τ, select an appropriate square-wave frequency, generally the period T of the square waves should be larger than 10τ, so that the transient process can be reflected more completely, and use an appropriate oscilloscope sweep speed to fully display the transient process.

(2) Change the R value or C value, observe the change rule of U_R or U_C, record the waveform under different RC values, and measure the time constant τ ($\tau=RC$) respectively.

(3) Change the frequency of the square-wave pulses, observe the change of the waveform, and analyze the variation of waveforms under the same τ value at different frequencies.

R= 500 Ω

τ \ C	0.022μF	10μF	100μF
Period of square waves (T)			
Time constant τ			
Waveform			

C= 100 μF

τ \ R	10Ω	50Ω	100Ω
Period of square waves (T)			
Time constant τ			

2. Transient characteristics of the series RL circuit (Use square-wave pulses with amplitude V_{pp}=10V)

Select appropriate L and R values for the experiment. Note that the value of R cannot be too small, because there is internal resistance in L. If the waveform is distorted or self-excited, the L value and R value should be readjusted for the experiment.

(1) Select appropriate R and L values such as R=1000 Ω, L=10 mH. According to the time constant τ, select an appropriate square-wave frequency (generally the period T of the square wave should be larger than 10τ) and oscilloscope sweep speed to fully display the transient process.

(2) Change the R value or L value, observe the variation of U_R, record the waveform under different RL values, and measure the time constant τ (τ=L/R) respectively.

(3) Change the square wave frequency, observe the change of the waveform, and analyze the waveform change under the same τ value at different frequencies.

L= 10 mH

τ \ R	100 Ω	500 Ω	900 Ω
Voltage on R (U_R)			
Time constant τ			

R= 1000 Ω

τ \ L	10 mH	50 mH	100 mH
Voltage on R (U_R)			
Time constant τ			

3. Transient characteristics of RLC series circuit (Use square-wave pulses for the experiment)

In the underdamped state, peaks of U_c present when $\cos(\omega t+\varphi)$=-1. Measure the peak value at an arbitrary time t_1 (U_{ct_1}) and the peak value at time t_1+nT ($U_{c(t_1+nT)}$) of the underdamped U_C charging oscillation waveform during the **charging** process. Substitute U_C and t into the formula

$$U_C(t)=E\left(1-\sqrt{\frac{4L}{4L-R^2C}}e^{-\frac{t}{\tau}}\cos(\omega t+\varphi)\right),$$

and use the graphical method (or the least-squares method) to find the slope of $\ln\left(\frac{U_C}{E}-1\right)\sim t$. Calculate the time constant τ, and compare it with the theoretical value $\tau = 2L/R$ (where $R=R_{\text{resistor}}+R_S+R_L$). Analyze the causes of the error.

V. Requirements for Reports

1. Record the values of *R*, *C*, and *L* parameters, the waveforms observed on the oscilloscope, and the time constant *τ* during each experimental task.

2. Analyze the errors that occurred during the experiment.

VI. Precautions

The oscilloscope and function generator used in this experiment have many functions. Operate them after the teacher's explanation. The instruments are designed in an open manner, so when using them, you need to make the connections correctly and do not short-circuit the power signal source to avoid damage.

VII. Questions

1. In RC and RL circuits, if the square-wave frequency *f* is fixed while changing the resistance *R*, why will you get different waveforms? If *R* is fixed while changing the square-wave frequency *f*, will you get similar waveforms? Why?

2. In an RLC circuit, why do you need to adjust the square-wave frequency appropriately to observe the damped oscillation waveform? What will happen if the frequency is too high? Try to observe.

Experiment VII: Speed of Sound in Air

I. Preparation Guide

For speed-of-sound measurements, what are the principles of and experimental set-ups for the standing-wave method, phase-comparison method, and time-difference method?

II. Objectives and Tasks

1. Measure the speed of sound in air using the standing-wave method, phase-comparison method, and time-difference method;

2. Observe the propagation and reflection of sound waves;

3. Familiarize yourself with the use of an oscilloscope.

III. Principle

1. Ultrasound and Piezoelectric Ceramic Transducers

Mechanical vibrations in an elastic medium at frequencies above 20kHz are referred to as ultrasound. The frequencies of ultrasound in this experiment range from 20kHz to 60kHz, which are optimal for the use of piezoelectric ceramic transducers as transmitters or receivers.

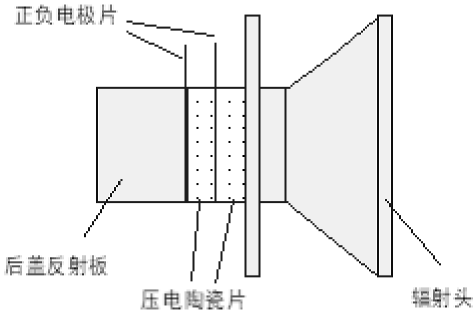


Figure 7-1 Schematic Illustration of a Transducer

According to their vibration modes, piezoelectric ceramic transducers are classified into three types, namely (i) longitudinal transducers, (ii) radial transducers, and (iii) bending transducers. In this experiment, a pair of longitudinal transducers (Figure 7-1) are used for speed-of-sound measurements.

2. The Standing-wave Method for Speed-of-sound Measurements

Consider the ideal presence of only a point source S1 (transmitter) and a receiving plane (receiver S2). In the absence of any plane of reflection other than S2, we assume that any sound wave emitted by S1 can only be reflected once by S2, with a phase change of π.

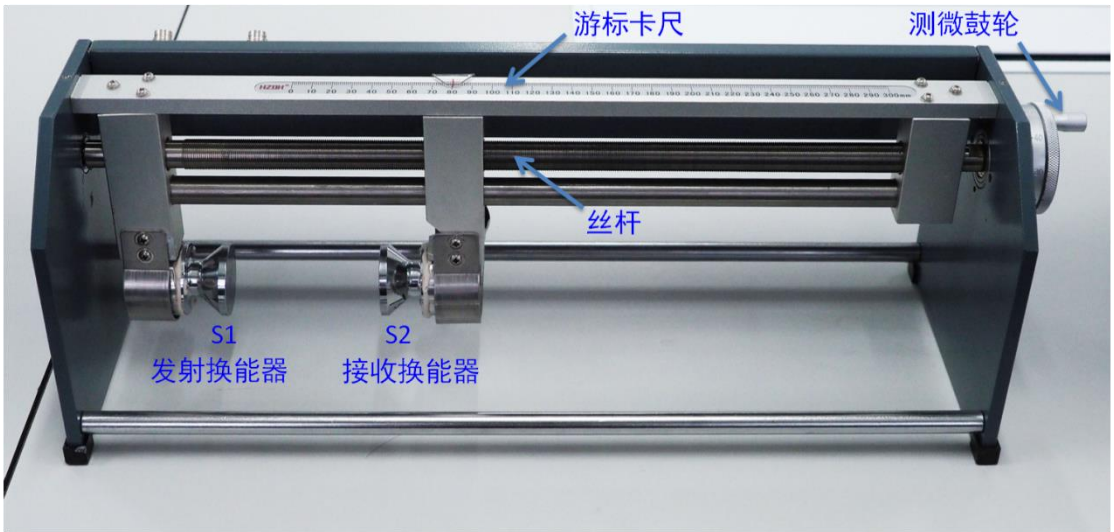


Figure 7-2 A Pair of Transducers S1 and S2 for Speed-of-sound Measurements, S1 is Tied and S2 is Movable.

For an incident wave

$$y_1 = A_1 \cos\left(\omega t - \frac{2\pi x}{\lambda}\right) \tag{7-1}$$

and a reflected wave

$$y_2 = A_2 \cos\left(\omega t + \frac{2\pi x}{\lambda} + \pi\right) \tag{7-2}$$

at any position x of S2 (For each wave, A is the amplitude and $\omega = 2\pi f$ is the angular frequency), the superposition of the two waves is given by

$$y = y_1 + y_2 = (A_1 - A_2)\cos\left(\frac{2\pi x}{\lambda}\right)\cos(\omega t) + (A_1 + A_2)\sin\left(\frac{2\pi x}{\lambda}\right)\sin(\omega t) \tag{7-3}$$

According to acoustics theory, the acoustic pressure at position x is given by

$$p = -\rho_0 v^2 \frac{\partial y}{\partial x} = \rho_0 \omega v\left[(A_1 - A_2)\sin\left(\frac{2\pi x}{\lambda}\right)\cos(\omega t) - (A_1 + A_2)\cos\left(\frac{2\pi x}{\lambda}\right)\sin(\omega t)\right] \tag{7-4}$$

where ρ_0 is the static density of air. For a pair of ideal transducers, we have

$$A_1 = A_2 \tag{7-5}$$

such that the acoustic pressure at position x is given by the standing-wave solution

$$p = -(A_1 + A_2)\rho_0 \omega v \sin(\omega t)\cos\left(\frac{2\pi x}{\lambda}\right) \tag{7-6}$$

In the set-up shown in Figure 7-2, S1 is a transmitter that converts alternating electrical signals into sound waves via the inverse piezoelectric effect, and S2 is a receiver that converts the acoustic pressure it perceives into a sinusoidal electrical signal via the direct piezoelectric effect. According to Equation (7-6), the amplitude of this signal reaches its peak value wherever the separation between S1 and S2 is a multiple of the half-wavelength $\lambda/2$, i.e.

$$\cos\left(\frac{2\pi x}{\lambda}\right) = \pm 1 \tag{7-7}$$

By moving S2 along and recording multiple positions of S2 at which the amplitude of this waveform reaches a maximum, the value of λ can be evaluated using the method of successive differences.

3. The Phase-comparison Method for Speed-of-sound Measurements

In this approach, we observe the phase difference

$$\varphi = \frac{2\pi x}{\lambda} \tag{7-8}$$

between the electrical signals at S1 and S2. By connecting S1 and S2 to respectively Channel 1 and Channel 2 of the oscilloscope and then setting the display to X-Y mode for Lissajous figures, the value of λ can be evaluated. As shown in Figure 7-3, if the phase difference between the two signals is a multiple of the half-wavelength $\lambda/2$, the corresponding Lissajous figure will be a straight line (positive slope for a phase difference of 0, and negative slope for a phase difference of π). By moving S2 along and recording multiple positions of S2 at which the corresponding Lissajous figures are straight lines, the value of λ can be evaluated using the method of successive differences.

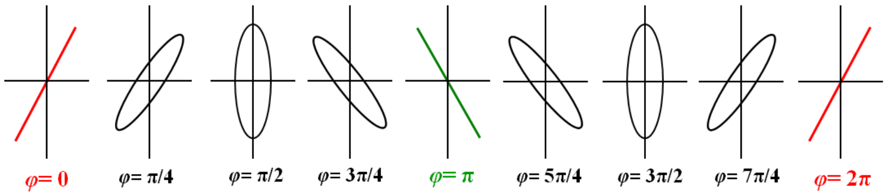


Figure 7-3 Lissajous figures at different phase differences between Channel 1 and Channel 2

4. The Time-difference Method of Speed-of-sound Measurements

In this approach, we measure the time t an ultrasonic pulse takes to travel a distance L from S1 to S2. By recording the values of t for multiple positions of S2, the speed of sound can be evaluated from the slope of a linear fit between the position x of S2 and the time t, i.e.

$$v = \frac{\Delta L}{\Delta t} \tag{7-9}$$

IV. Procedure

1. Turn on the signal generator and the oscilloscope.

2. Check the connection: The transmitter of the signal generator should be connected to transducer S1 and to Channel 1 of the oscilloscope, and the receiver of the signal generator should be connected to transducer S2 and to Channel 2 of the oscilloscope (see Figure 7-4).

3. Tune the frequency of the signal generator to any resonant value around 37 kHz, at which the amplitude of the waveform of Channel 2 is a local maximum. (The natural frequency of the transducers is 37±3 kHz).

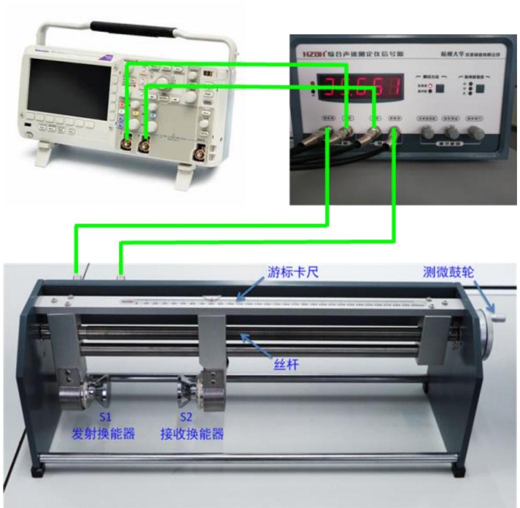


Figure 7-4 Circuit Connection for the Transducers, the Signal Generator and the Oscilloscope

4. Measure the speed of sound using the standing-wave method.

(a) Move the transducer S2 from one end to the other and observe the periodic variation in the amplitude of the waveform of Channel 2.

(b) Record 10 positions of S2 at which the amplitude of the waveform reaches a local maximum.

(c) Evaluate the speed of sound using the method of successive differences.

5. Measure the speed of sound using the phase-comparison method.

(a) Set the display to X-Y mode for Lissajous figures.

(b) Move the transducer S2 from one end to the other and observe the periodic variation in the Lissajous figure.

(c) Record 10 positions of S2 at which the corresponding Lissajous figures are straight lines.

(d) Evaluate the speed of sound using the method of successive differences.

6. Measure the speed of sound using the time-difference method.

(a) Set the mode of the signal generator to “ultrasonic pulse”, and optimize the settings for “pulse-emission intensity” and “receiver gain”.

(b) Move the transducer S2 from one end to the other, and record the values of time t for 10 evenly spaced positions of S2.

(c) Evaluate the speed of sound using the method of linear regression.

7. Calculate the standard value of the speed of sound

(a) Record the indoor temperature t in Celsius.

(b) Use the following formula to compute the theoretical value of the speed of sound in ms^{-1}:

$$v = 331.45\sqrt{1+\frac{t}{273.15}} \qquad (7\text{-}10)$$

(c) Use this theoretical value to compute the relative error of the experimental values.

V. Precautions

1. Remember to tune the frequency of the signal generator to any resonant value around 37 kHz, at which the amplitude of the waveform of Channel 2 is a local maximum.

2. Avoid any collision between S1 and S2.

3. When moving the transducer S2 from one end to the other during data acquisition, do not move the transducer backwards in any circumstance, for otherwise there might be backlash errors in the measurement.

VI. Lab Report Requirements

1. For experimental data obtained via the standing-wave method and the phase-comparison method, evaluate the wavelength of sound via the method of successive differences, and then compute the speed of sound via the relation $v = f\lambda$.

2. For experimental data obtained via the time-difference method, evaluate the speed of sound via the method of linear regression.

3. Compute the theoretical value of the speed of sound, and the relative error in each method of measurement.

4. List the pros and cons of each method of measurement.