INTRODUCTION

- Course presentation
- Classification of transducers
- Transducer descriptions
- Transducer parameters, definitions and terminology
- Transducer effects in silicon and other materials
SENSORS and TRANSDUCERS

Course presentation
  ➤ Classification and descriptions of transducers
  ➤ Survey of possible energy conversions
    ➥ Optical, mechanical, thermal, magnetic and chemical
  ➤ Sensor characteristics
  ➤ Sensor compensation
SENSORS and TRANSDUCERS

SENSORS convert energy information

One energy form must be converted into the same or another energy form with exactly the same information content as the originating energy form.

*Example:*

- Mic
- Amplifier
- Loudspeaker
SENSORS and TRANSDUCERS

SENSORS use some form of energy to get the information

*Example*: Ultrasonic distance measurement
One form of energy can be used for measuring different quantities

*Example:* Applications of inductive sensors
SENSORS and TRANSDUCERS

TRANSDUCER - *latin tranducere* - ‘to convert’
Input transducer - sensor
Output transducer - actuator

**Diagram:**
- **Input:** Sensor → F₁ → Fₖ → Actuator
- **Output:** Biological or technical system

**Symbols:**
- Sensor
- Actuator
- F₁, Fₖ
- Biological or technical system

**Legend:**
- "Information" symbol
Classification of transducers

*Types of energy form*

- Radiant
- Mechanical
- Thermal
- Electrical
- Magnetic
- Chemical

Energy domains

Sensors

Electrical system

Electrical energy

Modifying unit

(A/D or D/A)
Classification of transducers

- Modulating and self-generating transducers
  - Modulating transducer requires an auxiliary energy source
    - Strain gauge, thermal resistor, liquid-crystal-display
  - Self-generating transducer requires no auxiliary energy source
    - Solar cell, thermocouple, piezoelectric element

- X-axis input energy domain
- Y-axis output energy domain
- Z-axis modulating energy domain
Classification of transducers

* Miller index - three dimensional vector

\[ [x \ y \ z] \Rightarrow [\text{input energy, output energy, modulating energy}] \]

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Miller index ([x \ y \ z])</th>
<th>Type description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transistor</td>
<td>[el, el, el]</td>
<td>Modulating shape transducer</td>
</tr>
<tr>
<td>Thermocouple</td>
<td>[th, el, 00]</td>
<td>Self-generating input transducer</td>
</tr>
<tr>
<td>pH meter</td>
<td>[ch, el, 00]</td>
<td>Self-generating input transducer</td>
</tr>
<tr>
<td>LED display</td>
<td>[el, ra, 00]</td>
<td>Self-generating output transducer</td>
</tr>
<tr>
<td>LCD display</td>
<td>[ra, ra, el]</td>
<td>Modulating output transducer</td>
</tr>
<tr>
<td>Coil</td>
<td>[ma, el, 00]</td>
<td>Self-generating output transducer</td>
</tr>
<tr>
<td>Magnetoresistor</td>
<td>[ma, el, el]</td>
<td>Modulating input transducer</td>
</tr>
<tr>
<td>Photoconductor</td>
<td>[ra, el, el]</td>
<td>Modulating input transducer</td>
</tr>
</tbody>
</table>
**State description of transducers**

- The steady state description reveals characteristics of transducers.

**Note!** No transducer is sensitive to one physical energy only

Consider a small volume $dV$ in which transducer is placed

The energy content $dW$ in this volume contains the summation of all possible energies

$$
dW = \sum I_i e_i = \sigma \cdot dl + P \frac{\partial \rho}{\rho} + V \cdot dq + E \cdot dD + H \cdot dB + T \cdot dS + w_r
$$

- $I_i$ - intensive quantity (can carry power, e.g., force, pressure, voltage)
- $e_i$ - extensive quantity (cannot carry power, e.g., displacement, resistance)
- $\sigma$ - mechanical force
- $P$ - pressure
- $V$ - voltage
- $E$ - electrical field
- $H$ - magnetic field
- $T$ - absolute temperature
- $\rho$ - volume density of mass
- $dq$ - volume density of charge
- $dD$ - charge per unit surface
- $dB$ - magnetic induction
- $dS$ - entropy per unit volume
- $w_r$ - radiation per unit volume
Static Characteristics

* Systematic Characteristics
  - **Range** - min and max values of input or output variables
    - Example: input range 100 - 250°C or output range 4 to 20 mA
  - **Span** - maximum variation of input or output
    - Example: 150 °C or 16 mA
  - **Linearity** - input values \( I \) and output values \( O \) lie on a straight line
    \[
    O_{\text{ideal}} = KI + a \quad K = \frac{O_{\text{max}} - O_{\text{min}}}{I_{\text{max}} - I_{\text{min}}}
    \]
  - **Nonlinearity**
    \[
    N(I) = O(I) - (KI + a)
    \]
Dynamic Characteristics

- Transfer functions
  - First order elements
  - Example: Temperature sensor is described by heat balance equation

\[
\tau \frac{dT}{dt} + T = T_F \quad \Rightarrow \quad G(s) = \frac{1}{1 + \tau s}
\]

where:
- \(\tau\) - time constant
- T - sensor temperature
- \(T_F\) - ambient temperature

Graph showing the response of the system with the given time constants and corresponding values:

- \(t = \tau, \ f(t) = 1 - e^{-1} = 0.63\)
- \(t = 2\tau, f(t) = 1 - e^{-2} = 0.87\)
- \(t = 3\tau, f(t) = 1 - e^{-3} = 0.95\)
- \(t = 4\tau, f(t) = 1 - e^{-4} = 0.98\)
- \(t = 5\tau, f(t) = 1 - e^{-5} = 0.99\)
Dynamic Characteristics

- Transfer functions
  - Second order elements
    - Example: Mass-spring-damper (accelerometer)

\[
\frac{1}{\omega_n} \frac{d^2 x}{dt^2} + \frac{2\xi}{\omega_n} \frac{dx}{dt} + x = \frac{1}{k} F \quad \Rightarrow \quad G(s) = \frac{1}{\left(\frac{s^2}{\omega_n^2} + \frac{2\xi}{\omega_n} s + 1\right)}
\]

where:

\[
\omega_n = \sqrt{\frac{k}{m}} \quad \text{rad/sec} \quad \text{- undamped natural frequency}
\]

\[
\xi = \frac{\lambda}{2\sqrt{km}} \quad \text{- damping ratio}
\]
### Transducer parameters

*The state description - Example*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling (response) time</td>
<td>s</td>
<td>Time for signal to respond to step input signal within a rated accuracy</td>
</tr>
<tr>
<td>Rise time</td>
<td>s</td>
<td>Time for signal to change from 10% to 90% of its p-p value</td>
</tr>
<tr>
<td>Excitation</td>
<td>V or A</td>
<td>Power supply voltage/current required for normal operation</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>dV/dx&lt;sub&gt;i&lt;/sub&gt;</td>
<td>The rate of change at the output at the change at the input</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>any</td>
<td>Permanent deviation from zero for zero input</td>
</tr>
<tr>
<td>Offset voltage</td>
<td>mV</td>
<td>Output voltage obtained for zero (reference) input conditions</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>ppm K&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>The rate of change of reading as a function of temperature</td>
</tr>
<tr>
<td>Repeatability</td>
<td>%</td>
<td>Measure of agreement between successive measurement (same conditions)</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>%</td>
<td>Measure of agreement between successive measurement (changed conditions)</td>
</tr>
<tr>
<td>Temperature range</td>
<td>T(K)</td>
<td>Operating span for specified accuracy</td>
</tr>
</tbody>
</table>
Static errors - error reducing techniques

Compensating non-linear element

\[ V_{out} = K k_{cor} F_{in} \]

High gain negative feedback

\[ V_{out} = \frac{K k_A}{1 + K k_A T_F} F_{in} \approx \frac{1}{k_F} F_{in} \quad \text{if} \quad K k_A T_F >> 1 \]
Dynamic errors - Compensating techniques

* Open-loop dynamic compensation

\[ V_{out}(\omega) = G_u(\omega)G_c(\omega)F_{in}(\omega) \]

Diagram:

- **Uncompensated element**
  - Thermocouple: \( \frac{1}{1 + \tau s} \)

- **Compensating element**
  - Lead/lag circuit: \( \frac{1 + \tau_1 s}{1 + \tau_2 s} \)
  - \( \tau_1 \approx \tau \)
  - \( \tau_2 \ll \tau_1 \)

Equivalence:

\[ \equiv \]

\[ \frac{1}{1 + \tau_2 s} \]
Dynamic errors - Compensating techniques

* High gain negative feedback

\[ V_{out}(\omega) = \frac{G(\omega)G_A(\omega)}{1 + G(\omega)G_A(\omega)G_F(\omega)} F_{in}(\omega) = \frac{1}{G_F(\omega)} F_{in}(\omega) \quad \text{for} \quad \omega_{\text{min}} < \omega < \omega_{\text{max}} \]

\[ |G(\omega)G_A(\omega)G_F(\omega)| >> 1 \]

\[ \Delta V(s) = \frac{K_S}{\omega^2_{ns} - s^2 + \frac{2\xi_s}{\omega_{ns}} s + 1} \]

\[ \Delta a(s) = \frac{K_S}{\omega^2_{ns} - s^2 + \frac{2\xi_s}{\omega_{ns}} s + 1} \]

\[ \omega_{ns} = \omega_n \sqrt{\frac{K_A K_D K_F}{k}} \]

\[ \xi_s = \xi \sqrt{\frac{k}{K_A K_D K_F}} \]
Definitions and terminology

- **Biophotonics** - application of photonic technology in medical or biotechnology products
- **Biosensor** - sensor for the measurements of ion concentrations in living systems or in organic compounds
- **Mechatronics** - discipline that combines mechanical and electronic components into a larger functional unit
- **Micromechanics** - the design, the development and the production of extremely small mechanical devices
- **Optoelectronics** - discipline combining optics or photonics and electronics on one device
- **Smart sensor** - single-chip functional unit combining sensing and processing functions
Transducer effects in silicon and other compatible materials

* Transducer effects in silicon - electrons are the information carrier

<table>
<thead>
<tr>
<th>Energy domain</th>
<th>I/Out</th>
<th>Modulating</th>
<th>Examples of smart transducers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation</td>
<td>Volta effect, solar cell</td>
<td>Photoconductor, Photodiode, Phototransistor</td>
<td>Photo-IC, CCD</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Not known, Piezojunction</td>
<td>Piezoresistivity, Piezotransistor</td>
<td>Accelerometer, Piezo IC</td>
</tr>
<tr>
<td>Thermal</td>
<td>Seebeck effect, thermocouple</td>
<td>R = f(T), Reverse biased $I_{rev}= f(T)$, Forward biased $U_{BE}= f(T)$</td>
<td>Temperature IC</td>
</tr>
<tr>
<td>Electrical</td>
<td>Thermal energy, resistance, Electric field, MOSFET</td>
<td>Electric field, FET, Dual gate MOSFET</td>
<td>All types of IC</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Maxwell diffused coil, Magnetoresistor</td>
<td>Magnetic diode, Hall effect, Hall IC</td>
<td></td>
</tr>
<tr>
<td>Chemical</td>
<td>Galvanic, Ion concentration</td>
<td>Not known, ISFET</td>
<td>Smart nose</td>
</tr>
</tbody>
</table>
Review Questions

➤ Describe difference between modulating and self-generating transducers
➤ Define type and Miller index for
  ➤ termistor
  ➤ TV screen
  ➤ Loudspeaker
➤ Give an example of self-generating sensor for thermal energy
➤ Give an example of modulating sensor for magnetic energy
➤ Derive transfer function for a temperature sensor
➤ Derive transfer function for a mass-spring-damper
➤ Describe the principle of compensation using open-loop correction
➤ Describe the principle of compensation using high gain negative feedback for
  ➤ static characteristics
  ➤ dynamic characteristics