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

浙江大学实验报告

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姓名：
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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：Physical Sensors　实验类型：　同组学生姓名：

1. 2-1 First-Order Sensor Analysis

(1) Problem Description

One first-order sensor is used to measure a 100Hz sine signal.

1. If the limit of amplitude error is within ±5%, what is the value of the time constant?

2. If the sensor is used to measure a 50Hz sine signal, what are the values for the limit of amplitude error and phase error?

(2) Solution

For a first-order sensor, the differential equation is:

$$\tau \frac{dy(t)}{dt} + y(t) = Kx(t)$$

with its amplitude ratio $A(\omega)$ given by:

$$A(\omega) = \frac{1}{\sqrt{1 + (\omega\tau)^2}}$$

and phase ratio $\Phi(\omega)$ given by:

$$\Phi(\omega) = \arctan(-\omega\tau)$$

Part 1: Calculate the time constant τ when amplitude error is within ±5% at 100Hz. Given $f = 100$ Hz, the angular frequency $\omega = 2\pi f = 2\pi \times 100 = 200\pi$ rad/s. The amplitude error being within ±5% means the amplitude ratio $A(\omega) \geq 95\% = 0.95$.

$$0.95 \leq \frac{1}{\sqrt{1 + (200\pi\tau)^2}}$$

Squaring both sides and rearranging:

$$0.95^2 \leq \frac{1}{1 + (200\pi\tau)^2}$$

$$1 + (200\pi\tau)^2 \leq \frac{1}{0.95^2}$$

$$(200\pi\tau)^2 \leq \frac{1}{0.95^2} - 1$$
$$(200\pi\tau)^2 \leq \frac{1 - 0.95^2}{0.95^2}$$
$$(200\pi\tau)^2 \leq \frac{1 - 0.9025}{0.9025}$$
$$(200\pi\tau)^2 \leq \frac{0.0975}{0.9025}$$
$$(200\pi\tau)^2 \leq 0.108033$$
$$200\pi\tau \leq \sqrt{0.108033} \approx 0.32868$$
$$\tau \leq \frac{0.32868}{200\pi} \approx \frac{0.32868}{628.318} \approx 0.000523 \text{ s}$$

So, the maximum value of the time constant is $\tau \approx 0.523$ ms.

Part 2: Calculate amplitude error and phase error when measuring 50Hz sine signal with $\tau \approx 0.523$ ms. Given $f' = 50$ Hz, the angular frequency $\omega' = 2\pi f' = 2\pi \times 50 = 100\pi$ rad/s. The time constant $\tau \approx 0.000523$ s.

First, calculate $\omega'\tau$:

$$\omega'\tau = 100\pi \times 0.000523 \approx 0.16438$$

Now, calculate the amplitude ratio $A(\omega')$:

$$A(\omega') = \frac{1}{\sqrt{1 + (\omega'\tau)^2}} = \frac{1}{\sqrt{1 + (0.16438)^2}}$$
$$A(\omega') = \frac{1}{\sqrt{1 + 0.02702}} = \frac{1}{\sqrt{1.02702}} \approx \frac{1}{1.01342} \approx 0.9867$$

The amplitude error is $1 - A(\omega') = 1 - 0.9867 = 0.0133 = 1.33\%$. The limit of amplitude error is $\pm 1.33\%$.

Next, calculate the phase error $\Phi(\omega')$:

$$\Phi(\omega') = \arctan(-\omega'\tau) = \arctan(-0.16438)$$
$$\Phi(\omega') \approx -9.33^\circ$$

The phase error is approximately -9.33°.

2. 2-2 Second-Order Force Sensor Analysis

(1) Problem Description

The natural frequency of a second-order force sensor is 800Hz, and the damping ratio ξ is 0.14.

1. When using this sensor to measure a 400Hz sine force, what will be the values of amplitude $A(\omega)$ and phase $\Phi(\omega)$?
2. If the damping ratio ξ is 0.7, how will the values of $A(\omega)$ and $\Phi(\omega)$ change?

(2) Solution

For a second-order system, the amplitude-frequency $A(\omega)$ and phase-frequency $\Phi(\omega)$ characteristics are given by:

$$A(\omega) = \frac{K}{\sqrt{[1-(\omega/\omega_0)^2]^2 + 4\xi^2(\omega/\omega_0)^2}}$$

$$\Phi(\omega) = -\arctan\left[\frac{2\xi(\omega/\omega_0)}{1-(\omega/\omega_0)^2}\right]$$

where K is the static sensitivity (which is typically assumed to be 1 for normalized amplitude response unless otherwise specified). ω_0 is the natural frequency, ξ is the damping ratio, and ω is the input signal frequency.

Part 1: $\omega_0 = 800$ Hz, $\xi = 0.14$, $\omega = 400$ Hz. First, calculate the frequency ratio $\frac{\omega}{\omega_0}$:

$$\frac{\omega}{\omega_0} = \frac{400\text{ Hz}}{800\text{ Hz}} = 0.5$$

Now, calculate the amplitude $A(\omega)$ (assuming $K = 1$ for the normalized response):

$$A(\omega) = \frac{1}{\sqrt{[1-(0.5)^2]^2 + 4(0.14)^2(0.5)^2}}$$

$$A(\omega) = \frac{1}{\sqrt{[1-0.25]^2 + 4(0.0196)(0.25)}}$$

$$A(\omega) = \frac{1}{\sqrt{[0.75]^2 + 0.0196}}$$

$$A(\omega) = \frac{1}{\sqrt{0.5625 + 0.0196}}$$

$$A(\omega) = \frac{1}{\sqrt{0.5821}} \approx \frac{1}{0.76295} \approx 1.3106$$

Next, calculate the phase $\Phi(\omega)$:

$$\Phi(\omega) = -\arctan\left[\frac{2(0.14)(0.5)}{1-(0.5)^2}\right]$$

$$\Phi(\omega) = -\arctan\left[\frac{0.14}{1-0.25}\right]$$

$$\Phi(\omega) = -\arctan\left[\frac{0.14}{0.75}\right]$$

$$\Phi(\omega) = -\arctan[0.18667] \approx -10.57^\circ$$

So, for $\xi = 0.14$, the amplitude is approximately $1.3106K$ and the phase is approximately -10.57°.

Part 2: Change in $A(\omega)$ and $\Phi(\omega)$ if $\xi = 0.7$. Keep $\omega_0 = 800$ Hz and $\omega = 400$ Hz, so $\frac{\omega}{\omega_0} = 0.5$. New damping ratio $\xi = 0.7$.

Calculate the new amplitude $A(\omega)$:

$$A(\omega) = \frac{1}{\sqrt{[1-(0.5)^2]^2 + 4(0.7)^2(0.5)^2}}$$

$$A(\omega) = \frac{1}{\sqrt{[1-0.25]^2 + 4(0.49)(0.25)}}$$

$$A(\omega) = \frac{1}{\sqrt{[0.75]^2 + 0.49}}$$

$$A(\omega) = \frac{1}{\sqrt{0.5625 + 0.49}}$$

$$A(\omega) = \frac{1}{\sqrt{1.0525}} \approx \frac{1}{1.0259} \approx 0.9748$$

Next, calculate the new phase $\Phi(\omega)$:

$$\Phi(\omega) = -\arctan\left[\frac{2(0.7)(0.5)}{1-(0.5)^2}\right]$$

$$\Phi(\omega) = -\arctan\left[\frac{0.7}{1-0.25}\right]$$

$$\Phi(\omega) = -\arctan\left[\frac{0.7}{0.75}\right]$$

$$\Phi(\omega) = -\arctan[0.9333] \approx -43.04°$$

Summary of Changes: When the damping ratio ξ changes from 0.14 to 0.7:

- The amplitude $A(\omega)$ decreases from approximately $1.3106K$ to $0.9748K$. This indicates that as damping increases, the resonance peak (if any) is flattened, and the amplitude response at this frequency decreases.
- The phase $\Phi(\omega)$ changes from approximately $-10.57°$ to $-43.04°$. This means the phase lag increases significantly with increased damping.

3. 2-3 Sensor Characteristics and Biocompatibility

(1) Difference between Static and Dynamic Characteristics of Sensors

The static characteristics of sensors refer to their performance under steady-state conditions, where inputs and outputs remain constant or change negligibly over time. These characteristics are calibrated under standardized static conditions, including controlled environmental factors such as temperature (20 ± 5°C), humidity ($\leq 85\%$), and atmospheric pressure (101.3 ± 8kPa), with no external disturbances like vibration or acceleration. Calibration involves testing the sensor with high-precision instruments to generate static curves or tables, from which key metrics—linearity, sensitivity, accuracy, hysteresis, and repeatability—are derived. These metrics define how reliably a sensor converts a static input into a stable output.

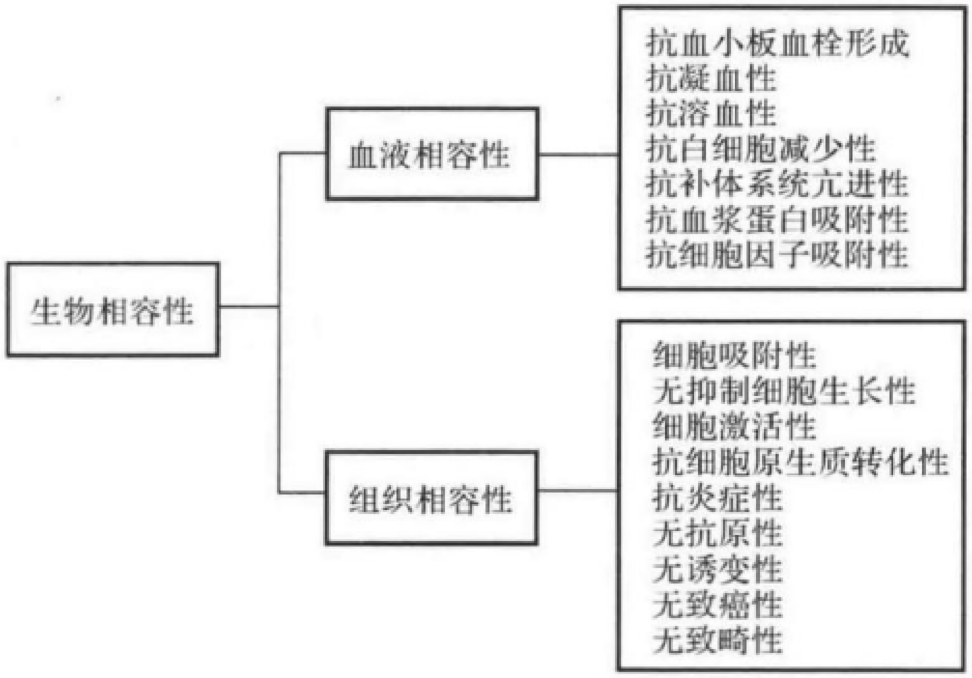

图 1: 传感器特性示意图

In contrast, dynamic characteristics describe a sensor's ability to track time-varying inputs. These are evaluated through transient and steady-state responses. The transient response captures the sensor's behavior as it transitions from an initial state to a new output state, while the steady-state response reflects its performance after stabilization. Dynamic analysis often employs standardized input signals, such as sinusoidal or step signals, to quantify tracking errors and phase delays. For instance, a sensor's frequency response (amplitude attenuation and phase shift) determines its suitability for measuring oscillating signals. Ensuring strong dynamic characteristics is critical for applications where the sensor must mirror rapidly changing physical quantities, such as vibration monitoring or biomedical signal acquisition.

(2) Biocompatibility of Sensors and Their Main Classifications

Biocompatibility is a fundamental requirement for sensors used in biological or medical contexts, particularly those in direct contact with tissues or bodily fluids. It refers to the material's ability to perform without eliciting adverse biological reactions, such as toxicity, immune responses, or inflammation. For invasive sensors (e.g., implantable devices), biocompatibility demands non-toxic, non-irritating materials that resist corrosion and mechanical degradation within the body. Key considerations include electrical insulation to prevent leakage currents, structural durability to withstand physiological conditions, and design compatibility with anatomical features to avoid tissue damage. Non-invasive sensors, such as wearable or in vitro diagnostic tools, must also minimize skin irritation or chemical leaching.

Biocompatibility is classified into blood compatibility and histocompatibility.

- **Blood compatibility** ensures that cardiovascular implants (e.g., catheters) do not trigger clotting or release harmful substances. Materials like PTFE, with extended blood clotting times, are preferred for such applications.

- **Histocompatibility** focuses on minimizing immune rejection for non-cardiovascular implants, requiring materials that evade immune detection.

4. 2-4 Linear Pressure Sensor Error Analysis

(1) Problem Description

A linear pressure sensor has a measuring range of -50 150kPa, and the corresponding output voltage is -5 5V. When 140kPa pressure is measured by the sensor and the measurement value is 142kPa. What is the absolute error, the relative error, and the static sensitivity of the sensor?

(2) Solution

Given:

- Measuring range of pressure (input): $P_{min} = -50$ kPa, $P_{max} = 150$ kPa
- Output voltage range: $V_{min} = -5$ V, $V_{max} = 5$ V
- True pressure (true value): $P_{true} = 140$ kPa
- Measured pressure (result): $P_{measured} = 142$ kPa

1. Calculate the Absolute Error Absolute error is defined as the difference between the measured result and the true value.

$$\text{Absolute Error} = P_{measured} - P_{true}$$

$$\text{Absolute Error} = 142\text{ kPa} - 140\text{ kPa} = 2\text{ kPa}$$

2. Calculate the Relative Error Relative error is defined as the absolute error divided by the true value.

$$\text{Relative Error} = \frac{\text{Absolute Error}}{P_{true}}$$

$$\text{Relative Error} = \frac{2\text{ kPa}}{140\text{ kPa}} = \frac{1}{70} \approx 0.0142857$$

Expressed as a percentage:

$$\text{Relative Error} \approx 0.0142857 \times 100\% \approx 1.43\%$$

3. Calculate the Static Sensitivity of the Sensor For a linear sensor, the static sensitivity (K) is the ratio of the change in output to the change in input over the full operating range. The full-scale input range (span) is:

$$\text{Input Span} = P_{max} - P_{min} = 150\text{ kPa} - (-50\text{ kPa}) = 200\text{ kPa}$$

The full-scale output range (span) is:

$$\text{Output Span} = V_{max} - V_{min} = 5\ \text{V} - (-5\ \text{V}) = 10\ \text{V}$$

The static sensitivity (K) is:

$$K = \frac{\text{Output Span}}{\text{Input Span}}$$

$$K = \frac{10\ \text{V}}{200\ \text{kPa}} = 0.05\ \text{V/kPa}$$

Summary of Results:

- **Absolute Error:** 2 kPa
- **Relative Error:** $\approx 1.43\%$
- **Static Sensitivity:** 0.05 V/kPa

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物理传感器

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实验名称：物理传感器　实验类型：　同组学生姓名：

1. 2-1 一阶传感器分析

(1) 问题描述

一个一阶传感器用于测量 100Hz 正弦信号。

1. 如果幅值误差限制在 $\pm 5\%$ 以内，时间常数的值是多少？

2. 如果传感器用于测量 50Hz 正弦信号，幅值误差和相位误差的限制值是多少？

(2) 解答

对于一阶传感器，微分方程为：

$$\tau \frac{dy(t)}{dt} + y(t) = Kx(t)$$

其幅值比 $A(\omega)$ 为：

$$A(\omega) = \frac{1}{\sqrt{1+(\omega\tau)^2}}$$

相位比 $\Phi(\omega)$ 为：

$$\Phi(\omega) = \arctan(-\omega\tau)$$

第一部分：当 100Hz 时幅值误差在 $\pm 5\%$ 以内时，计算时间常数 τ。 给定 $f = 100$ Hz，角频率 $\omega = 2\pi f = 2\pi \times 100 = 200\pi$ rad/s。幅值误差在 $\pm 5\%$ 以内意味着幅值比 $A(\omega) \geq 95\% = 0.95$。

$$0.95 \leq \frac{1}{\sqrt{1+(200\pi\tau)^2}}$$

两边平方并重新整理：

$$0.95^2 \leq \frac{1}{1+(200\pi\tau)^2}$$

$$1+(200\pi\tau)^2 \leq \frac{1}{0.95^2}$$

$$(200\pi\tau)^2 \leq \frac{1}{0.95^2} - 1$$

$$(200\pi\tau)^2 \leq \frac{1-0.95^2}{0.95^2}$$

$$(200\pi\tau)^2 \leq \frac{1-0.9025}{0.9025}$$

$$(200\pi\tau)^2 \le \frac{0.0975}{0.9025}$$
$$(200\pi\tau)^2 \le 0.108033$$
$$200\pi\tau \le \sqrt{0.108033} \approx 0.32868$$
$$\tau \le \frac{0.32868}{200\pi} \approx \frac{0.32868}{628.318} \approx 0.000523 \text{ s}$$

因此，时间常数的最大值为 $\tau \approx 0.523$ ms。

第二部分：当测量 50Hz 正弦信号且 $\tau \approx 0.523$ ms 时，计算幅值误差和相位误差。 给定 $f' = 50$ Hz，角频率 $\omega' = 2\pi f' = 2\pi \times 50 = 100\pi$ rad/s。时间常数 $\tau \approx 0.000523$ s。

首先，计算 $\omega'\tau$：

$$\omega'\tau = 100\pi \times 0.000523 \approx 0.16438$$

现在，计算幅值比 $A(\omega')$：

$$A(\omega') = \frac{1}{\sqrt{1 + (\omega'\tau)^2}} = \frac{1}{\sqrt{1 + (0.16438)^2}}$$

$$A(\omega') = \frac{1}{\sqrt{1 + 0.02702}} = \frac{1}{\sqrt{1.02702}} \approx \frac{1}{1.01342} \approx 0.9867$$

幅值误差为 $1 - A(\omega') = 1 - 0.9867 = 0.0133 = 1.33\%$。幅值误差限制为 $\pm 1.33\%$。

接下来，计算相位误差 $\Phi(\omega')$：

$$\Phi(\omega') = \arctan(-\omega'\tau) = \arctan(-0.16438)$$

$$\Phi(\omega') \approx -9.33^\circ$$

相位误差约为 -9.33°。

2. 2-2 二阶力传感器分析

(1) 问题描述

一个二阶力传感器的固有频率为 800Hz，阻尼比 ξ 为 0.14。

1. 当使用该传感器测量 400Hz 正弦力时，幅值 $A(\omega)$ 和相位 $\Phi(\omega)$ 的值是多少？

2. 如果阻尼比 ξ 为 0.7，$A(\omega)$ 和 $\Phi(\omega)$ 的值如何变化？

(2) 解答

对于二阶系统，幅频特性 $A(\omega)$ 和相频特性 $\Phi(\omega)$ 由以下公式给出：

$$A(\omega) = \frac{K}{\sqrt{[1 - (\omega/\omega_0)^2]^2 + 4\xi^2(\omega/\omega_0)^2}}$$

$$\Phi(\omega) = -\arctan\left[\frac{2\xi(\omega/\omega_0)}{1 - (\omega/\omega_0)^2}\right]$$

其中 K 是静态灵敏度（对于归一化幅值响应，通常假设为 1，除非另有说明）。ω_0 是固有频率，ξ 是阻尼比，ω 是输入信号频率。

第一部分：$\omega_0 = 800$ **Hz，**$\xi = 0.14$**，**$\omega = 400$ **Hz。** 首先，计算频率比 $\frac{\omega}{\omega_0}$：

$$\frac{\omega}{\omega_0} = \frac{400\text{ Hz}}{800\text{ Hz}} = 0.5$$

现在，计算幅值 $A(\omega)$（假设归一化响应 $K = 1$）：

$$A(\omega) = \frac{1}{\sqrt{[1-(0.5)^2]^2 + 4(0.14)^2(0.5)^2}}$$

$$A(\omega) = \frac{1}{\sqrt{[1-0.25]^2 + 4(0.0196)(0.25)}}$$

$$A(\omega) = \frac{1}{\sqrt{[0.75]^2 + 0.0196}}$$

$$A(\omega) = \frac{1}{\sqrt{0.5625 + 0.0196}}$$

$$A(\omega) = \frac{1}{\sqrt{0.5821}} \approx \frac{1}{0.76295} \approx 1.3106$$

接下来，计算相位 $\Phi(\omega)$：

$$\Phi(\omega) = -\arctan\left[\frac{2(0.14)(0.5)}{1-(0.5)^2}\right]$$

$$\Phi(\omega) = -\arctan\left[\frac{0.14}{1-0.25}\right]$$

$$\Phi(\omega) = -\arctan\left[\frac{0.14}{0.75}\right]$$

$$\Phi(\omega) = -\arctan[0.18667] \approx -10.57^\circ$$

因此，对于 $\xi = 0.14$，幅值约为 $1.3106K$，相位约为 -10.57°。

第二部分：当 $\xi = 0.7$ **时，**$A(\omega)$ **和** $\Phi(\omega)$ **的变化。** 保持 $\omega_0 = 800$ Hz 和 $\omega = 400$ Hz，所以 $\frac{\omega}{\omega_0} = 0.5$。新的阻尼比 $\xi = 0.7$。

计算新的幅值 $A(\omega)$：

$$A(\omega) = \frac{1}{\sqrt{[1-(0.5)^2]^2 + 4(0.7)^2(0.5)^2}}$$

$$A(\omega) = \frac{1}{\sqrt{[1-0.25]^2 + 4(0.49)(0.25)}}$$

$$A(\omega) = \frac{1}{\sqrt{[0.75]^2 + 0.49}}$$

$$A(\omega) = \frac{1}{\sqrt{0.5625 + 0.49}}$$

$$A(\omega) = \frac{1}{\sqrt{1.0525}} \approx \frac{1}{1.0259} \approx 0.9748$$

接下来，计算新的相位 $\Phi(\omega)$：

$$\Phi(\omega) = -\arctan\left[\frac{2(0.7)(0.5)}{1-(0.5)^2}\right]$$

$$\Phi(\omega) = -\arctan\left[\frac{0.7}{1-0.25}\right]$$
$$\Phi(\omega) = -\arctan\left[\frac{0.7}{0.75}\right]$$
$$\Phi(\omega) = -\arctan[0.9333] \approx -43.04^\circ$$

变化总结： 当阻尼比 ξ 从 0.14 变化到 0.7 时：

- 幅值 $A(\omega)$ 从约 $1.3106K$ 降低到 $0.9748K$。这表明随着阻尼增加，共振峰（如果有的话）被平坦化，该频率下的幅值响应降低。
- 相位 $\Phi(\omega)$ 从约 -10.57° 变化到 -43.04°。这意味着随着阻尼增加，相位滞后显著增加。

3. 2-3 传感器特性和生物相容性

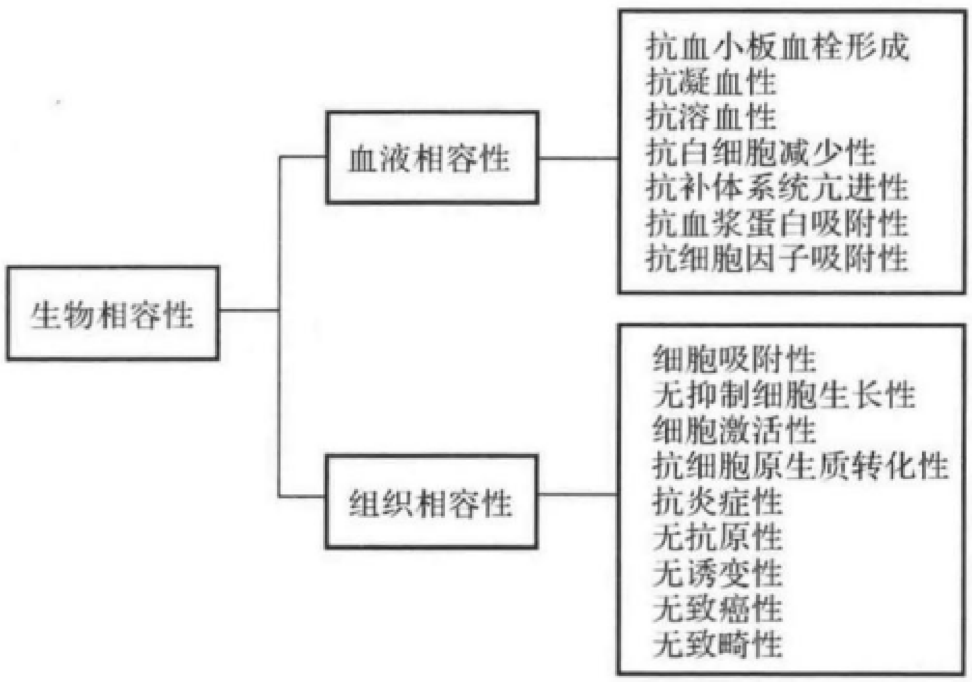

图 1: 传感器特性示意图

(1) 传感器静态特性和动态特性的区别

传感器的静态特性是指在稳态条件下的性能，即输入和输出保持恒定或随时间变化可忽略不计。这些特性在标准化的静态条件下进行校准，包括受控的环境因素，如温度（$20 \pm 5^\circ$C）、湿度（$\leq 85\%$）和大气压力（101.3 ± 8kPa），且无振动或加速度等外部干扰。校准涉及使用高精度仪器测试传感器以生成静态曲线或表格，从中得出关键指标——线性度、灵敏度、精度、滞后性和重复性。这些指标定义了传感器将静态输入转换为稳定输出的可靠性。

相比之下，动态特性描述传感器跟踪时变输入的能力。这些特性通过瞬态响应和稳态响应进行评估。瞬态响应捕获传感器从初始状态转换到新输出状态时的行为，而稳态响应反映其稳定后的性能。动态分析通常采用标准化输入信号，如正弦或阶跃信号，来量化跟踪误差和相位延迟。例如，传感器的频率响应（幅值衰减和相位偏移）决定了其测量振荡信号的适用性。确保强大的动态特性对于传感器必须镜像快速变化的物理量的应用至关重要，如振动监测或生物医学信号采集。

(2) 传感器的生物相容性及其主要分类

生物相容性是用于生物或医学环境中的传感器的基本要求，特别是那些与组织或体液直接接触的传感器。它指的是材料在不引起不良生物反应（如毒性、免疫反应或炎症）的情况下执行功能的能力。对于侵入性传感器（如植入式设备），生物相容性要求无毒、无刺激性的材料，能够抵抗体内的腐蚀和机械降解。关键考虑因素包括电绝缘以防止漏电流、结构耐久性以承受生理条件，以及与解剖特征的设计兼容性以避免组织损伤。非侵入性传感器，如可穿戴或体外诊断工具，也必须最小化皮肤刺激或化学渗漏。

生物相容性分为血液相容性和组织相容性。

- **血液相容性**确保心血管植入物（如导管）不会引发凝血或释放有害物质。具有延长血液凝固时间的材料如 PTFE 是此类应用的首选。
- **组织相容性**专注于最小化非心血管植入物的免疫排斥，要求能够逃避免疫检测的材料。

4. 2-4 线性压力传感器误差分析

(1) 问题描述

一个线性压力传感器的测量范围为-50 150kPa，对应的输出电压为-5 5V。当传感器测量 140kPa 压力时，测量值为 142kPa。求传感器的绝对误差、相对误差和静态灵敏度。

(2) 解答

已知：

- 压力测量范围（输入）：$P_{min} = -50\ \text{kPa}$，$P_{max} = 150\ \text{kPa}$
- 输出电压范围：$V_{min} = -5\ \text{V}$，$V_{max} = 5\ \text{V}$
- 真实压力（真值）：$P_{true} = 140\ \text{kPa}$
- 测量压力（结果）：$P_{measured} = 142\ \text{kPa}$

1. 计算绝对误差 绝对误差定义为测量结果与真值之间的差值。

$$\text{绝对误差} = P_{measured} - P_{true}$$

$$\text{绝对误差} = 142\ \text{kPa} - 140\ \text{kPa} = 2\ \text{kPa}$$

2. 计算相对误差 相对误差定义为绝对误差除以真值。

$$\text{相对误差} = \frac{\text{绝对误差}}{P_{true}}$$

$$\text{相对误差} = \frac{2\ \text{kPa}}{140\ \text{kPa}} = \frac{1}{70} \approx 0.0142857$$

以百分比表示：

$$\text{相对误差} \approx 0.0142857 \times 100\% \approx 1.43\%$$

3. 计算传感器的静态灵敏度 对于线性传感器，静态灵敏度（K）是在整个工作范围内输出变化与输入变化的比值。满量程输入范围（跨度）为：

$$\text{输入跨度} = P_{max} - P_{min} = 150\ \text{kPa} - (-50\ \text{kPa}) = 200\ \text{kPa}$$

满量程输出范围（跨度）为：

$$\text{输出跨度} = V_{max} - V_{min} = 5\ \text{V} - (-5\ \text{V}) = 10\ \text{V}$$

静态灵敏度（K）为：

$$K = \frac{\text{输出跨度}}{\text{输入跨度}}$$

$$K = \frac{10\ \text{V}}{200\ \text{kPa}} = 0.05\ \text{V/kPa}$$

结果总结：

- **绝对误差：** 2 kPa
- **相对误差：** $\approx 1.43\%$
- **静态灵敏度：** 0.05 V/kPa