University of Dhaka
Department of Computer Science and Engineering

CSE-2205: Introduction to Mechatronics

Lec-3: Basics of Sensors and Transducers

Mechatronics: Electronic Control Systems in Mechanical Engineering by W. Bolton

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4.7 Hysteresis Error

Hysteresis Error occurs when a sensor or transducer *provides different outputs for the same input*, depending on whether the input is *increasing or decreasing*.

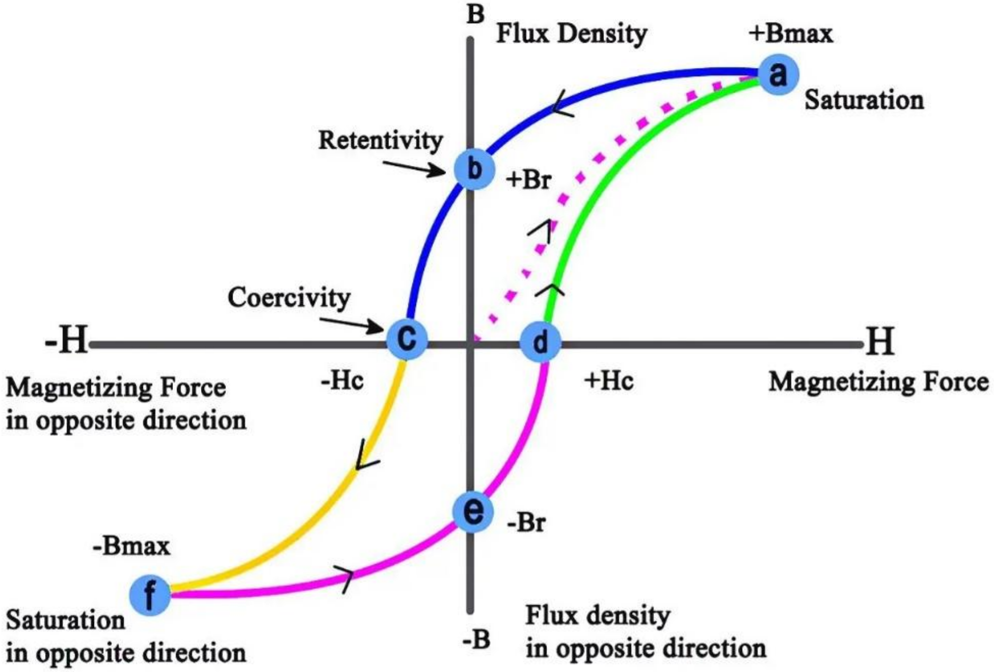
This results from the system's tendency to "*remember" its previous state*.

$$\text{Hysteresis Error} = \frac{|B_{\text{up}} - B_{\text{down}}|}{B_{\text{max}}} \times 100$$

B_{up} is the magnetic field when increasing,

B_{down} is the magnetic field when decreasing,

B_{max} is the maximum magnetic field value.



Problem 1:

A pressure sensor shows a reading of **50 psi** when the pressure is increased to that value and then drops back to **40 psi**. When the pressure is increased again to **50 psi**, it shows **52 psi**. What is the hysteresis error?

$$\text{Hysteresis Error} = \text{Output when increasing} - \text{Output when decreasing} = 52\,\text{psi} - 50\,\text{psi} = 2\,\text{psi}$$

Problem 2:

A magnetic sensor exhibits a magnetization of **30 A/m** when a magnetic field of **5 T** is applied. When the field is decreased to **2 T**, the magnetization drops to **25 A/m**. Upon increasing the field back to **5 T**, the magnetization reads **28 A/m**. Calculate the hysteresis error.

$$\text{Hysteresis Error} = \text{Magnetization on increase} - \text{Magnetization on decrease} = 28\,\text{A/m} - 30\,\text{A/m} = -2\,\text{A/m}$$

Problem 3:

A load cell measures **100 kg** when the load is applied and **98 kg** when the load is removed. If the load is then reapplied and measured at **99 kg**, what is the hysteresis error?

Problem 4:

A temperature sensor has a hysteresis error characterized as follows: when increasing temperature to **80°C**, it reads **79°C**, and when the temperature is decreased back to **70°C**, it reads **71°C**. What is the hysteresis error?

Problem 5:

A voltage regulator shows an output of **12 V** when the input voltage is raised to **15 V**, but when the input is decreased back to **10 V**, the output drops to **11 V**. If the input is increased to **15 V** again, the output reads **12.5 V**. Calculate the hysteresis error.

4.8 Linearity

Linearity refers to a *direct proportional relationship between two variables*, meaning that if one variable changes, the other changes in a predictable, constant ratio.

Problem: A sensor outputs 5 mV at 0°C and 25 mV at 100°C. Check if the relationship is linear.

Calculate the output change:

$$\Delta V = 25\,\mathrm{mV} - 5\,\mathrm{mV} = 20\,\mathrm{mV}$$

Calculate the temperature change:

$$\Delta T = 100\ ^{\circ}\mathrm{C} - 0\ ^{\circ}\mathrm{C} = 100\ ^{\circ}\mathrm{C}$$

Determine sensitivity:

$$\text{Sensitivity} = \frac{\Delta V}{\Delta T} = \frac{20\,\mathrm{mV}}{100\ ^{\circ}\mathrm{C}} = 0.2\,\mathrm{mV}/^{\circ}\mathrm{C}$$

If the sensor outputs consistent changes in voltage for equal temperature changes, it is linear.

For a sensor to be linear, the output voltage should increase by the same amount (0.2 mV) for each degree Celsius increase in temperature.

$$5\,\mathrm{mV} + (1\,^\circ\mathrm{C} \times 0.2\,\mathrm{mV}/^\circ\mathrm{C}) = 5.2\,\mathrm{mV}$$

$$5\,\mathrm{mV} + (2\,^\circ\mathrm{C} \times 0.2\,\mathrm{mV}/^\circ\mathrm{C}) = 5.4\,\mathrm{mV}$$

it is linear

4.9 Non-linearity

Non-linearity occurs when the *relationship between the input and output* of a sensor *is not constant*, leading to *deviations from a straight line*.

This deviation can be due to various factors, such as sensor design, environmental conditions, or manufacturing tolerances.

Problem: A sensor has the following outputs for specified pressures:

0 psi: 0 mV
50 psi: 20 mV
100 psi: 45 mV

Determine if the sensor is linear.

Step 1: Calculate the Expected Output for a Linear Sensor

To check for linearity, first find the expected output at **50 psi** if the relationship were linear.

Calculate the total change in output voltage (ΔV) from **0 psi** to **100 psi**:

$$\Delta V = \text{Output at 100 psi} - \text{Output at 0 psi} = 45\,\text{mV} - 0\,\text{mV} = 45\,\text{mV}$$

Calculate the change in pressure (ΔP):

$$\Delta P = 100\,\text{psi} - 0\,\text{psi} = 100\,\text{psi}$$

Determine the sensitivity (slope) of the output with respect to pressure:

$$\text{Sensitivity} = \frac{\Delta V}{\Delta P} = \frac{45\,\text{mV}}{100\,\text{psi}} = 0.45\,\text{mV}/\text{psi}$$

Step 2: Calculate the Expected Output at 50 psi

Using the sensitivity, we can find the expected output at **50 psi**:

Calculate the expected output at 50 psi:

$$V_{\text{expected}} = \text{Output at 0 psi} + (\text{Sensitivity} \times 50\,\text{psi})$$

$$V_{\text{expected}} = 0\,\text{mV} + (0.45\,\text{mV/psi} \times 50\,\text{psi}) = 0 + 22.5\,\text{mV} = 22.5\,\text{mV}$$

Step 3: Compare Actual Output with Expected Output

Actual output at 50 psi: 20 mV

Expected output at 50 psi: 22.5 mV

Since the **actual output (20 mV)** differs from the **expected output (22.5 mV)**, the sensor does not maintain a linear relationship. Therefore, the sensor exhibits **non-linearity**.

4.10 Repeatability

Repeatability measures a transducer's *ability to produce consistent outputs* when the *same input is applied* multiple times under the *same conditions*.

Example: If a pressure transducer is tested multiple times at a constant pressure of 100 psi and outputs values of 20.00 mV, 20.01 mV, and 19.99 mV, the variation is minimal, indicating good repeatability.

$$\text{repeatability} = \frac{\text{max.} - \text{min. values given}}{\text{full range}} \times 100$$

Problem: A pressure transducer has a full range of 0 to 150 psi and is specified to have a repeatability of ±0.02% of the full range. Calculate the allowable output variation for repeated measurements at a specific input pressure of 75 psi.

Determine the Full Range:

$$\text{Full Range} = 150\,\text{psi}$$

Calculate the Allowable Variation:

$$\text{Allowable Variation} = \text{Full Range} \times \frac{\text{Repeatability}}{100}$$

$$\text{Allowable Variation} = 150\,\text{psi} \times \frac{0.02}{100}$$

$$\text{Allowable Variation} = 150\,\text{psi} \times 0.0002 = 0.03\,\text{psi}$$

The allowable output variation for repeated measurements at 75 psi is **±0.03 psi**. This indicates that the transducer's output should remain consistent within this range for repeated measurements at the same input pressure.

4.11 Drift

Drift is the *gradual change in the output* of a sensor or measurement instrument over time while *the input conditions remain unchanged*.

Drift can occur due to several factors, including:

Environmental Changes: *Fluctuations in temperature, humidity, or pressure* can affect sensor performance.

Aging of Components: Over time, electronic or mechanical *components may degrade*, impacting accuracy.

Mechanical Stress: *Physical forces* applied to the sensor can alter its output.

Electronic Noise: *Variations in electrical signals* can introduce errors in measurements.

Problem: A temperature sensor is calibrated to read 25°C at a constant temperature. Over the course of six months, the output gradually shifts, and after this period, it reads 27°C. Calculate the drift in the sensor output.

Initial Reading:

$$\text{Initial Reading} = 25^\circ C$$

Final Reading:

$$\text{Final Reading} = 27^\circ C$$

Calculate Drift:

$$\text{Drift} = \text{Final Reading} - \text{Initial Reading}$$

$$\text{Drift} = 27^\circ C - 25^\circ C = 2^\circ C$$

The drift in the sensor output over the six-month period is **2°C**. This indicates that the sensor has shifted by this amount while the actual temperature remained constant.

4.12 Stability

Stability measures a *transducer's ability* to produce a *consistent output* when the *input remains constant over time*.

It indicates how reliably the sensor maintains its output without significant variation.

Relation to Drift: Stability is closely related to drift, which refers to gradual changes in the sensor's output.

A stable sensor will have minimal drift, ensuring that its output remains close to the true value over time.

Problem: A temperature sensor is designed to measure a constant temperature of 30°C. Over a period of one hour, it produces the following output readings every 10 minutes: 30.1°C, 29.9°C, 30.0°C, 30.2°C, 29.8°C. Calculate the stability of the sensor based on the given readings.

1. **List the Output Readings**:

$$\text{Readings} = [30.1^\circ C, 29.9^\circ C, 30.0^\circ C, 30.2^\circ C, 29.8^\circ C]$$

2. **Calculate the Mean Output**:

$$\text{Mean} = \frac{\sum \text{Readings}}{N}$$

Where N is the number of readings.

$$\text{Mean} = \frac{30.1 + 29.9 + 30.0 + 30.2 + 29.8}{5} = \frac{150.0}{5} = 30.0^\circ C$$

3. **Calculate the Variance:**

$$\text{Variance} = \frac{\sum(\text{Reading} - \text{Mean})^2}{N}$$

$$= \frac{(30.1 - 30.0)^2 + (29.9 - 30.0)^2 + (30.0 - 30.0)^2 + (30.2 - 30.0)^2 + (29.8 - 30.0)^2}{5}$$

$$= \frac{(0.1)^2 + (-0.1)^2 + (0)^2 + (0.2)^2 + (-0.2)^2}{5}$$

$$= \frac{0.01 + 0.01 + 0 + 0.04 + 0.04}{5} = \frac{0.10}{5} = 0.02$$

4. **Calculate the Standard Deviation** (for stability assessment):

$$\text{Standard Deviation} = \sqrt{\text{Variance}} = \sqrt{0.02} \approx 0.1414^{\circ}C$$

The stability of the sensor, indicated by a standard deviation of approximately **0.1414°C**, shows that the output readings are relatively consistent around the mean value of 30.0°C. A lower standard deviation indicates better stability.

4.13 Dead Band

Dead band refers to the *range of input values* where a transducer or sensor does *not produce any output*.

It represents a *threshold* below which *changes in input do not result* in measurable *output* due to internal factors like friction or system limitations.

Problem: A flowmeter has a dead band of 0.5 m/s. It is designed to measure fluid velocity. If the flowmeter shows no output for velocities below 0.5 m/s, determine the output for the following fluid velocities: 0.3 m/s, 0.4 m/s, 0.5 m/s, 0.6 m/s, and 1.0 m/s.

Identify the Dead Band: Dead Band = 0.5 m/s

List the Fluid Velocities: $\text{Velocities} = [0.3\,\text{m/s}, 0.4\,\text{m/s}, 0.5\,\text{m/s}, 0.6\,\text{m/s}, 1.0\,\text{m/s}]$

Determine Output Based on Dead Band:
For each velocity, check if it is below the dead band threshold (0.5 m/s):

0.3 m/s: Output = 0 (below dead band)

0.4 m/s: Output = 0 (below dead band)

0.5 m/s: Output = Value measured (could be 0.5 m/s depending on calibration)

0.6 m/s: Output = Value measured (could be 0.6 m/s)

1.0 m/s: Output = Value measured (could be 1.0 m/s)

The flowmeter does not provide any output for fluid velocities below 0.5 m/s due to the dead band. Outputs start being measurable at or above this threshold.

4.14 Dead Time

Dead time is the *delay* between the application of an *input signal and the observed output response* from a sensor or transducer.

It represents the time lag that occurs before the output begins to change following an input change.

Problem: A temperature sensor has a dead time of 3 seconds. If the input temperature suddenly increases from 20°C to 30°C, calculate the time it will take for the sensor to register a change in its output after the input change.

Since the dead time is the period during which the sensor does not respond to the change, the output will only start changing after this period.

Time taken for the sensor to respond = Dead Time = 3 seconds

4.15 Resolution

It's the *smallest change in the input value* that *produces an observable change in the output*.

Problem: A temperature sensor has a resolution of 0.2°C. If the sensor currently reads 25.0°C, determine the output readings for the following temperature inputs: 25.1°C, 25.2°C, and 25.3°C.

Identify the Resolution:

$$\text{Resolution} = 0.2°\text{C}$$

Determine Output Readings:

At 25.0°C: The output is **25.0°C**.

At 25.1°C: This change (0.1°C) is less than the resolution (0.2°C), so the output remains at **25.0°C**.

At 25.2°C: This change (0.2°C) matches the resolution, so the output updates to **25.2°C**.

At 25.3°C: This change (0.3°C) exceeds the resolution, and since it's above 25.2°C, the output will be **25.3°C**.

Question: Consider the following specifications of a temperature sensor:

Range: -20°C to 100°C
Accuracy: ±2°C
Precision: ±0.5°C
Sensitivity: 0.1 mV/°C
Hysteresis Error: ±1 mV
Non-linearity: ±0.5% of full-scale output
Repeatability: ±0.01% of full range
Drift: 0.02°C per month
Stability: Maintains output within ±0.5 mV over 24 hours
Resolution: 0.1°C

Tasks:

i. Define each static characteristic listed in the specifications.
ii. Calculate the span of the sensor.
iii. If the sensor reads 95°C under stable conditions, discuss the implications of its accuracy and precision on this measurement.
iv. If the actual temperature is 93°C, calculate the error and discuss the effects of hysteresis on the output.
v. Determine whether the sensor is linear based on its specified non-linearity and provide an example of a situation where non-linearity might affect measurements.
vi. Discuss the importance of repeatability in applications where this sensor might be used.
vii. Explain how drift could affect long-term measurements and how stability plays a role in reliable data collection.

5. Dynamic characteristics of a sensor

Dynamic characteristics of a sensor *describe its performance* when the *input parameter changes over time*.

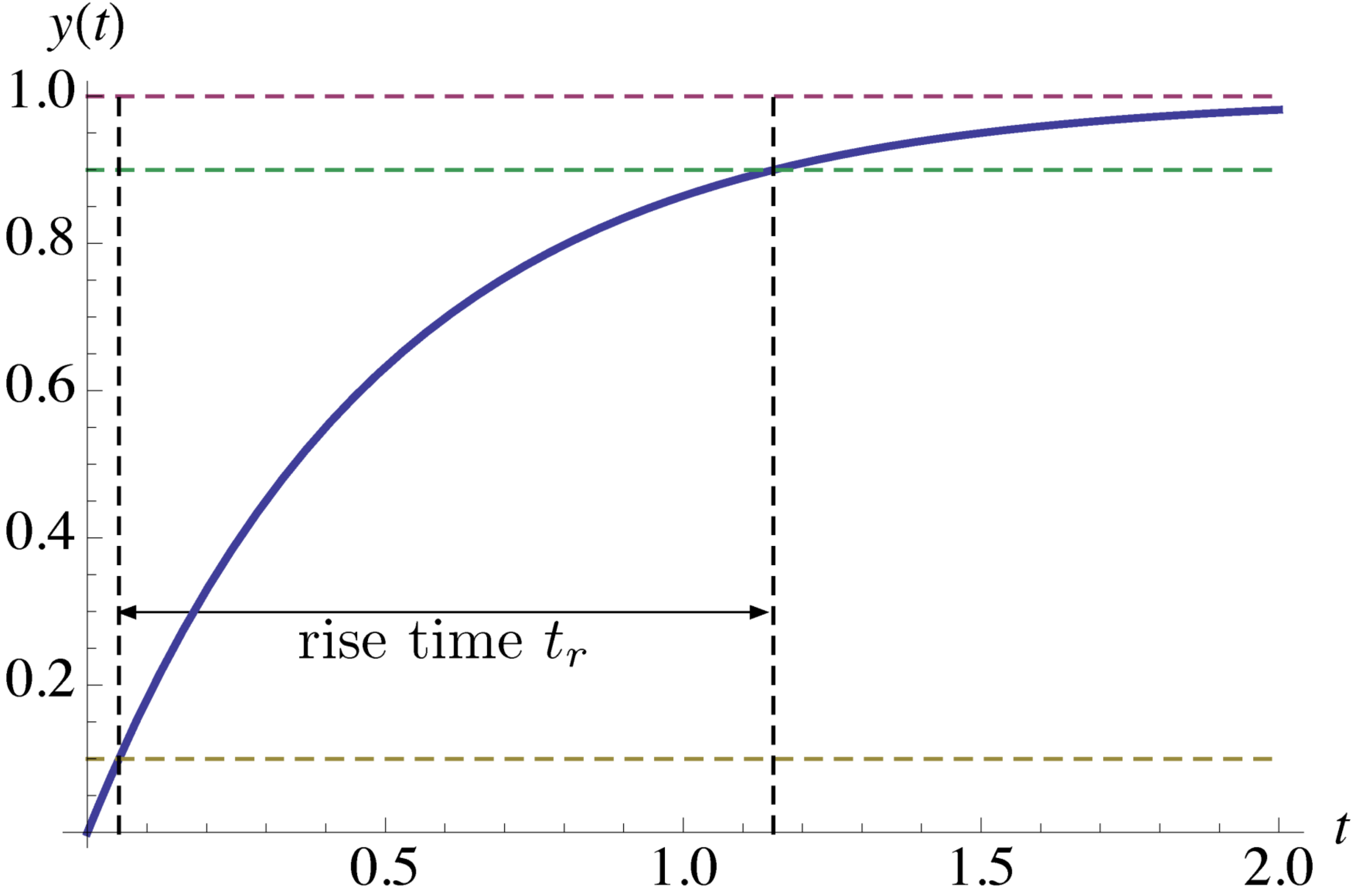
5.1 Rise Time

The *time it takes* for a *sensor's output* to move *from 10% to 90% of its final* steady-state value *after a sudden change in input*.

Suppose the final steady-state value of a sensor is **100 units**.

10% of the final value is **10 units**, and 90% is **90 units**.

If the sensor takes **2 seconds** to go from **10 units** to **90 units**, the **rise time** is **2 seconds**.



y(t)
1.0
0.8
0.6
0.4
0.2
rise time t_r
0.5
1.0
1.5
2.0
t

5.2 Fall Time

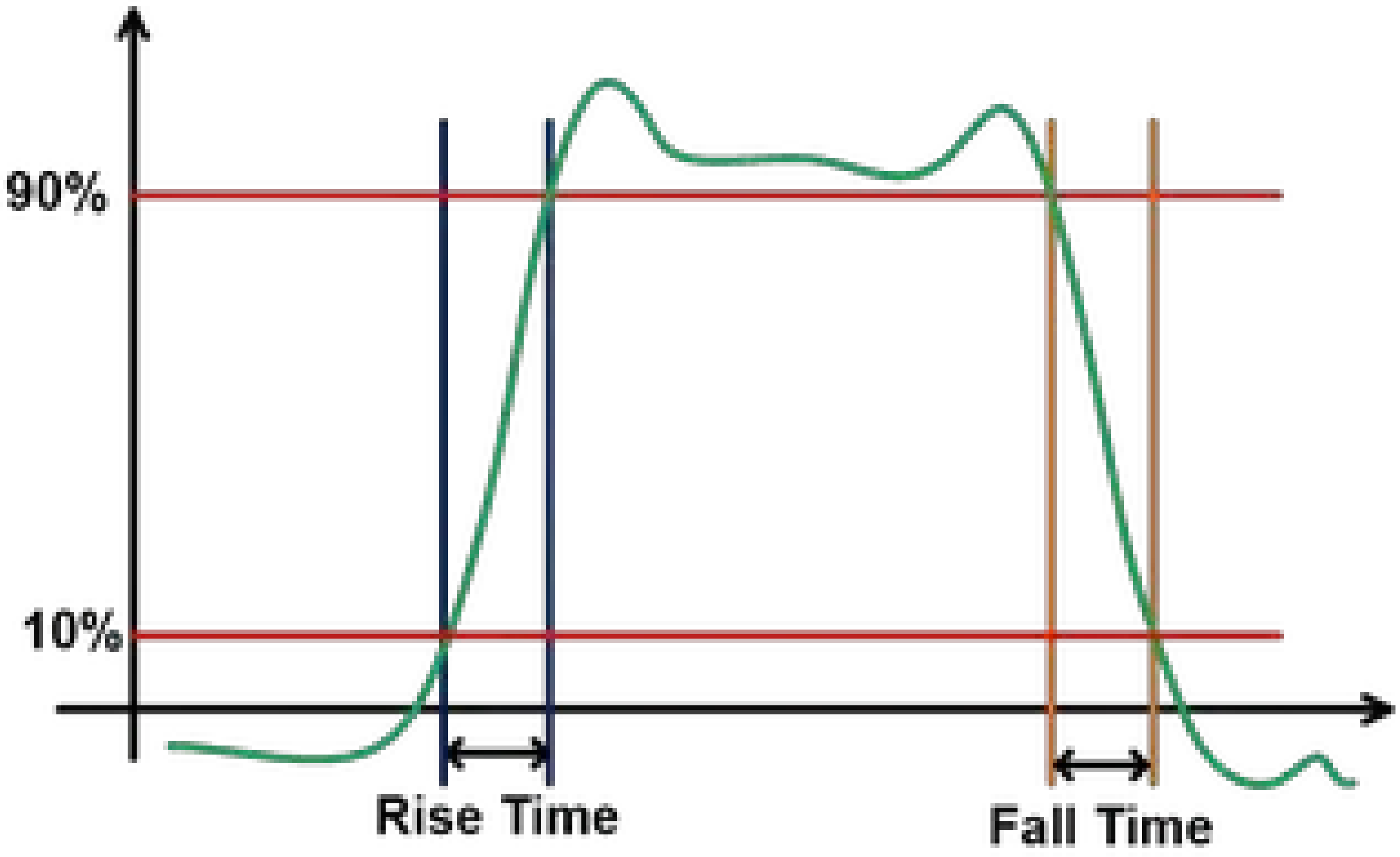
Fall time is the *time it takes* for a sensor or signal output to *transition from a higher level (typically 90%* of the maximum value) *to a lower level (typically 10%* of the maximum value) in *response to a sudden change* (step change) in input.

Suppose the output of a system is **100 units** at its highest.

After a sudden step change, the output begins to drop.

90% of the maximum value is **90 units**, and **10% of the maximum value** is **10 units**.

If the output drops from **90 units** to **10 units** in **4 seconds**, then the **fall time** is **4 seconds**.


90%
10%
Rise Time
Fall Time

5.3 Settling time

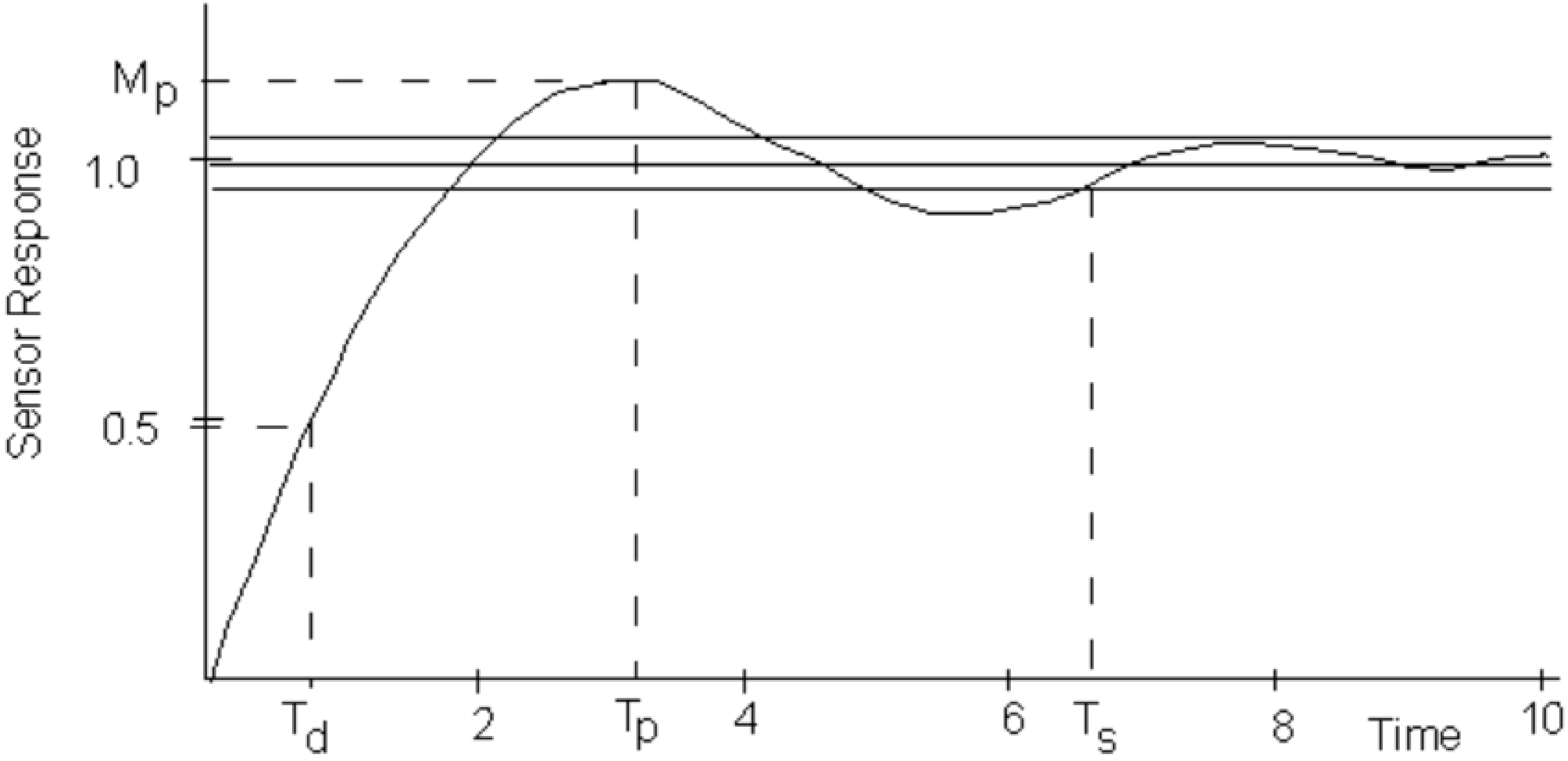
Settling time refers to the time taken for a sensor or system's *output to stabilize within a specific percentage* of the *final steady-state value*, often after a *sudden change in the input* (like a step input). Typically, this percentage is small, such as *±1% or ±5% of the final value*.

Suppose a temperature sensor responds to a sudden temperature increase and the final steady-state temperature is **100°C**.

The sensor may initially overshoot or oscillate around **100°C**.

If the specification is **±1%**, the output must settle between **99°C** and **101°C**.

The time taken for the output to remain within this range is the **settling time**.



Sensor Response
M_p
1.0
0.5
T_d
2
T_p
4
6
T_s
8
Time
10

5.4 Dynamic Range

Dynamic Range is the *difference between the smallest and largest input values* a sensor can *measure accurately* without losing sensitivity or introducing significant distortion.

It indicates the sensor's *ability to detect both very weak and very strong* signals.

If a pressure sensor can detect pressures as low as 1 psi and as high as 500 psi without error, its dynamic range is from 1 psi to 500 psi.

5.5 Bandwidth

Bandwidth refers to the *range of frequencies* over which a *sensor can accurately respond* to *variations in the input signal*.

It determines how well a sensor can *follow fast changes in the input parameter*.

If a temperature sensor has a bandwidth of 0 Hz to 1 kHz, it means the sensor can effectively detect and respond to input signals with frequencies up to 1 kHz.

In practical terms, a sensor with higher bandwidth can capture quicker or more frequent changes in the input signal compared to one with lower bandwidth.

5.6 Transient Response

Transient response refers to the *short-term behavior or temporary state* of a system immediately following a *change in its input* or operating conditions.

5.7 Steady-State Response

Steady-state response refers to the *long-term or final behavior of a system* after it has *settled into a stable condition* following a change in its input or operating conditions.