浙江大学

本科实验报告

Physical Sensors

课程名称：	生物医学传感与检测
姓名：	
学院：	生物医学工程与仪器科学学院
专业：	生物医学工程
学号：	
指导老师：	唐志峰

2025 年 5 月 25 日

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实验名称：Physical Sensors　实验类型：　同组学生姓名：

一、 Homework 4

Question 1

See Fig.3.4.4 in textbook, for an area-changeable capacitance sensor, the distance between different plates is 10mm, and $\epsilon = 50\mu\text{F/m}$. The two plates have the same shape 30mm×20mm×5mm. Under external force, the moveable plate moves to left 10mm away. Please calculate the change of capacitance ΔC and the sensitivity of sensor K.

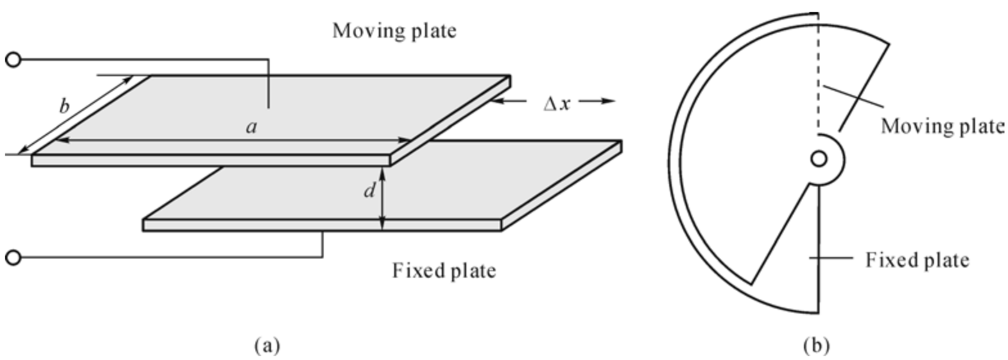

图 1: Area-changeable capacitance sensor structure

Solution

The dimensions of the plates are $L = 30\text{mm}$ (length), $W = 20\text{mm}$ (width), $T = 5\text{mm}$ (thickness).
The distance between the plates is $d = 10\text{mm} = 0.01\text{m}$.
The dielectric constant is $\epsilon = 50\mu\text{F/m} = 50 \times 10^{-6}$ F/m.
The initial overlapping area $A_0 = L \times W = (30 \times 10^{-3}\text{m}) \times (20 \times 10^{-3}\text{m}) = 600 \times 10^{-6}\ \text{m}^2$.
The initial capacitance $C_0 = \frac{\epsilon A_0}{d} = \frac{50\times10^{-6}\ \text{F/m}\times600\times10^{-6}\ \text{m}^2}{0.01\ \text{m}} = 3000 \times 10^{-9}\ \text{F} = 3\ \text{nF}$.
The moveable plate moves to the left by $x = 10\text{mm} = 0.01\text{m}$.
The new overlapping length is $L' = L - x = 30\text{mm} - 10\text{mm} = 20\text{mm} = 0.02\text{m}$.
The new overlapping area $A' = L' \times W = (20 \times 10^{-3}\text{m}) \times (20 \times 10^{-3}\text{m}) = 400 \times 10^{-6}\ \text{m}^2$.
The new capacitance $C' = \frac{\epsilon A'}{d} = \frac{50\times10^{-6}\ \text{F/m}\times400\times10^{-6}\ \text{m}^2}{0.01\ \text{m}} = 2000 \times 10^{-9}\ \text{F} = 2\ \text{nF}$.
The change in capacitance $\Delta C = C' - C_0 = 2\ \text{nF} - 3\ \text{nF} = -1\ \text{nF}$.

The sensitivity of the sensor K for an area-changeable capacitance sensor is given by $K = \frac{dC}{dx} = \frac{\epsilon W}{d}$.

$$K = \frac{50 \times 10^{-6}\ \text{F/m} \times 20 \times 10^{-3}\ \text{m}}{0.01\ \text{m}} = 100 \times 10^{-6}\ \text{F/m} = 100\mu\text{F/m}$$

Question 2

See Fig.3.4.5 in textbook, the following is the measuring principle diagram of capacitive liquid level meter. Please draw out the measuring circuit according to the measuring system, and the output voltage U_0 must be in linear relationship with the liquid level h.

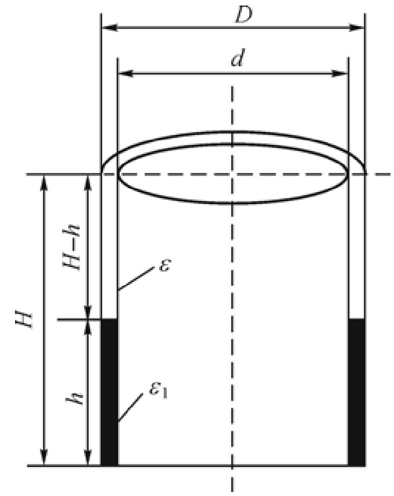

图 2: Capacitive liquid level meter principle

Solution

The capacitive liquid level sensor can be expressed as:

$$C_x = \frac{2\pi\varepsilon A}{ln(D/d)} = \frac{2\pi\varepsilon(H+h)}{ln(D/d)}$$

$$= C_0 + \frac{2\pi\varepsilon h}{ln(D/d)}$$

Adopt the ring diode charge and discharge circuit: S produces square wave signal at frequency of f. C_d is zero-adjusting capacitor to balance the initial capacitance of the sensor. C is the filter capacitor that smooths the output current.

Charging Process: When $U_s = E_2$, diodes V_{D1} and V_{D4} conduct with charging current i_1 and i_4. The voltage across C_x and C_d changes to E_2.

Discharging Process: When $U_s = E_1$, diodes V_{D2} and V_{D3} conduct with discharging current i_2 and i_3. The voltage across C_x and C_d changes from E_2 to E_1.

During T_1, the charges flowing from A to L is denoted by i_3: Thus $q_1 = C_d(E_2 - E_1)$ Average current $I_1 = q_1 f = C_d f(E_2 - E_1)$

During T_2, the charges flowing from L to A is denoted by i_2: $q_2 = C_x(E_2 - E_1)$ $I_2 = q_2 f = C_x f(E_2 - E_1)$

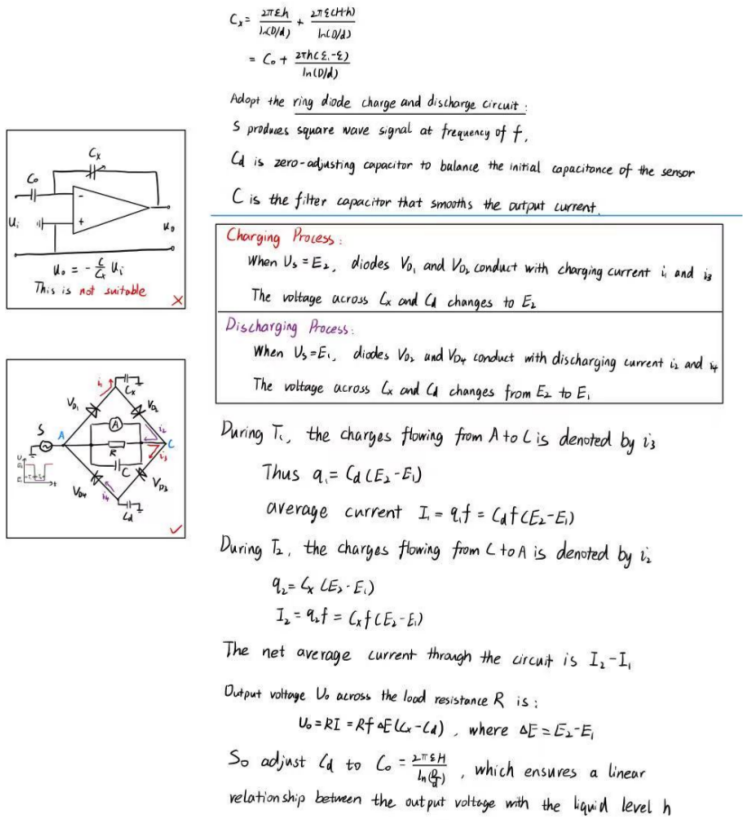

图 3: Ring diode charge and discharge circuit analysis

The net average current through the circuit is $I_1 - I_2$.

Output voltage U_0 across the load resistance R is: $U_0 = RI = Rf\Delta E(C_x - C_d)$, where $\Delta E = E_2 - E_1$

So adjust C_d to $C_0 = \frac{2\pi\varepsilon H}{ln(D/d)}$, which ensures a linear relationship between the output voltage and the liquid level h.

Question 3

For one capacitive plate sensor with air medium, one plate moves 15 mm from original place, having 20 mm^2 available overlap area with the other plate and the distance between the two plates is 1mm. The relative dielectric constant of the air ϵ_r is 1 and the dielectric constant of vacuum ϵ_0 is 8.854×10^{-12} F/m. Please calculate the displacement sensitivity of the sensor K.

Solution

The displacement is $x = 15$mm.

The available overlap area $A = 20\text{mm}^2 = 20 \times 10^{-6}$ m^2.

The distance between the two plates is $d = 1\text{mm} = 0.001$m.

The relative dielectric constant of air $\epsilon_r = 1$ (dimensionless).

The dielectric constant of vacuum $\epsilon_0 = 8.854 \times 10^{-12}$ F/m.

The dielectric constant of the medium is $\epsilon = \epsilon_r\epsilon_0 = 1 \times 8.854 \times 10^{-12}$ F/m $= 8.854 \times 10^{-12}$ F/m.

For a parallel plate capacitor, the capacitance $C = \frac{\epsilon A}{d}$.

Assuming this is a gap-changing sensor where the displacement changes the distance between plates, the sensitivity is:

$$K = \left|\frac{dC}{dd}\right| = \frac{\epsilon A}{d^2}$$

$$K = \frac{8.854 \times 10^{-12}\ \text{F/m} \times 20 \times 10^{-6}\ \text{m}^2}{(0.001\ \text{m})^2} = \frac{177.08 \times 10^{-18}}{1 \times 10^{-6}}\ \text{F/m} = 1.7708 \times 10^{-10}\ \text{F/m}$$

Thus, the displacement sensitivity of the sensor is $K = 1.7708 \times 10^{-10}$ F/m.

Question 4

Please draw out the two equivalent circuits for piezoelectric element.

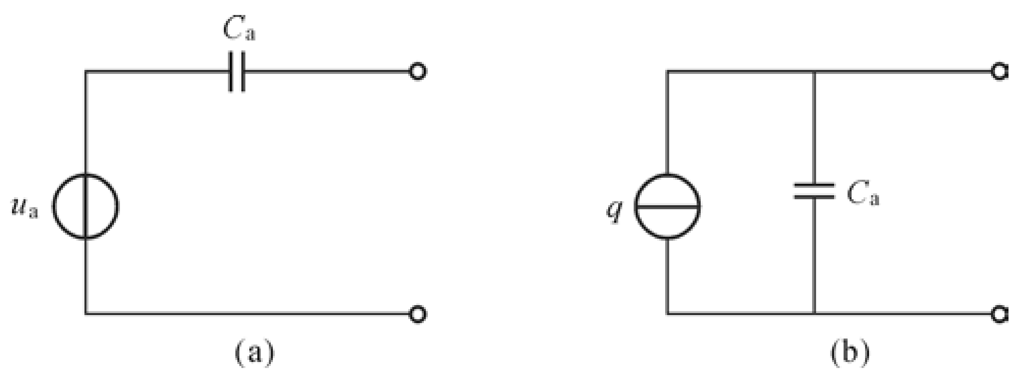

图 4: Two equivalent circuits for piezoelectric element

Equivalent Circuits for Piezoelectric Element

The two equivalent circuits for piezoelectric elements are:

1. **Voltage source equivalent circuit:** A voltage source u_p in series with the capacitance C_p of the piezoelectric element.

2. **Current source equivalent circuit:** A current source i_p in parallel with the capacitance C_p of the piezoelectric element.

Question 5

What's the core problem in charge amplifier? Please deduce the relationship between input and output.

(1) Core Problems to be addressed

- **High Input Impedance:** A charge amplifier must have extremely high input impedance to ensure all charge signals are linearly converted to voltage outputs. This requires high input impedance of the amplifier, excellent PCB insulation, and minimal feedback capacitor loss.

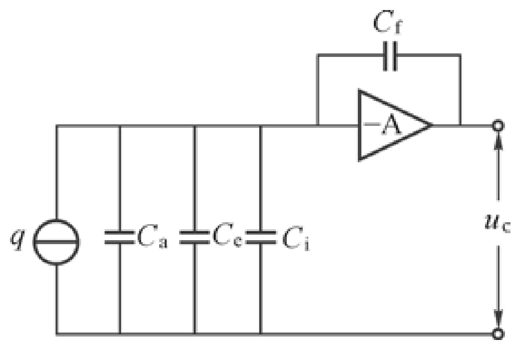

图 5: Charge amplifier circuit diagram

- **Charge-to-Voltage Conversion:** The key function is to convert weak charge signals from piezoelectric sensors into proportional voltage signals, involving signal amplification and impedance matching.
- **Insensitivity to Cable Capacitance:** A major design goal is to minimize the impact of cable connections, ensuring cable capacitance and length don't affect the amplifier's output.
- **Stability:** The amplifier must operate stably under various environmental conditions, resisting external interference and internal drift, including protection against electromagnetic interference and preventing self-excitation oscillations from signal cables.
- **Wide Frequency Response:** It should work across a broad frequency range to meet diverse measurement needs, from quasi-static amplification of low-frequency signals to fast response to high-frequency signals.
- **Low Noise and Fast Response:** To precisely measure weak charge signals, the amplifier needs low noise and a fast response to input signal changes.

(2) Relationship between input and output

Since the piezoelectric sensors has high inner resistance and low output energy, it's necessary to include the preamplifier circuit with high input resistance.

A charge amplifier is used to convert the charge output from a piezoelectric sensor into a stable voltage signal.

$$U_0 = \frac{A_2}{C_a + C_c + C_i + C_f + (1+A)C_f}$$

Usually, $A = 10^4 \sim 10^8$, so when $(1+A)C_f >> C_a + C_c + C_i$, the formula could be approximated by $U_0 \approx -\frac{q}{C_f}$

Question 6

Please describe the working principles of the magnetoelectric induction sensor with open magnetic circuit and indicate its differences with constant magnetic flux.

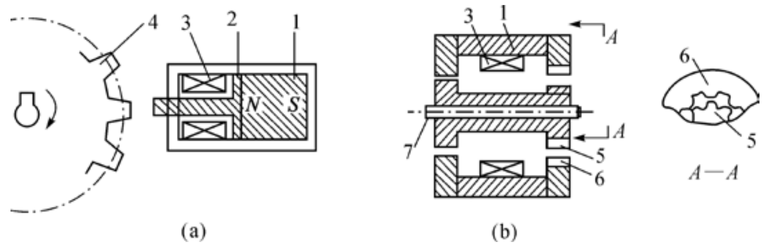

图 6: Open magnetic circuit magnetoelectric induction sensor

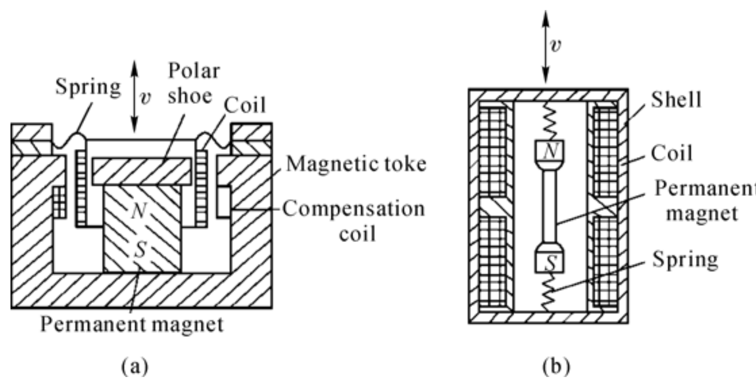

图 7: Constant magnetic flux sensor comparison

Working Principle of Open Magnetic Circuit Magnetoelectric Induction Sensor

The open-magnetic-circuit magnetoelectric induction sensor belongs to the variable-magnetic-flux type. According to Faraday's law of electromagnetic induction, when a conductor moves in a stable magnetic field perpendicular to the magnetic-field direction, an induced electromotive force (emf) is generated.

In this type of sensor, such as when an iron gear rotates, the teeth-bumping action causes changes in the magnetic flux passing through the induced coil. As the magnetic flux Φ changes over time, the induced emf e of the induction coil is given by:

$$e = -w\frac{d\Phi}{dt}$$

where w is the number of turns of the coil in the time-varying electromagnetic field.

The change in magnetic flux is due to the movement of the ferromagnetic gear relative to the magnetic field, which disturbs the magnetic-field lines and thus induces an emf in the coil. This induced emf can then be used to measure the rotational angular velocity of the rotating object, as the frequency and amplitude of the induced emf are related to the speed of rotation.

Differences with Constant Magnetic Flux (Closed Magnetic Circuit) Sensor

Question 7

Please explain how the magnetoelectric induction sensor measures speed, displacement and acceleration using circuit diagram.

表 1: Comparison between Open and Closed Magnetic Circuit Sensors

Aspect	**Open Magnetic Circuit (Variable Magnetic Flux)**	**Constant Magnetic Flux (Closed Magnetic Circuit)**
Structure	Consists of a permanent magnet, a coil, and a movable magnetic component. The magnetic circuit is open.	Consists of a permanent magnet, a coil, and a movable magnetic component. The magnetic circuit is closed.
Working Principle	The magnetic flux changes as the measured object moves, generating an induced electromotive force.	The magnetic flux remains constant. The induced electromotive force is generated by changes in the position or movement of the coil or magnet within the constant magnetic field.
Applications	Used for measuring rotational speed, particularly in high-speed applications.	Used for measuring vibration, acceleration, and torque where precise measurements are required.
Characteristics	1. High magnetic reluctance 2. Suitable for measuring large changes in rotational speed 3. Simple structure, low cost 4. Less resistant to interference	1. High magnetic conductivity 2. More sensitive to small changes in rotational speed 3. High precision and stability 4. More resistant to interference, suitable for complex environments

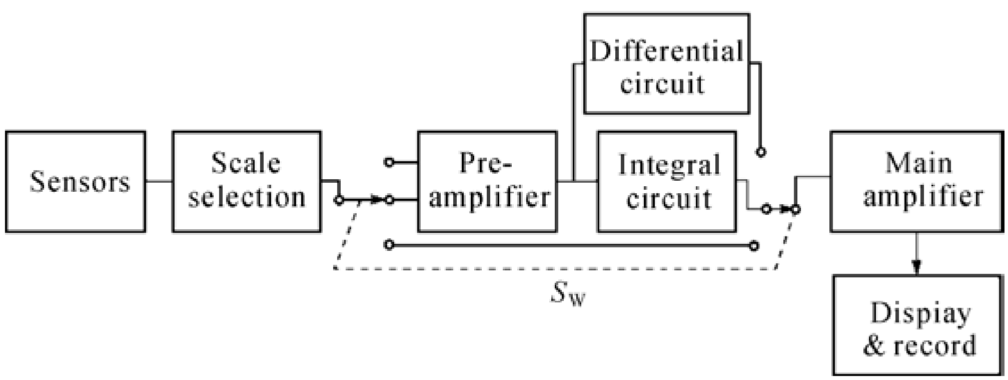

图 8: Magnetoelectric induction sensor measurement principles

Speed Measurement

A magnetoelectric induction speed sensor typically consists of a permanent magnet and a coil. When a rotating object with a ferromagnetic gear or tooth passes by the sensor, the magnetic flux through the coil changes. This change in magnetic flux induces an electromotive force (EMF) in the coil according to Faraday's law of electromagnetic induction.

The frequency of the induced EMF is proportional to the rotational speed of the object. Magnetoelectric induction sensors output the induced electromotive force directly, with high sensitivity, so

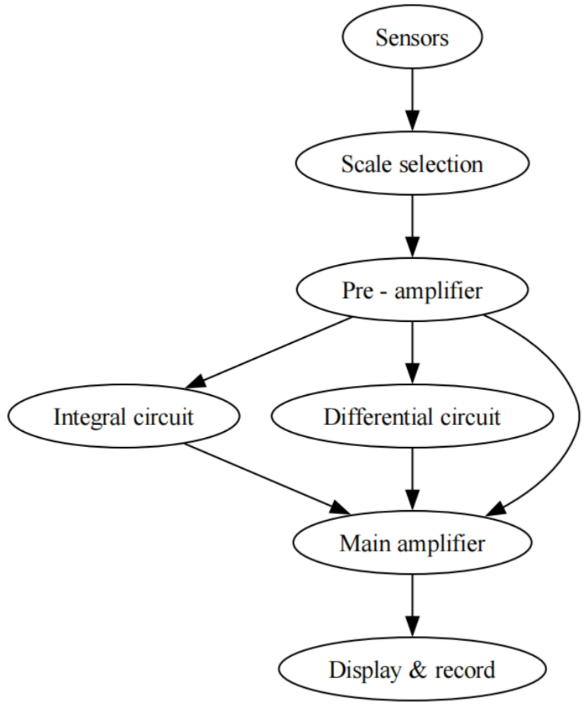

图 9: Circuit diagrams for speed, displacement and acceleration measurement

a gain amplifier is not necessary in the measuring circuits. This kind of sensors can measure speed directly.

Displacement Measurement

For displacement measurement, a linear-motion version of the magnetoelectric induction sensor is often used. A magnet is attached to the object whose displacement is to be measured, and a coil is fixed in a stationary position. As the magnet moves relative to the coil, the magnetic flux through the coil changes, inducing an EMF.

The magnitude and direction of the induced EMF depend on the displacement of the magnet. By measuring the induced EMF, the displacement of the object can be determined. For displacement measurement, integral circuits are needed.

Acceleration Measurement

To measure acceleration, a magnetoelectric induction accelerometer can be used. It typically consists of a mass-spring-damper system with a magnet attached to the mass. When the accelerometer is subjected to an acceleration, the mass moves relative to the coil due to the inertia force.

This movement causes a change in the magnetic flux through the coil, inducing an EMF. The magnitude of the induced EMF is proportional to the acceleration of the device. For acceleration measurement, differential circuits are needed.

Question 8

Please describe the working principles of the Hall sensor and give the mathematic equation between the response and the measured signals.

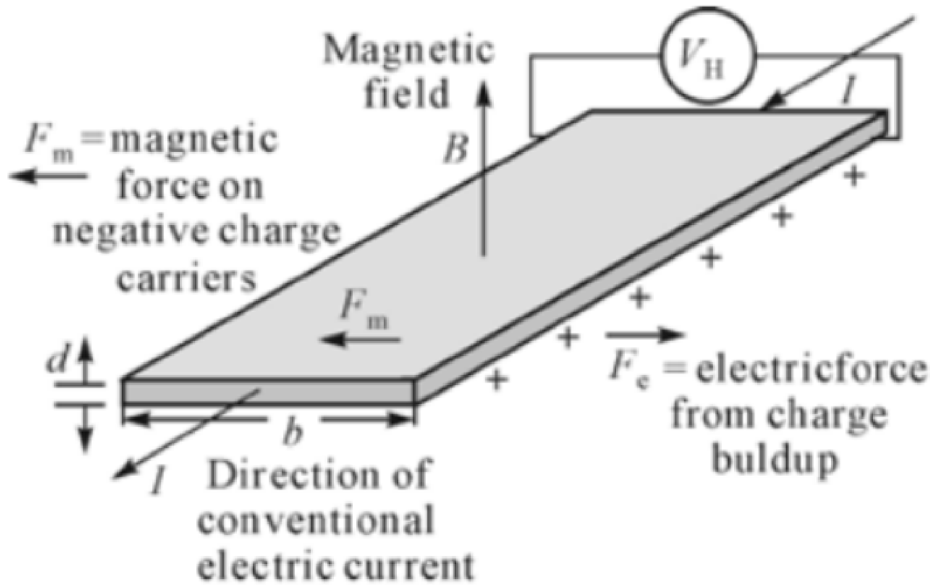

图 10: Hall sensor working principle and structure

Working Principles of the Hall Sensor

A Hall sensor is a device that uses the Hall effect to measure various physical quantities, such as magnetic fields, current, and displacement. When a current-carrying conductor is placed in a magnetic field perpendicular to the direction of the current, the charged particles (usually electrons) in the conductor will be deflected by the Lorentz force.

This causes an accumulation of charge on one side of the conductor, creating a potential difference across the conductor perpendicular to both the current and the magnetic field. This potential difference is called the Hall voltage.

Mathematic Equation

The basic physical principles involved are:
Current: $I = nevbd$
Lorentz Force: $F_m = eBv$
Hall Voltage: $U_H = E_H b$
At equilibrium, $F_m = F_E$:

$$eB \cdot \frac{I}{nebd} = \frac{U_H}{b}$$

Therefore:

$$U_H = \frac{BI}{ned} = R_H \frac{IB}{d} = K_H IB$$

where R_H is the Hall coefficient of the material, I is the current flowing through the sensor, B is the magnetic field strength perpendicular to the current, and d is the thickness of the conductor.

Question 9

What is the zero error of Hall sensors and how to eliminate or compensate it using measurement circuits.

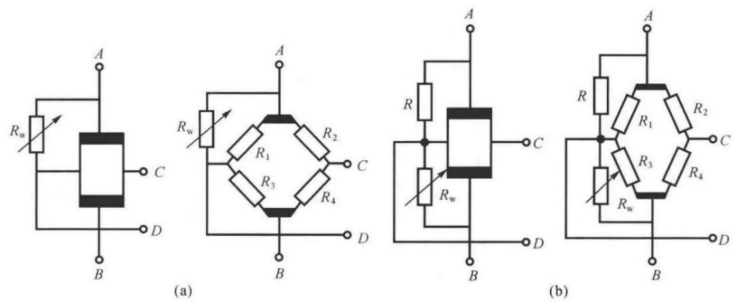

图 4.5.13 不等位电势补偿电路

图 11: Hall sensor zero error phenomenon

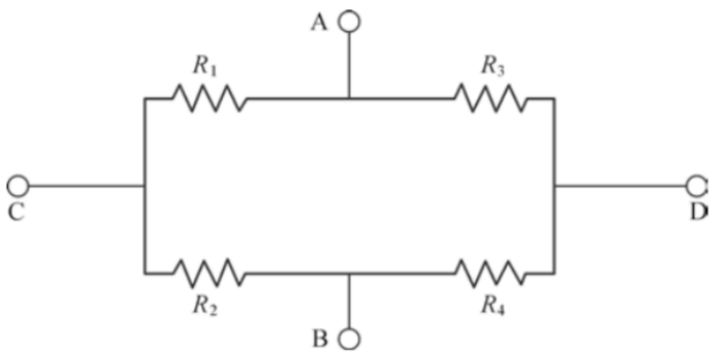

Fig. 3.6.9. Equivalent bridge of Hall device. A, B: Hall electrode; C, D: exciting electrode

图 12: Zero error compensation circuits

Zero Error of Hall Sensors

The zero error of Hall sensors (also referred to as offset voltage) is the phenomenon where a non-zero voltage exists across the Hall electrodes even in the absence of an external magnetic field. The reasons for this phenomenon are:

(1) Hall electrodes asymmetry, or not in the same equipotential surface.

(2) Non-uniform resistivity semiconductor material causing non-uniform resistance or geometry.

(3) The poor contact of the excitation electrodes causes the unevenness of the electrode current.

Elimination or Compensation using Measurement Circuits

Common methods to eliminate or compensate zero error include:

- **Potentiometer adjustment:** Using a potentiometer across the Hall electrodes to balance out the zero-offset voltage.
- **Bridge circuits:** Integrating the Hall element into a bridge circuit and balancing the bridge to nullify the zero error.
- **AC excitation with phase-sensitive detection:** Using an AC excitation current and detecting the AC Hall voltage, which can help in separating the Hall voltage from the DC zero offset.

Question 10

What is the temperature error of Hall sensors and please analyze the principle of the following compensating circuit.

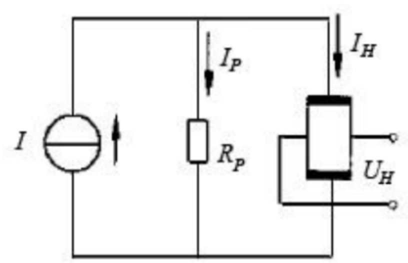

Figure 3 Temperature compensating circuit of Hall sensors

图 13: Temperature compensation circuit for Hall sensors

Temperature Error of Hall Sensors

Hall sensors are subject to temperature errors due to the temperature-dependent characteristics of the Hall element materials. The main reasons for temperature errors include changes in the carrier mobility and concentration in the Hall element with temperature, which causes unstable Hall voltage output, affecting measurement accuracy.

Principle of Compensating Circuit

Initially, $I_{H1} = \frac{R_p}{R_H + R_p} I_x$
$U_{H1} = K_{H1} I_{H1} B$
As T rises to T_1: $R_c = R_{c0}(1 + \beta \Delta T)$ $R_p = R_{p0}(1 + \beta \Delta T)$
$I_{H1} = \frac{R_p I_x}{R_H + R_p} = \frac{R_{p0}(1+\beta\Delta T) I_x}{R_{H0}(1+\beta\Delta T) + R_{p0}(1+\beta\Delta T)}$
$K_H = K_{H0}(1 + \alpha \Delta T)$
$U_H = K_{H1} I_{H1} B$
To make sure $U_H = U_{H0}$, $K_{H1} I_{H1} = K_{H0} I_{H0}$

By arranging the equations above and omitting the high items as $\alpha, \beta, \Delta T$:
$R_{p0} = \frac{(b-\alpha-\beta)R_{i0}}{\alpha}$

Where: - α: temperature coefficient of Hall voltage - K_H: sensitivity coefficient - R_p: shunt resistance - β: temperature coefficient of shunt resistance - b: temperature coefficient of input resistance

When the devices are selected, the input resistance R_{I0}, temperature coefficient α, and the temperature coefficient of Hall voltage are set values. The shunt resistor R_{P0} and temperature coefficient β can be calculated. When the temperature increases, the Hall voltage will increase by $\alpha\Delta T$ times. If the exciting current is decreased to keep the Hall sensitivity (K_H) unchanged, the effect of K_H change could be avoided.

Question 11

Please explain the working principles of photoelectric sensors for measurement of speed, displacement and acceleration.

(1) Speed Measurement

In the measurement of speed, a photoelectric sensor typically works in conjunction with a rotating or moving object with a patterned surface. For example, a disc with evenly spaced slots or a code wheel with alternating light-transmissive and opaque regions is often used.

As the object rotates or moves, the photoelectric sensor emits a beam of light, which is alternately blocked and transmitted by the patterned surface. When the light is transmitted, the photoelectric sensor detects the light and generates an electrical signal; when the light is blocked, the signal changes.

The frequency of these signal changes is directly related to the speed of the object. By counting the number of signal changes within a specific time interval and knowing the physical characteristics of the patterned surface (such as the number of slots or the size of the code wheel), the speed of the object can be accurately calculated. For linear motion, a similar principle is applied, where a moving object with a light-sensitive pattern passes by the photoelectric sensor, and the speed is determined by analyzing the frequency of the sensor's output signals.

(2) Displacement Measurement

For displacement measurement, the photoelectric sensor usually measures the relative movement between two parts. One part is the object whose displacement needs to be measured, and the other is a fixed reference part. A common method is to use a grating or a scale with a fine-pitch pattern.

The photoelectric sensor projects light onto the grating or scale and measures the change in the light-receiving pattern as the object moves. As the object moves, the grating or scale causes the light to be diffracted or modulated in a way that is related to the displacement. The photoelectric sensor detects these changes and converts them into electrical signals.

By analyzing the phase and amplitude of these signals, the precise displacement of the object can be determined. In some cases, multiple photoelectric sensors may be used in combination to improve the accuracy and resolution of displacement measurement, especially for small-scale displacements.

(3) Acceleration Measurement

In the measurement of acceleration, a photoelectric sensor is often used in conjunction with a mass-spring system or a piezoelectric element. When an acceleration is applied to the system, the mass in the mass-spring system will move according to Newton's second law. This movement causes a change in the optical path or the light-receiving condition of the photoelectric sensor.

For example, the movement of the mass may cause a mirror to tilt, which changes the direction of the light beam received by the photoelectric sensor. The photoelectric sensor detects this change and converts it into an electrical signal. The magnitude of the acceleration can be calculated by analyzing the relationship between the change in the electrical signal and the known characteristics of the mass-spring system.

Additionally, in some advanced acceleration measurement systems, multiple photoelectric sensors may be arranged in different directions to measure the acceleration in multiple axes, providing a more comprehensive understanding of the object's motion.

Question 12

Please explain the spectrum characteristic of the photosensitive diode or transistor sensors and indicate their differences of Ge sensor and Si sensor in the following figure.

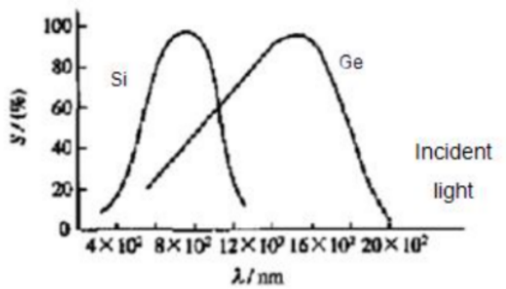

Figure 4 the spectrum characteristic of the Photosensitive diode or transistor

图 14: Spectrum characteristics of Ge and Si photosensitive sensors

Spectrum Characteristic of Photosensitive Diode or Transistor Sensors

The relationship between the relative photosensitivity of the photosensitive diode and transistor and the incidence wavelength is defined as the spectrum characteristic or the spectrum response. Different materials have different spectrum responses. Even the same material will have different photosensitivity due to the change of the wavelength.

表 2: Comparison between Silicon and Germanium Photosensitive Sensors

Aspect	**Silicon (Si) Sensors**	**Germanium (Ge) Sensors**
Sensitivity Range	Approximately 400 nm to 1100 nm (visible to near-infrared)	Approximately 800 nm to 2000 nm (infrared)
Peak Sensitivity	Around 800 nm to 900 nm	Around 1500 nm to 1600 nm
Bandgap Energy	1.1 eV	0.67 eV
Applications	Visible light and near-infrared detection, e.g., optical communication, ambient light detection	Infrared detection, e.g., fiber-optic communication, infrared imaging, gas detection

Differences of Ge Sensor and Si Sensor

Question 13

Please explain the frequency characteristic and the differences of two kind of the photosensitive resistances.

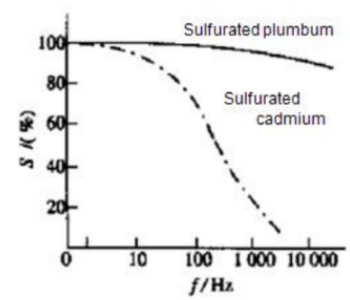

Figure 5 The frequency characteristic of the photosensitive resistance

图 15: Frequency characteristics of photosensitive resistances

Frequency Characteristic of Photosensitive Resistances

The frequency characteristic of photosensitive resistances describes how their sensitivity and response time vary with the frequency of the incident light. As the frequency of light increases, the ability of the photoresistor to respond to rapid changes in light intensity might decrease due to the inherent response time of the material.

Differences of Two Kinds of Photosensitive Resistances

Question 14

Please explain the working principle of the flame detector using sulfurated lead (PbS) photosensitive resistance. Its bright resistance is 0.2 MΩ and dark resistance is 1 MΩ. The optical signal is 0.01 W/m^2 and its wavelength is 2.2 m.

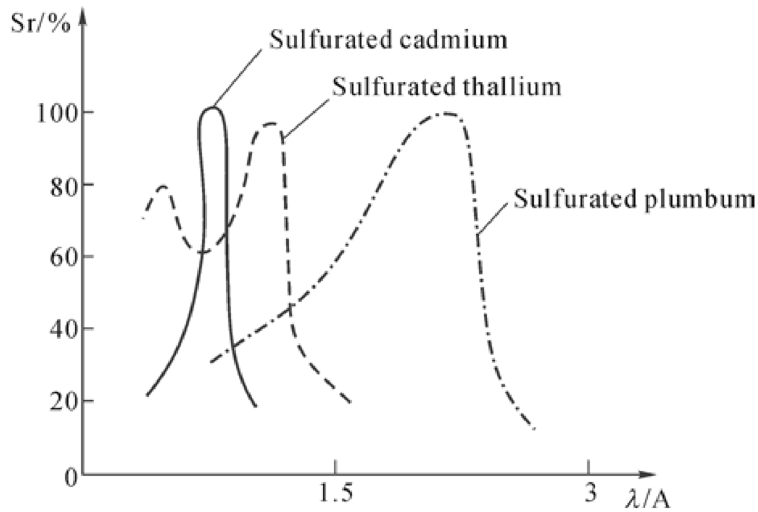

图 16: PbS photosensitive resistance characteristics

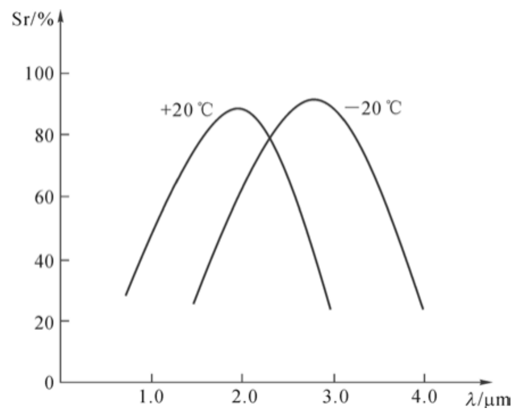

图 17: CdS photosensitive resistance characteristics

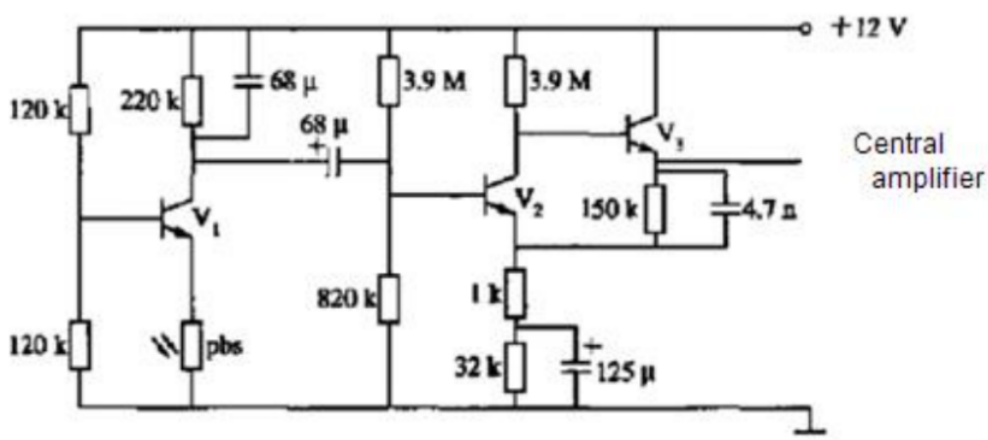

Figure 6 The circuit diagram of flame detector

图 18: PbS flame detector circuit diagram

表 3: Comparison between PbS and CdS Photosensitive Resistances

Aspect	**Sulfurated Plumbum (PbS)**	**Sulfurated Cadmium (CdS)**
Frequency Response	Broad frequency response, stable at higher frequencies.	Limited frequency response, sensitivity drops at higher frequencies.
Sensitivity	High sensitivity across a wide frequency range.	High sensitivity at low frequencies, decreases at higher frequencies.
Applications	Used in broadband light detection, such as in optical communication and infrared detection.	Used in low-frequency or static light detection, such as in light intensity measurement and simple photodetection.
Response Time	Faster response due to shorter carrier lifetime.	Slower response due to longer carrier lifetime.
Dark Resistance	Lower dark resistance compared to CdS.	Higher dark resistance.
Light Absorption	Strong absorption in the infrared range.	Strong absorption in the visible light range.

Working Principle of the Flame Detector using PbS Photosensitive Resistance

The PbS photoresistor operates based on the photoconductive effect. When exposed to light with an optical signal of 0.01 W/m^2 and a wavelength of 2.2 m, the resistance of the PbS photoresistor changes. In the dark, its resistance (dark-resistance) is 1 MΩ, and when illuminated, its resistance (bright-resistance) is 0.2 MΩ.

Photons with energy $h\nu$ (where h is Planck's constant and ν is the frequency of light, $\nu = c/\lambda$, c is the speed of light) excite electrons from the valence band to the conduction band in the PbS semiconductor, increasing the number of charge carriers and thus decreasing the resistance.

The main function of transistor V1 is to provide a constant-voltage bias. When the resistance of the PbS photoresistor changes due to light exposure, V1 ensures that the base voltage remains relatively stable. This stable bias voltage allows the subsequent amplification stages V2 and V3 to operate at an appropriate operating point. For example, without a stable bias voltage, the subsequent amplifiers may experience distortion, saturation, or cutoff due to fluctuations in the input signal's DC level.

Next, V2 and V3 serve as stage amplification. Through multi-stage amplification, the overall gain of the circuit is increased, and the signal strength is enhanced, improving the sensitivity and reliability of the flame detector.

When light is incident on the PbS photoresistor, its resistance becomes the bright-resistance value of 0.2 MΩ. According to the voltage-division principle in the circuit, this change in resistance alters the base voltage of V1, which in turn changes the collector current of V1. This varying signal is then amplified by V2 and V3. As the resistance change caused by light is significant, the resulting change in the electrical signal is also large. After multi-stage amplification, the final output signal is large.

In the absence of light, the resistance of the PbS photoresistor is the dark-resistance value of 1 MΩ. The change in the base voltage of V1 is different from the case when there is light. The change in the collector current of V1 is relatively small. After being amplified by V2 and V3, the final output signal is small because the change in the electrical signal caused by the large dark-resistance is less significant compared to the bright-resistance case.

浙江大学实验报告	专业： 生物医学工程 姓名： 学号： 日期： 2025 年 5 月 25 日 地点：

课程名称：	生物医学传感与检测	指导老师：	唐志峰	成绩：	
实验名称：	物理传感器	实验类型：		同组学生姓名：	

一、 作业 4

题目 1

参见教材图 3.4.4，对于面积可变型电容传感器，极板间距离为 10mm，$\epsilon = 50\mu\text{F/m}$。两极板形状相同，尺寸为 30mm×20mm×5mm。在外力作用下，可动极板向左移动 10mm。请计算电容变化量 ΔC 和传感器灵敏度 K。

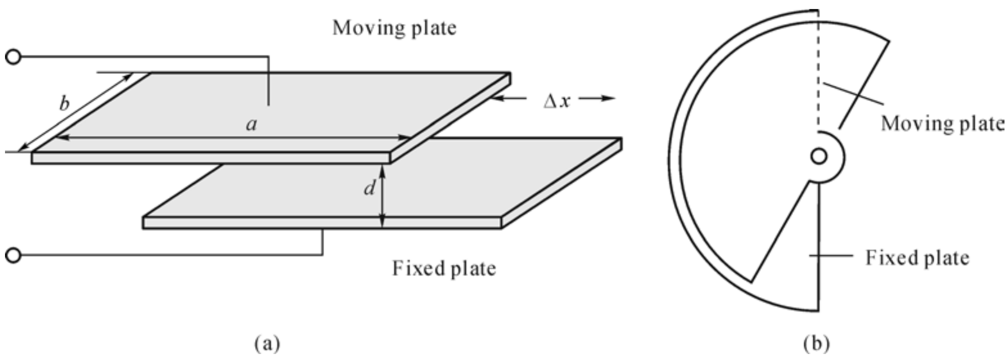

图 1: 面积可变型电容传感器结构

解答

极板尺寸为：$L = 30\text{mm}$（长度），$W = 20\text{mm}$（宽度），$T = 5\text{mm}$（厚度）。
极板间距离为 $d = 10\text{mm} = 0.01\text{m}$。
介电常数为 $\epsilon = 50\mu\text{F/m} = 50 \times 10^{-6}\ \text{F/m}$。
初始重叠面积 $A_0 = L \times W = (30 \times 10^{-3}\text{m}) \times (20 \times 10^{-3}\text{m}) = 600 \times 10^{-6}\ \text{m}^2$。
初始电容 $C_0 = \frac{\epsilon A_0}{d} = \frac{50\times10^{-6}\ \text{F/m}\times600\times10^{-6}\ \text{m}^2}{0.01\ \text{m}} = 3000 \times 10^{-9}\ \text{F} = 3\ \text{nF}$。
可动极板向左移动 $x = 10\text{mm} = 0.01\text{m}$。
新的重叠长度为 $L' = L - x = 30\text{mm} - 10\text{mm} = 20\text{mm} = 0.02\text{m}$。
新的重叠面积 $A' = L' \times W = (20 \times 10^{-3}\text{m}) \times (20 \times 10^{-3}\text{m}) = 400 \times 10^{-6}\ \text{m}^2$。
新的电容 $C' = \frac{\epsilon A'}{d} = \frac{50\times10^{-6}\ \text{F/m}\times400\times10^{-6}\ \text{m}^2}{0.01\ \text{m}} = 2000 \times 10^{-9}\ \text{F} = 2\ \text{nF}$。
电容变化量 $\Delta C = C' - C_0 = 2\ \text{nF} - 3\ \text{nF} = -1\ \text{nF}$。

对于面积可变型电容传感器，传感器灵敏度 K 由 $K = \frac{dC}{dx} = \frac{\epsilon W}{d}$ 给出。

$$K = \frac{50 \times 10^{-6}\ \mathrm{F/m} \times 20 \times 10^{-3}\ \mathrm{m}}{0.01\ \mathrm{m}} = 100 \times 10^{-6}\ \mathrm{F/m} = 100\mu\mathrm{F/m}$$

题目 2

参见教材图 3.4.5，下图为电容式液位计的测量原理图。请根据测量系统画出测量电路，要求输出电压 U_0 与液位高度 h 成线性关系。

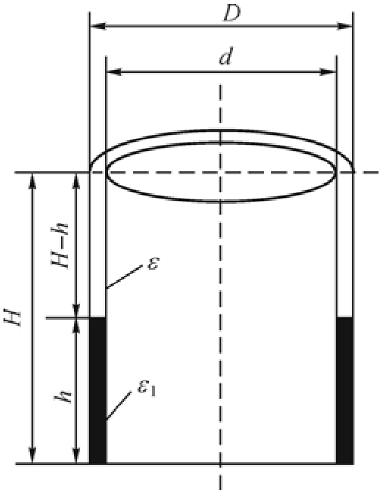

图 2: 电容式液位计原理图

解答

电容式液位传感器可以表示为：

$$C_x = \frac{2\pi\varepsilon A}{ln(D/d)} = \frac{2\pi\varepsilon(H+h)}{ln(D/d)}$$

$$= C_0 + \frac{2\pi\varepsilon h}{ln(D/d)}$$

采用环形二极管充放电电路：S 产生频率为 f 的方波信号。C_d 是零点调节电容器，用于平衡传感器的初始电容。C 是滤波电容器，用于平滑输出电流。

充电过程：当 $U_s = E_2$ 时，二极管 V_{D1} 和 V_{D4} 导通，充电电流为 i_1 和 i_4。C_x 和 C_d 两端的电压变为 E_2。

放电过程：当 $U_s = E_1$ 时，二极管 V_{D2} 和 V_{D3} 导通，放电电流为 i_2 和 i_3。C_x 和 C_d 两端的电压从 E_2 变为 E_1。

在 T_1 期间，从 A 到 L 流动的电荷用 i_3 表示：因此 $q_1 = C_d(E_2 - E_1)$ 平均电流 $I_1 = q_1 f = C_d f(E_2 - E_1)$

在 T_2 期间，从 L 到 A 流动的电荷用 i_2 表示：$q_2 = C_x(E_2 - E_1)$ $I_2 = q_2 f = C_x f(E_2 - E_1)$

通过电路的净平均电流为 $I_1 - I_2$。

负载电阻 R 两端的输出电压 U_0 为：$U_0 = RI = Rf\Delta E(C_x - C_d)$，其中 $\Delta E = E_2 - E_1$

因此调节 C_d 为 $C_0 = \frac{2\pi\varepsilon H}{ln(D/d)}$，这确保了输出电压与液位高度 h 之间的线性关系。

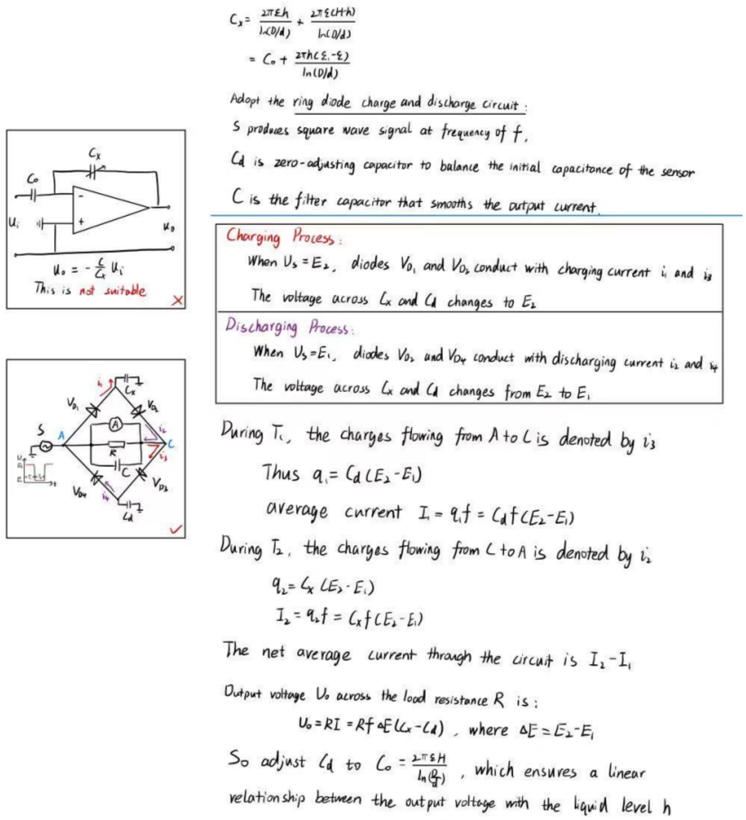

图 3: 环形二极管充放电电路分析

题目 3

对于空气介质的电容式平板传感器，一个极板从原位置移动 15mm，与另一极板的有效重叠面积为 20mm^2，两极板间距离为 1mm。空气的相对介电常数 ϵ_r 为 1，真空介电常数 ϵ_0 为 8.854×10^{-12} F/m。请计算传感器的位移灵敏度 K。

解答

位移为 $x = 15\text{mm}$。
有效重叠面积 $A = 20\text{mm}^2 = 20 \times 10^{-6}\ \text{m}^2$。
两极板间距离为 $d = 1\text{mm} = 0.001\text{m}$。
空气的相对介电常数 $\epsilon_r = 1$（无量纲）。
真空介电常数 $\epsilon_0 = 8.854 \times 10^{-12}$ F/m。
介质的介电常数为 $\epsilon = \epsilon_r\epsilon_0 = 1 \times 8.854 \times 10^{-12}\ \text{F/m} = 8.854 \times 10^{-12}\ \text{F/m}$。
对于平行板电容器，电容 $C = \frac{\epsilon A}{d}$。
假设这是一个间隙变化型传感器，位移改变极板间距离，灵敏度为：

$$K = \left|\frac{dC}{dd}\right| = \frac{\epsilon A}{d^2}$$

$$K = \frac{8.854 \times 10^{-12}\ \mathrm{F/m} \times 20 \times 10^{-6}\ \mathrm{m}^2}{(0.001\ \mathrm{m})^2} = \frac{177.08 \times 10^{-18}}{1 \times 10^{-6}}\ \mathrm{F/m} = 1.7708 \times 10^{-10}\ \mathrm{F/m}$$

因此，传感器的位移灵敏度为 $K = 1.7708 \times 10^{-10}$ F/m。

题目 4

请画出压电元件的两种等效电路。

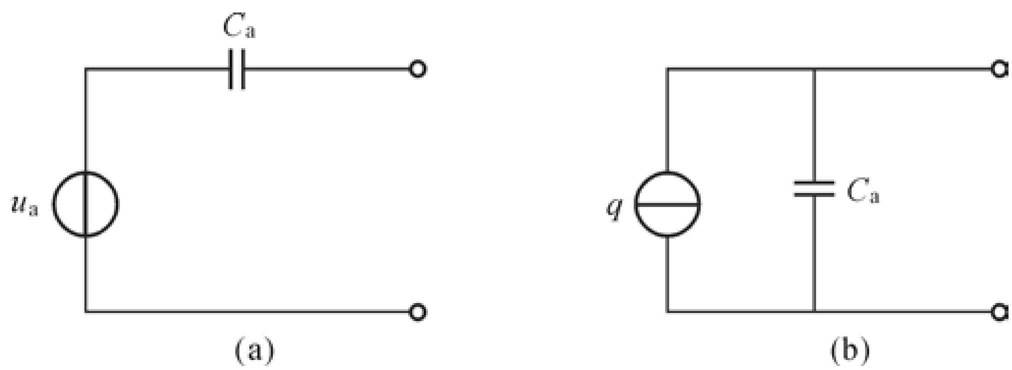

图 4: 压电元件的两种等效电路

压电元件的等效电路

压电元件的两种等效电路为：
1. **电压源等效电路：** 电压源 u_p 与压电元件的电容 C_p 串联。
2. **电流源等效电路：** 电流源 i_p 与压电元件的电容 C_p 并联。

题目 5

电荷放大器的核心问题是什么？请推导输入与输出的关系。

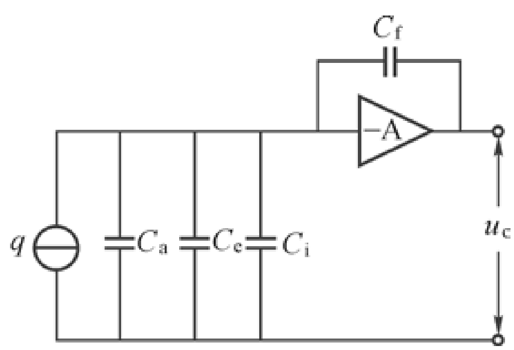

图 5: 电荷放大器电路图

(1) 需要解决的核心问题

- **高输入阻抗：**电荷放大器必须具有极高的输入阻抗，以确保所有电荷信号都能线性转换为电压输出。这需要放大器具有高输入阻抗、优良的 PCB 绝缘和最小的反馈电容损耗。
- **电荷-电压转换：**关键功能是将压电传感器的微弱电荷信号转换为成比例的电压信号，涉及信号放大和阻抗匹配。
- **对电缆电容不敏感：**主要设计目标是最小化电缆连接的影响，确保电缆电容和长度不影响放大器的输出。
- **稳定性：**放大器必须在各种环境条件下稳定工作，抵抗外部干扰和内部漂移，包括防止电磁干扰和防止信号电缆的自激振荡。
- **宽频响：**应在宽频率范围内工作，以满足不同的测量需求，从低频信号的准静态放大到高频信号的快速响应。
- **低噪声和快速响应：**为了精确测量微弱电荷信号，放大器需要低噪声和对输入信号变化的快速响应。

(2) 输入与输出的关系

由于压电传感器具有高内阻和低输出能量，因此需要包含具有高输入电阻的前置放大器电路。
电荷放大器用于将压电传感器的电荷输出转换为稳定的电压信号。

$$U_0 = \frac{A_2}{C_a + C_c + C_i + C_f + (1+A)C_f}$$

通常，$A = 10^4 \sim 10^8$，因此当 $(1+A)C_f >> C_a + C_c + C_i$ 时，公式可以近似为 $U_0 \approx -\frac{q}{C_f}$

题目 6

请描述开磁路磁电感应传感器的工作原理，并说明其与恒磁通的区别。

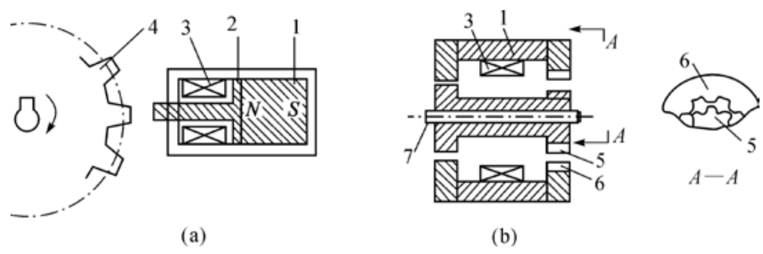

图 6: 开磁路磁电感应传感器

开磁路磁电感应传感器的工作原理

开磁路磁电感应传感器属于变磁通型。根据法拉第电磁感应定律，当导体在稳定磁场中垂直于磁场方向运动时，会产生感应电动势 (emf)。

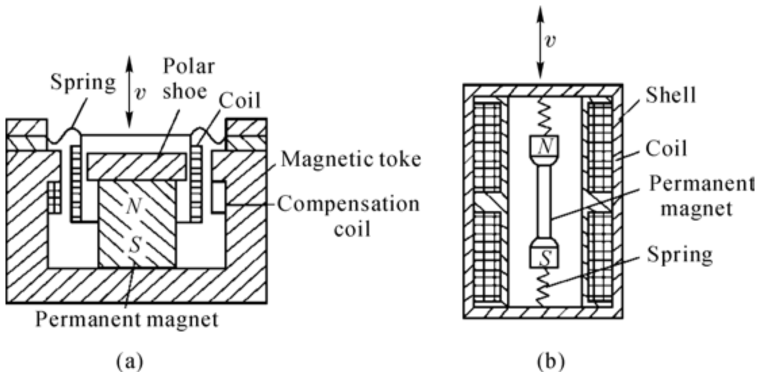

图 7: 恒磁通传感器对比

在这种传感器中，例如当铁齿轮旋转时，齿轮的凸起作用引起通过感应线圈的磁通量变化。当磁通量 Φ 随时间变化时，感应线圈的感应电动势 e 为：

$$e = -w\frac{d\Phi}{dt}$$

其中 w 是时变电磁场中线圈的匝数。

磁通量的变化是由于铁磁齿轮相对于磁场的运动，这扰动了磁力线，从而在线圈中感应出电动势。这个感应电动势可以用来测量旋转物体的角速度，因为感应电动势的频率和幅度与旋转速度相关。

与恒磁通（闭磁路）传感器的区别

表 1: 开磁路与闭磁路传感器比较

方面	**开磁路（变磁通）**	**恒磁通（闭磁路）**
结构	由永磁体、线圈和可动磁性元件组成。磁路是开放的。	由永磁体、线圈和可动磁性元件组成。磁路是闭合的。
工作原理	磁通量随被测物体的运动而变化，产生感应电动势。	磁通量保持恒定。感应电动势由恒定磁场中线圈或磁体位置或运动的变化产生。
应用	用于测量转速，特别是高速应用。	用于测量振动、加速度和扭矩，需要精确测量。
特性	1. 高磁阻 2. 适合测量转速的大变化 3. 结构简单，成本低 4. 抗干扰能力较差	1. 高磁导率 2. 对转速的小变化更敏感 3. 精度高，稳定性好 4. 抗干扰能力强，适合复杂环境

题目 7

请说明磁电感应传感器如何利用电路图测量速度、位移和加速度。

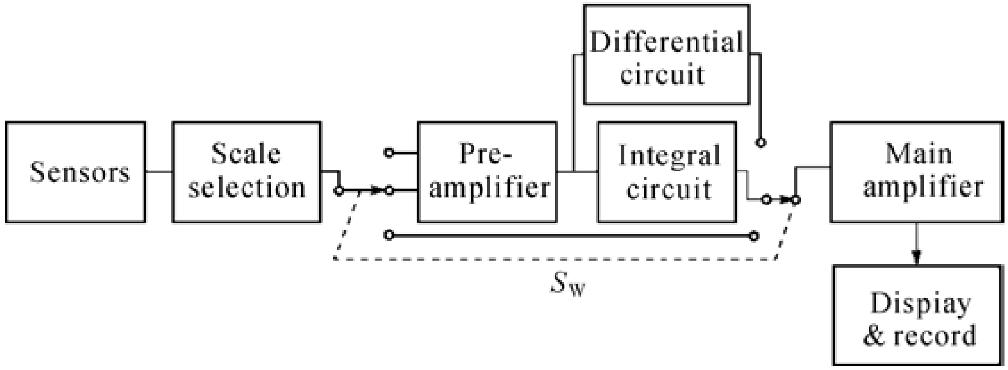

图 8: 磁电感应传感器测量原理

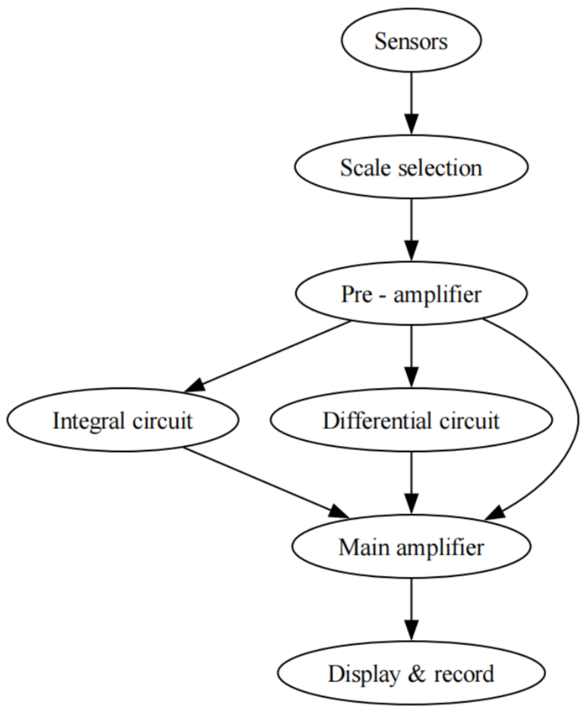

图 9: 速度、位移和加速度测量电路图

速度测量

磁电感应速度传感器通常由永磁体和线圈组成。当带有铁磁齿轮或齿的旋转物体经过传感器时，通过线圈的磁通量发生变化。根据法拉第电磁感应定律，这种磁通量变化在线圈中感应出电动势 (EMF)。

感应 EMF 的频率与物体的转速成正比。磁电感应传感器直接输出感应电动势，灵敏度高，因此测量电路中不需要增益放大器。这种传感器可以直接测量速度。

位移测量

对于位移测量，通常使用磁电感应传感器的直线运动版本。将磁体附着在需要测量位移的物体上，线圈固定在静止位置。当磁体相对于线圈运动时，通过线圈的磁通量发生变化，感应出 EMF。

感应 EMF 的大小和方向取决于磁体的位移。通过测量感应 EMF，可以确定物体的位移。对于位移测量，需要积分电路。

加速度测量

为了测量加速度，可以使用磁电感应加速度计。它通常由质量-弹簧-阻尼系统组成，磁体附着在质量上。当加速度计受到加速度作用时，由于惯性力，质量相对于线圈运动。

这种运动引起通过线圈的磁通量变化，感应出 EMF。感应 EMF 的大小与设备的加速度成正比。对于加速度测量，需要微分电路。

题目 8

请描述霍尔传感器的工作原理，并给出响应与被测信号之间的数学方程。

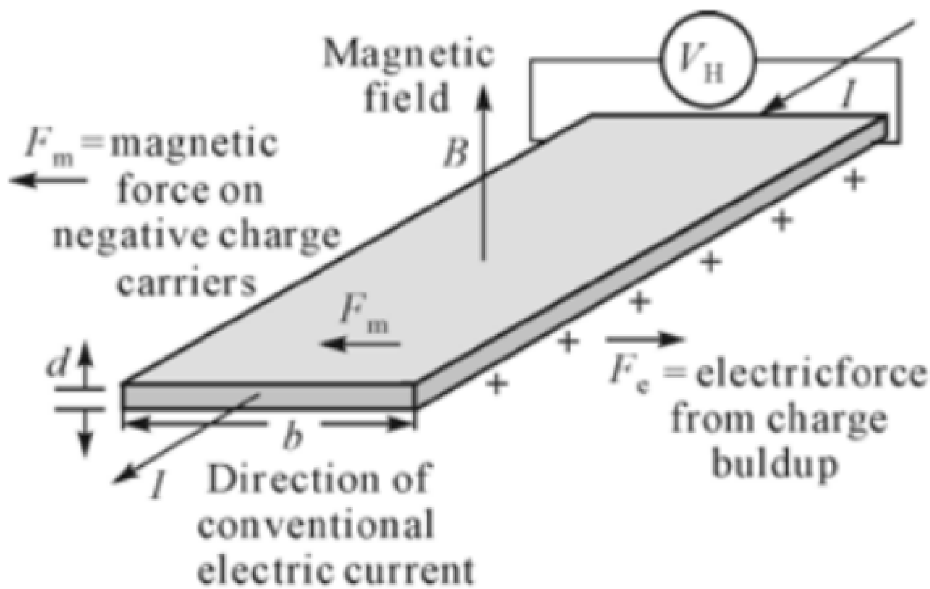

图 10: 霍尔传感器工作原理和结构

霍尔传感器的工作原理

霍尔传感器是利用霍尔效应测量各种物理量（如磁场、电流和位移）的器件。当载流导体置于垂直于电流方向的磁场中时，导体中的带电粒子（通常是电子）会受到洛伦兹力的偏转。

这导致电荷在导体的一侧积累，在导体上产生垂直于电流和磁场的电位差。这个电位差称为霍尔电压。

数学方程

涉及的基本物理原理有：
电流：$I = nevbd$
洛伦兹力：$F_m = eBv$
霍尔电压：$U_H = E_H b$
在平衡状态下，$F_m = F_E$：

$$eB \cdot \frac{I}{nebd} = \frac{U_H}{b}$$

因此：

$$U_H = \frac{BI}{ned} = R_H \frac{IB}{d} = K_H IB$$

其中 R_H 是材料的霍尔系数，I 是流过传感器的电流，B 是垂直于电流的磁场强度，d 是导体的厚度。

该方程表明霍尔电压与磁场强度、通过传感器的电流和材料的霍尔系数成正比，与材料厚度成反比。通过测量霍尔电压，可以确定磁场或其他相关物理量。

例如，如果已知电流 I、霍尔系数 R_H 和厚度 d，可以通过测量霍尔电压 V_H 来计算磁场 B。在实际应用中，霍尔传感器通常经过校准，以建立测量的霍尔电压与感兴趣的物理量之间的特定关系。

题目 9

什么是霍尔传感器的零点误差，如何利用测量电路消除或补偿它？

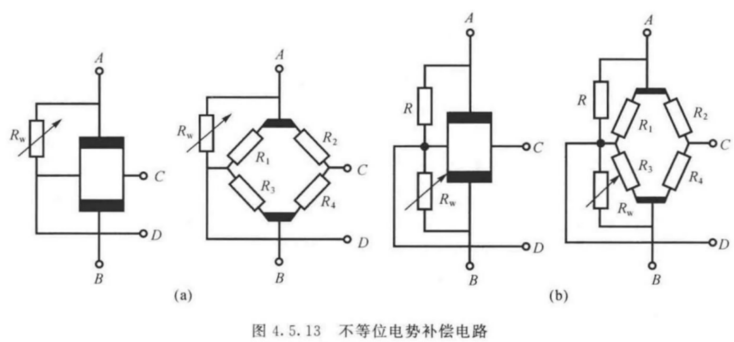

图 11: 霍尔传感器零点误差现象

霍尔传感器的零点误差

霍尔传感器的零点误差（也称为偏置电压）是指即使在没有外部磁场的情况下，霍尔电极之间也存在非零电压的现象。产生这种现象的原因有：

(1) 霍尔电极不对称，或不在同一等电位面上。

(2) 半导体材料电阻率不均匀，导致电阻或几何形状不均匀。

(3) 激励电极接触不良导致电极电流不均匀。

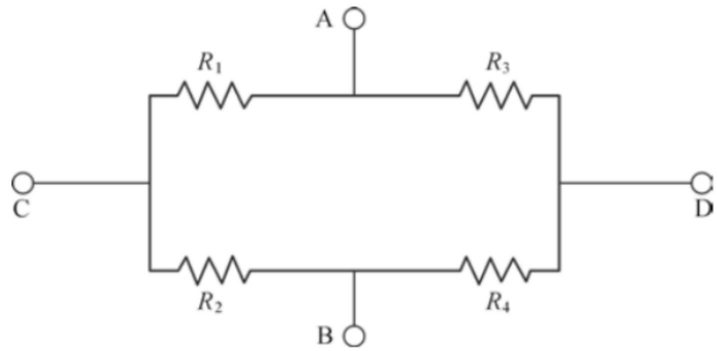

Fig. 3.6.9. Equivalent bridge of Hall device. A, B: Hall electrode; C, D: exciting electrode

图 12: 零点误差补偿电路

利用测量电路消除或补偿

消除或补偿零点误差的常用方法包括:

- **电位器调节**:在霍尔电极之间使用电位器来平衡零偏置电压。
- **桥式电路**:将霍尔元件集成到桥式电路中,通过平衡桥路来消除零点误差。
- **交流激励与相敏检测**:使用交流激励电流并检测交流霍尔电压,这有助于将霍尔电压与直流零偏置分离。

题目 10

什么是霍尔传感器的温度误差,请分析以下补偿电路的原理。

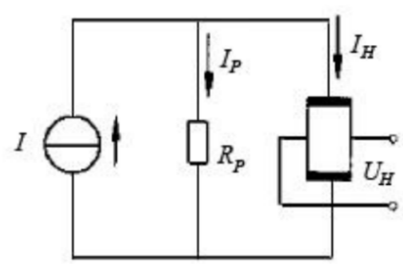

Figure 3 Temperature compensating circuit of Hall sensors

图 13: 霍尔传感器温度补偿电路

霍尔传感器的温度误差

霍尔传感器由于霍尔元件材料的温度相关特性而产生温度误差。温度误差的主要原因包括霍尔元件中载流子迁移率和浓度随温度的变化,这导致霍尔电压输出不稳定,影响测量精度。

补偿电路原理

初始时，$I_{H1} = \frac{R_p}{R_H + R_p} I_x$
$U_{H1} = K_{H1} I_{H1} B$
当 T 升高到 T_1 时：$R_c = R_{c0}(1 + \beta\Delta T)$ $R_p = R_{p0}(1 + \beta\Delta T)$
$I_{H1} = \frac{R_p I_x}{R_H + R_p} = \frac{R_{p0}(1+\beta\Delta T) I_x}{R_{H0}(1+\beta\Delta T) + R_{p0}(1+\beta\Delta T)}$
$K_H = K_{H0}(1 + \alpha\Delta T)$
$U_H = K_{H1} I_{H1} B$
为了确保 $U_H = U_{H0}$，$K_{H1} I_{H1} = K_{H0} I_{H0}$
通过整理上述方程并忽略 $\alpha, \beta, \Delta T$ 的高次项：
$R_{p0} = \frac{(b-\alpha-\beta) R_{i0}}{\alpha}$
其中：- α：霍尔电压的温度系数 - K_H：灵敏度系数 - R_p：分流电阻 - β：分流电阻的温度系数 - b：输入电阻的温度系数

当选定器件时，输入电阻 R_{I0}、温度系数 α 和霍尔电压的温度系数是设定值。可以计算分流电阻 R_{P0} 和温度系数 β。当温度升高时，霍尔电压将增加 $\alpha\Delta T$ 倍。如果减少激励电流以保持霍尔灵敏度 (K_H) 不变，可以避免 K_H 变化的影响。

题目 11

请说明光电传感器测量速度、位移和加速度的工作原理。

(1) 速度测量

在速度测量中，光电传感器通常与具有图案表面的旋转或移动物体配合工作。例如，经常使用具有均匀间隔槽的圆盘或具有交替透光和不透明区域的编码轮。

当物体旋转或移动时，光电传感器发出光束，该光束被图案表面交替阻挡和透射。当光透射时，光电传感器检测到光并产生电信号；当光被阻挡时，信号发生变化。

这些信号变化的频率与物体的速度直接相关。通过计算特定时间间隔内的信号变化次数并了解图案表面的物理特性（如槽数或编码轮的大小），可以准确计算物体的速度。对于直线运动，应用类似原理，具有光敏图案的移动物体经过光电传感器，通过分析传感器输出信号的频率来确定速度。

(2) 位移测量

对于位移测量，光电传感器通常测量两个部分之间的相对运动。一部分是需要测量位移的物体，另一部分是固定的参考部分。常用方法是使用具有细间距图案的光栅或标尺。

光电传感器将光投射到光栅或标尺上，并测量物体移动时光接收图案的变化。当物体移动时，光栅或标尺使光以与位移相关的方式发生衍射或调制。光电传感器检测这些变化并将其转换为电信号。

通过分析这些信号的相位和幅度，可以确定物体的精确位移。在某些情况下，可以组合使用多个光电传感器来提高位移测量的精度和分辨率，特别是对于小尺度位移。

(3) 加速度测量

在加速度测量中，光电传感器通常与质量-弹簧系统或压电元件结合使用。当系统受到加速度作用时，质量-弹簧系统中的质量将根据牛顿第二定律运动。这种运动导致光电传感器的光路或光接收条件发生变化。

例如，质量的运动可能导致镜子倾斜，这改变了光电传感器接收的光束方向。光电传感器检测这种变化并将其转换为电信号。可以通过分析电信号变化与质量-弹簧系统已知特性之间的关系来计算加速度的大小。

此外，在一些先进的加速度测量系统中，可以在不同方向上布置多个光电传感器来测量多轴加速度，提供对物体运动的更全面理解。

题目 12

请说明光敏二极管或晶体管传感器的光谱特性，并指出下图中 Ge 传感器和 Si 传感器的区别。

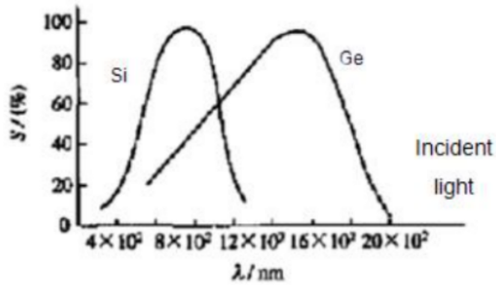

Figure 4 the spectrum characteristic of the Photosensitive diode or transistor

图 14: Ge 和 Si 光敏传感器的光谱特性

光敏二极管或晶体管传感器的光谱特性

光敏二极管和晶体管的相对光敏度与入射波长之间的关系定义为光谱特性或光谱响应。不同材料具有不同的光谱响应。即使是相同材料，由于波长的变化也会有不同的光敏度。

Ge 传感器和 Si 传感器的区别

表 2: 硅和锗光敏传感器比较

方面	**硅 (Si) 传感器**	**锗 (Ge) 传感器**
敏感范围	约 400 nm 至 1100 nm（可见光至近红外）	约 800 nm 至 2000 nm（红外）
峰值敏感度	约 800 nm 至 900 nm	约 1500 nm 至 1600 nm
带隙能量	1.1 eV	0.67 eV
应用	可见光和近红外检测，如光通信、环境光检测	红外检测，如光纤通信、红外成像、气体检测

题目 13

请说明光敏电阻的频率特性以及两种光敏电阻的区别。

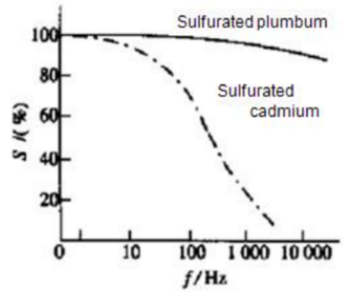

Figure 5 The frequency characteristic of the photosensitive resistance

图 15: 光敏电阻的频率特性

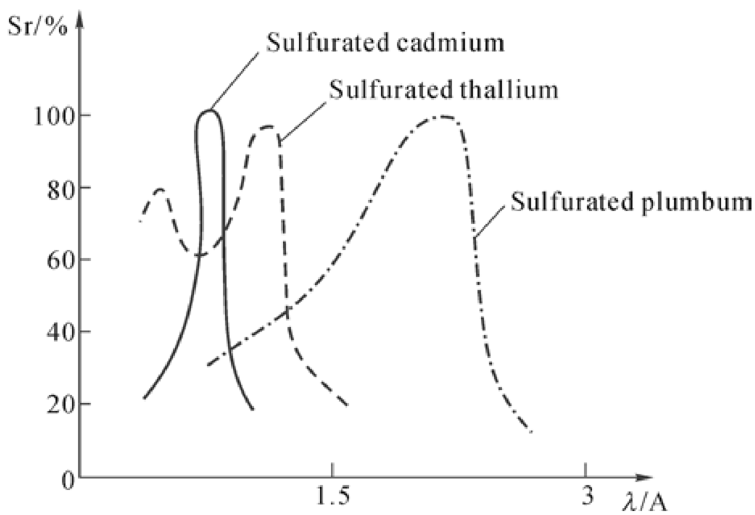

图 16: PbS 光敏电阻特性

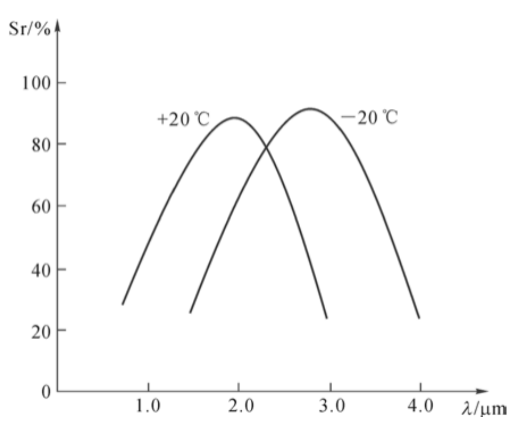

图 17: CdS 光敏电阻特性

光敏电阻的频率特性

光敏电阻的频率特性描述了它们的敏感度和响应时间如何随入射光频率变化。随着光频率的增加，由于材料固有的响应时间，光敏电阻对光强度快速变化的响应能力可能会降低。

两种光敏电阻的区别

表 3: PbS 和 CdS 光敏电阻比较

方面	**硫化铅 (PbS)**	**硫化镉 (CdS)**
频率响应	宽频响应，在较高频率下稳定。	频率响应有限，在较高频率下敏感度下降。
敏感度	在宽频率范围内具有高敏感度。	在低频时敏感度高，在较高频率时降低。
应用	用于宽带光检测，如光通信和红外检测。	用于低频或静态光检测，如光强度测量和简单光检测。
响应时间	由于载流子寿命较短，响应更快。	由于载流子寿命较长，响应较慢。
暗电阻	与 CdS 相比暗电阻较低。	暗电阻较高。
光吸收	在红外范围内有强吸收。	在可见光范围内有强吸收。

题目 14

请说明使用硫化铅 (PbS) 光敏电阻的火焰探测器的工作原理。其亮电阻为 0.2 MΩ，暗电阻为 1 MΩ。光信号为 0.01 W/m^2，波长为 2.2 m。

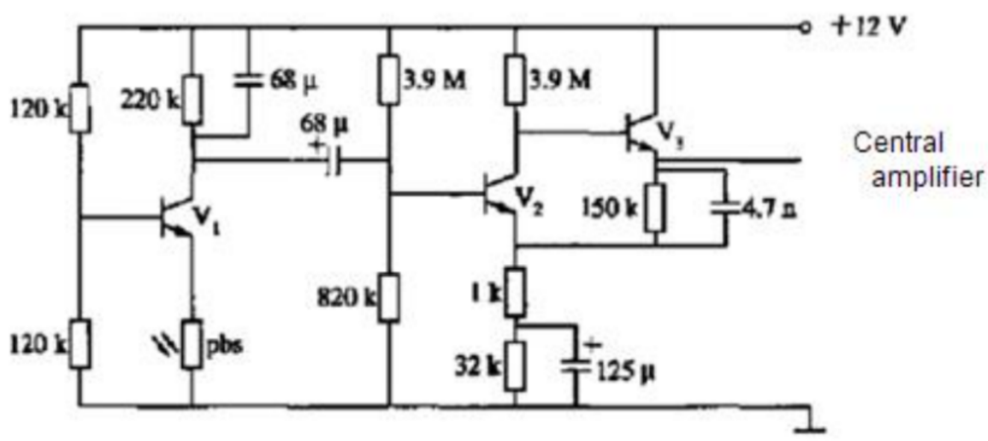

Figure 6 The circuit diagram of flame detector

图 18: PbS 火焰探测器电路图

使用 PbS 光敏电阻的火焰探测器工作原理

PbS 光敏电阻基于光电导效应工作。当暴露在光信号为 0.01 W/m^2、波长为 2.2 m 的光下时，PbS 光敏电阻的电阻发生变化。在黑暗中，其电阻（暗电阻）为 1 MΩ，当被照亮时，其电阻（亮电阻）为 0.2 MΩ。

能量为 $h\nu$ 的光子（其中 h 是普朗克常数，ν 是光的频率，$\nu = c/\lambda$，c 是光速）激发 PbS 半导体中的电子从价带跃迁到导带，增加载流子数量，从而降低电阻。

晶体管 V1 的主要功能是提供恒压偏置。当 PbS 光敏电阻的电阻由于光照而变化时，V1 确保基极电压保持相对稳定。这种稳定的偏置电压使后续放大级 V2 和 V3 能够在适当的工作点工作。例如，没有稳定的偏置电压，后续放大器可能由于输入信号直流电平的波动而出现失真、饱和或截止。

接下来，V2 和 V3 作为级联放大。通过多级放大，电路的总增益增加，信号强度增强，提高了火焰探测器的敏感度和可靠性。

当光入射到 PbS 光敏电阻上时，其电阻变为亮电阻值 0.2 MΩ。根据电路中的分压原理，这种电阻变化改变了 V1 的基极电压，进而改变了 V1 的集电极电流。这个变化的信号然后被 V2 和 V3 放大。由于光引起的电阻变化很大，电信号的相应变化也很大。经过多级放大后，最终输出信号很大。

在没有光的情况下，PbS 光敏电阻的电阻为暗电阻值 1 MΩ。V1 基极电压的变化与有光时的情况不同。V1 集电极电流的变化相对较小。经过 V2 和 V3 放大后，最终输出信号较小，因为大暗电阻引起的电信号变化与亮电阻情况相比不太显著。