TRANSDUCERS AND SENSORS

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Closed-loop Control System

controller error \( e(t) = (SP - PV) \)
controller output signal, CO
manipulated variable
Controlled variable process variable
set point, SP

Controller
Final Control Element (FCE)
Process

disturbance, D

measured process variable
signal, PV
Measurement Transducer/Sensor
CHAPTER ONE

Introduction

Functional Elements of a Measurement System

• **Basic Functional Elements**
  1-Transducer Element
  2- Signal Conditioning Element
  3- Data Presentation Element

• **Auxiliary Functional Elements**
  A- Calibration Element
  B- External Power supply
Functional Elements of a Measurement System

Physical quantity to be measured (Measurand)
- e.g. Force
- Velocity
- Pressure
- Displacement
- Temperature
- Flow
- Acceleration
- Strain
- Current
- Voltage
- Frequency
- pH value
- Humidity
- etc.

Transducer
Primary sensing
Secondary sensing (may be)
Transducer element
Transduced signal
Transmission path
Signal conditioning element
Amplifier
Filter
Integrator
A-D Converter

Calibration signal generator with known value of input variable

Calibration Element (Auxiliary Element)

External Power Element (Auxiliary Element)

Modified Signal
Terminal for recording/monitoring
0 5 10 15 20
Analog indicator

Digital display
Data logger
Graphical display
Printed output

Data Presentation Element (Output)

Transducer and Signal Conditioning

Physical quantity to be measured (Measurand)
- e.g. Force
- Velocity
- Pressure
- Displacement
- Temperature
- Flow
- Acceleration
- Strain
- Current
- Voltage
- Frequency
- pH value
- Humidity
- etc.

Input Signal

Primary sensing
Secondary sensing (may be)
Transducer element
Transduced signal
Transmission path

Signal conditioning element
Amplifier
Filter
Integrator
A-D Converter

Modified Signal

Transducer Element

• The Transducer is defined as a device, which when actuated by one form of energy, is capable of converting it to another form of energy. The transduction may be from mechanical, electrical, or optical to any other related form.

• The term transducer is used to describe any item which changes information from one form to another.

Transducer Element

• The Transducer element normally senses the desired input in one physical form and convert it to an output in another physical form. For example, the input variable to the transducer could be pressure, acceleration, or temperature and the output of transducer may be displacement, voltage, or resistance change depending on the type of transducer element.
Transducer Element

- Single stage
- Double stage
**Double Stage Transducer**

![Diagram of Double Stage Transducer]

**Typical Examples of Transducer Elements**

<table>
<thead>
<tr>
<th>S.No</th>
<th>Input variable to transducer</th>
<th>Output variable of transducer</th>
<th>Principle of operation</th>
<th>Type of device</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Temperature</td>
<td>Voltage</td>
<td>An emf is generated across the junctions of two dissimilar metals or semiconductors when that junction is heated</td>
<td>Thermocouple or Thermometer</td>
</tr>
<tr>
<td>2.</td>
<td>Temperature</td>
<td>Displacement</td>
<td>There is a thermal expansion in volume when the temperature of liquids or liquid metals is raised and this expansion can be shown as displacement of the liquid in the capillary</td>
<td>Liquid in Glass Thermometer</td>
</tr>
<tr>
<td>3.</td>
<td>Temperature</td>
<td>Resistance change</td>
<td>Resistance of a pure metal wire with positive temperature coefficient varies with temperature</td>
<td>Resistance Thermometer</td>
</tr>
<tr>
<td>4.</td>
<td>Temperature</td>
<td>Pressure</td>
<td>The pressure of a gas or vapour varies with the change in temperature</td>
<td>Pressure Thermometer</td>
</tr>
<tr>
<td>5.</td>
<td>Displacement</td>
<td>Inductance change</td>
<td>The differential voltage of the two secondary windings varies linearly with the displacement of the magnetic core</td>
<td>Linear Variable Differential Transducer (LVDT)</td>
</tr>
<tr>
<td>6.</td>
<td>Displacement</td>
<td>Resistance change</td>
<td>Positioning of a slider varies the resistance in a potentiometer or a bridge circuit</td>
<td>Potentiometric Device</td>
</tr>
<tr>
<td>7.</td>
<td>Motion</td>
<td>Voltage</td>
<td>Relative motion of a coil with respect to a magnetic field generates a voltage</td>
<td>Electromagnetic Generator</td>
</tr>
</tbody>
</table>
## Typical Examples of Transducer Elements

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Flow rate</td>
<td>Pressure</td>
<td>Differential pressure is generated between the main pipe-line and throat of the Venturimeter/Orifice-meter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Flow velocity</td>
<td>Resistance change</td>
<td>Resistance of a thin wire/film is varied by convection cooling in stream of gas/liquid flows</td>
<td></td>
<td>Hot Wire Anemometer (gas flows), Hot Film Anemometer (liquid flows)</td>
</tr>
<tr>
<td>10</td>
<td>Pressure</td>
<td>Movement of a liquid column</td>
<td>The impressed pressure is balanced by the pressure generated by a column of liquid</td>
<td></td>
<td>Manometer</td>
</tr>
<tr>
<td>11</td>
<td>Pressure</td>
<td>Displacement</td>
<td>The application of pressure causes displacement in elastic elements</td>
<td></td>
<td>Boardon Gauge</td>
</tr>
<tr>
<td>12</td>
<td>Gas pressure</td>
<td>Resistance change</td>
<td>Resistance of a heating element varies by convection cooling</td>
<td></td>
<td>Pirani Gauge</td>
</tr>
<tr>
<td>13</td>
<td>Force</td>
<td>Displacement</td>
<td>The application of force against a spring changes its length in proportion to the applied force</td>
<td></td>
<td>Spring Balance</td>
</tr>
<tr>
<td>14</td>
<td>Force/torque</td>
<td>Resistance change</td>
<td>The resistance of metallic wire or semiconductor element is changed by elongation or compression due to externally applied stress</td>
<td></td>
<td>Resistance Strain Gauge</td>
</tr>
</tbody>
</table>

### Additional Examples

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Force</td>
<td>Voltage</td>
<td>An emf is generated when external force is applied on certain crystalline materials such as quartz</td>
<td></td>
<td>Piezo-electric Device</td>
</tr>
<tr>
<td>16</td>
<td>Liquid level/thickness</td>
<td>Capacitance change</td>
<td>Variation of the capacitance due to the changes in effective dielectric constant</td>
<td></td>
<td>Dielectric gauge</td>
</tr>
<tr>
<td>17</td>
<td>Speech/music/noise</td>
<td>Capacitance change</td>
<td>Sound pressure varies the capacitance between a fixed plate and a movable diaphragm</td>
<td></td>
<td>Condenser Microphone</td>
</tr>
<tr>
<td>18</td>
<td>Light</td>
<td>Voltage</td>
<td>A voltage is generated in a semiconductor junction when radiant energy stimulates the photoelectric cell</td>
<td></td>
<td>Light Meter/Solar Cell</td>
</tr>
<tr>
<td>19</td>
<td>Light radiations</td>
<td>Current</td>
<td>Secondary electron emission due to incident radiations on the photosensitive cathode causes an electronic current</td>
<td></td>
<td>Photomultiplier tube</td>
</tr>
<tr>
<td>20</td>
<td>Humidity</td>
<td>Resistance change</td>
<td>Resistance of a conductive strip changes with the moisture content</td>
<td></td>
<td>Resistance Hygrometer</td>
</tr>
<tr>
<td>21</td>
<td>Blood flow/any other gas or liquid or two-phase flow</td>
<td>Frequency shift</td>
<td>The difference in the frequency of the incident and reflected beams of ultrasound known as Doppler's frequency shift is proportional to the flow velocity of the fluid</td>
<td></td>
<td>Doppler Frequency Shift Ultrasonic Flow Meter</td>
</tr>
</tbody>
</table>
Transducers classification

• Based on power type classification
  - Active transducer (Diaphragms, Bourdon Tubes, tachometers, piezoelectric, etc...)
  - Passive transducer (Capacitive, inductive, photo, LVDT, etc...)

Transducers classification

• Based on the type of output signal
  - Analogue Transducers (stain gauges, LVDT, etc...)
  - Digital Transducers (Absolute and incremental encoders)
### Transducers classification

- Based on the electrical phenomenon or parameter that may be changed due to the whole process.
  - Resistive transducer
  - Capacitive transducer
  - Inductive transducer
  - Photoelectric transducer

### Transducer Characteristics

- Static characteristics.
- Dynamic characteristics.
Type of Errors

• **Systematic errors**: Errors that tend to have the same magnitude and sign for the given set of conditions, such as instrument, environmental, and loading errors. This type of error can be eliminated by applying the proper calibration.

• **Random (or Accidental) errors**: These errors are of variable magnitude and sign and do not obey any known law. These errors caused due to random variation in the parameter or the system of measurement, such as the accuracy of measuring small quantities. This type of error can be calculated by using statistical analysis.

Type of Errors

• **Gross errors**: These are generally the fault of the person using the instruments, and are due to:
  - Incorrect reading of instruments.
  - Incorrect recording of experiment data.
  - Incorrect use of instruments.

  These errors may be of any magnitude and cannot be subjected to mathematical treatment.
**Statistical Analysis of Error in Measurement**

- **Mean Value**
  \[ \bar{x} = \frac{x_1 + x_2 + \ldots + x_n}{n} = \frac{\sum x_n}{n} \]

- **Standard Deviation**
  \[ \sigma = \sqrt{\frac{d_1^2 + d_2^2 + \ldots + d_n^2}{n}} \]

Where:
- \( d_1 = x_1 - \bar{x} \)
- \( d_2 = x_2 - \bar{x} \)

*Note: if the number of samples is less than 20, (n) in the standard deviation law will be replaced by (n-1)*

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**Interpretation of Standard deviation**

- If the error is truly random and we have large sample of readings, the data and the standard deviation is related to the normal probability curve.
- The normal probability curve has the following characteristics:
  - 68% of readings lie within \( \pm 1\sigma \) of the mean
  - 95.5% of readings lie within \( \pm 2\sigma \) of the mean
  - 99.7% of readings lie within \( \pm 3\sigma \) of the mean
Statistical Analysis of Error in Measurement

Example 1:
Temperature was measured in eight locations in a room, and the values obtained were 21.2°, 21.2°, 25.0°, 18.5°, 19.7°, 27.1°, 19.0°, and 20.0°C. Find the arithmetic mean and standard deviation.

Example 2:
Compare between two sets of pressure readings, the first one has a mean of 44 psi with a standard deviation of 3 psi and the second one has a mean of 44 psi with a standard deviation of 14 psi.

Static Characteristics

• **Accuracy**
  Accuracy is defined as the closeness of the transducer output to the true value of the measured quantity. However, in usual practice, it is specified as the inaccuracy of measurement from the true value by calculating the absolute and percent error. The accuracy of an instrument depends on the various systematic errors.
Static Characteristics

• **Accuracy**

- Absolute Error

\[ e_A = |Y_n - X_n| \]

Where: \( Y_n = \text{expected value} \)
\( X_n = \text{measured value} \) *(could be } \mu \text{ if the device is suffering from random and systematic errors)*

- Percent Error

\[ e_p = \left| \frac{Y_n - X_n}{Y_n} \right| \times 100\% \]

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Static Characteristics

• **Precision/Repeatability:**

**Precision** is defined as the ability of the instrument to reproduce a certain set of readings within a given accuracy.

**Repeatability** is defined as the ability of the instrument to reproduce a group of measurements of the same measured quantity, made by the same observer, using the same instrument, and under the same conditions. *The precision of the instrument depends on the factors that cause random errors.*
Static Characteristics

- Precision

\[ \text{precision\%} = \frac{2\sigma}{\text{Fullscale}} \times 100 \]

Static Characteristics

- Accuracy Versus Precision

(a) High precision with poor accuracy  (b) Good average accuracy with poor precision  (c) High accuracy with high precision  (d) Poor accuracy with poor precision
Static Characteristics

• **Resolution or Discrimination:**
  It is defined as the smallest increment in the measured value that can be detected with certainty by the instrument.
  • Resolution is also defined as the largest change in input that can occur without any corresponding change in output. Resolution is normally expressed as a percentage of input full scale as:

\[
\text{resolution} \ % = \frac{\Delta I}{\text{Fullscale}} \times 100
\]

Static Characteristics

• **Range or Span**
  The range or span of an instrument defines the minimum and maximum values of a quantity that the instrument is designed to measure.
Static Characteristics

- **Static Sensitivity (scale factor or gain):**
The static sensitivity is defined as the ratio of the magnitude of response (the change of output signal) to the magnitude of the quantity being measured (the change of input signal)

\[ Slop = K = \frac{\Delta q_o}{\Delta q_i} \]

Where \( q_0 \) and \( q_i \) are the values of output and input signals respectively.

- If the relationship between input and output is linear, the sensitivity is constant
- If the relationship between input and output is nonlinear, the sensitivity varies with the input value
Static Characteristics

• **Linearity:**
  It is the closeness to which a curve approximates a straight line. The linearity is one of the most desirable features of any instrument. However, linearity is not completely achieved.

Static Characteristics

• Many instruments are designed to achieve a linear relationship between the applied static input and indicated output values. Such a linear static calibration curve would have the general form

  \[ y_L(x) = a_0 + a_1 x \]

  where the curve fit \( y_L(x) \) provides a predicted output value based on a linear relation between \( x \) and \( y \).

• However, in real systems, truly linear behavior is only approximately achieved. As a result, measurement device specifications usually provide a statement as to the expected linearity of the static calibration curve for the device.
Static Characteristics

• The relationship between $y_L(x)$ and measured value $y(x)$ is a measure of the nonlinear behavior of a system:

$$u_L(x) = y(x) - y_L(x)$$

• where $u_L(x)$ is a measure of the linearity error that arises in describing the actual system behavior by the equation. Such behavior is illustrated in the following figure in which a linear curve has been fit through a calibration dataset.

Static Characteristics

• **Linearity:**

![Image of a graph showing actual data trend and best linear curve fit](image)
Static Characteristics

**Linearity:**
- For a measurement system that is essentially linear in behavior, the extent of possible nonlinearity in a measurement device is often specified in terms of the maximum expected linearity error as a percentage of full-scale output range.

\[
\% u_{L_{\text{max}}} = \frac{u_{L_{\text{max}}}}{r_o} \times 100
\]

Static Characteristics

- **Dead Zone (Dead Band):**
  Is the largest change of the measured quantity in which the instrument does not respond.
Static Characteristics

- Drift:
The variation of output for a given input caused due to change in the sensitivity of the instrument due to certain interfering inputs like temperature changes.
  - Sensitivity drift.
  - Zero drift.
Static Characteristics

• **Drift:**

[Diagram of drift showing output vs. input with labeled axes and curves for sensitivity and zero drift.]

Static Characteristics

• **Hysteresis:**

It is defined as the magnitude of error caused in the output for a given value of input, when this value is approached from opposite direction, i.e. from ascending order and then descending order. This is caused by backlash, elastic deformation, magnetic characteristics, and frictional effect.

[Diagram showing hysteresis with arrows indicating motion in opposite directions.]
Static Characteristics

• **Hysteresis:**
  
  Hysteresis is usually specified for a measurement system in terms of the maximum hysteresis error as a percentage of full-scale output range.

  \[ Hysteresis_{MAX} \% = \frac{Hysteresis_{MAX}}{Fullscale} \times 100 \]
Static Characteristics

**Overall Instrument Error and Uncertainty:**

• An estimate of the overall instrument error is made by combining the estimates of all known errors into a term called the instrument uncertainty. The estimate is computed from the square root of the sum of the squares of all known uncertainty values. For M known errors, the overall instrument uncertainty, \( u_c \), is estimated by:

\[
 u_c = \left[ u_1^2 + u_2^2 + \cdots + u_M^2 \right]^{1/2}
\]

• For example, for an instrument having known hysteresis, linearity, and sensitivity drift errors, the instrument uncertainty is estimated by

\[
 u_c = \left[ u_h^2 + u_l^2 + u_s^2 \right]^{1/2}
\]

---

**Loading Effect (Impedance Load)**

• Any measuring instrument with an input signal source would extract some energy, thereby changing the value of the measured variable. This means that the input signal suffers a change by virtue of the fact that it is being measured. This effect is termed **loading**.

• One of the most important concerns in analog signal conditioning is the loading of one circuit by another. This introduces uncertainty in the amplitude of a voltage as it passed through the measurement process. If this voltage represents some process variable, then we have uncertainty in the value of the variable.

• The loading error (effect) in the measurement system can never be zero, but it must be made as small as possible. How????
Loading Effect (Impedance Load)

- **Thévenin’s theorem** states that any network consisting of linear impedances and voltage sources can be replaced by an equivalent circuit consisting of a voltage source $E_{Th}$ and a series impedance $Z_{Th}$. The source $E_{Th}$ is equal to the open circuit voltage of the network across the output terminals, and $Z_{Th}$ is the impedance looking back into these terminals with all voltage sources reduced to zero and replaced by their internal impedances. Thus connecting a load $Z_L$ across the output terminals of the network is equivalent to connecting $Z_L$ across the Thévenin circuit.

\[
\begin{align*}
i &= \frac{E_{Th}}{Z_{Th} + Z_L} \\
V_L &= iZ_L = E_{Th} \frac{Z_L}{Z_{Th} + Z_L}
\end{align*}
\]
Loading Effect (Impedance Load)

- Example:
  An amplifier outputs a voltage that is ten times the voltage on its input terminals. It has an input resistance of 10 kΩ. A sensor outputs a voltage proportional to temperature with a transfer function of 20 mV/°C. The sensor has an output resistance of 5 kΩ. If the temperature is 50°C, find the amplifier output.
Impedance Matching

Dynamic Characteristics

- Zero order transducers (e.g. Potentiometer)

\[ a_0 q_0 = b_0 q_i \quad \text{or} \quad q_0 = \frac{b_0 q_i}{a_0} = K q_i \]
Dynamic Characteristics

• First order transducers (e.g. Thermocouple)

\[ a_1 \frac{dq_0}{dt} + a_0 q_0 = b_0 q_i \]
\[ q_0 = \frac{Kq_i}{1 + \tau D} \]

Dynamic Characteristics

• Second order transducers (e.g. Accelerometer)

\[ q_0 = \frac{b_0 q_i}{a_0 + a_1 D + a_2 D^2} \]
\[ K = \frac{b_0}{a_0}; \quad \omega = \sqrt{a_0/a_2}; \quad \xi = \frac{a_1}{2\sqrt{a_0a_2}} \]
\[ \frac{q_0}{q_i} = \frac{K}{D^2/\omega^2 + 2\xi D/\omega + 1} \]
Dynamic Characteristics

• Second order transducers

1. Delay time ($t_d$)
2. Rise time ($t_r$)
3. Peak time ($t_p$)
4. Maximum overshoot ($M_p$)
5. Settling time ($t_s$)
Dynamic Characteristics

- Second order transducers

![Graph showing dynamic characteristics with time (t) and signal (x(t)) axes, including parameters M_p, t_p, t_r, and allowable tolerance.

Basic Requirements of Transducers

- The transducer element should recognise and sense the desired input signal and should be insensitive to other signals.
- It should not alter the event to be measured.
- Good accuracy.
- Good precision.
- Amplitude linearity.
- Adequate dynamic response.
Basic Requirements of Transducers

- It should have high signal level and low impedance.
- Easily available, reasonable price, and compact in shape and size.
- Good reliability and ruggedness (Reliability indicates the transducer ability to achieve the predefined accuracy and tolerance repeatedly under various environmental conditions for a long period of time).