SENSORS and TRANSDUCERS

Tadeusz Stepinski, Signaler och system

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

SENSORS and TRANSDUCERS

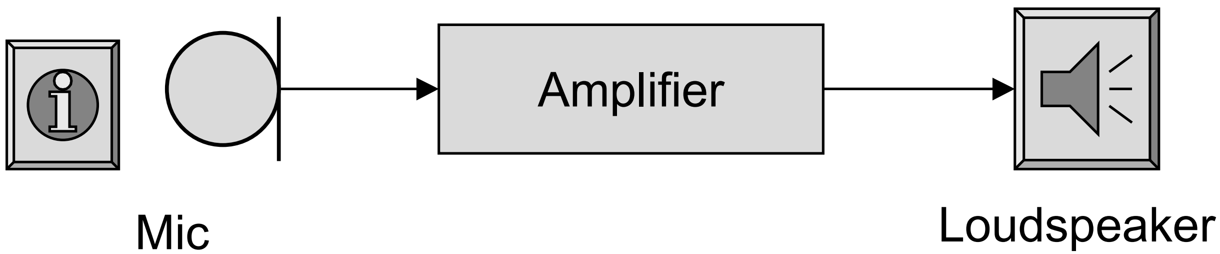
- Course presentation
  - Classification and descriptions of transducers
  - Survey of possible energy conversions
    - Optical, mechanical, thermal, magnetic and chemical
  - Sensor characteristics
  - Sensor compensation

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

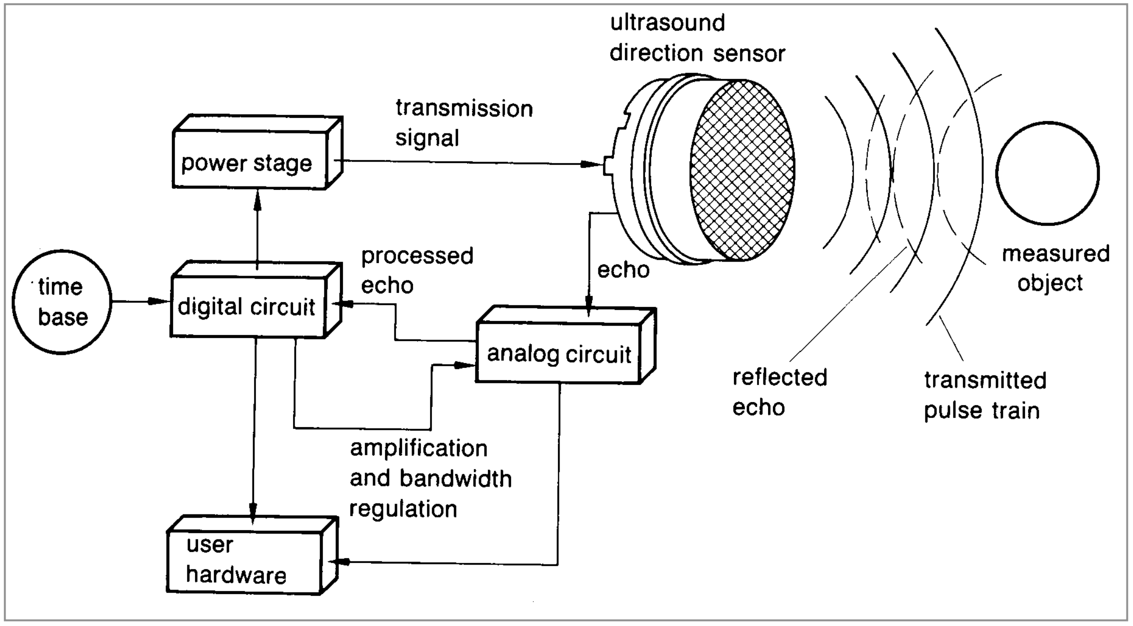
Example:



SENSORS and TRANSDUCERS

SENSORS use some form of energy to get the information

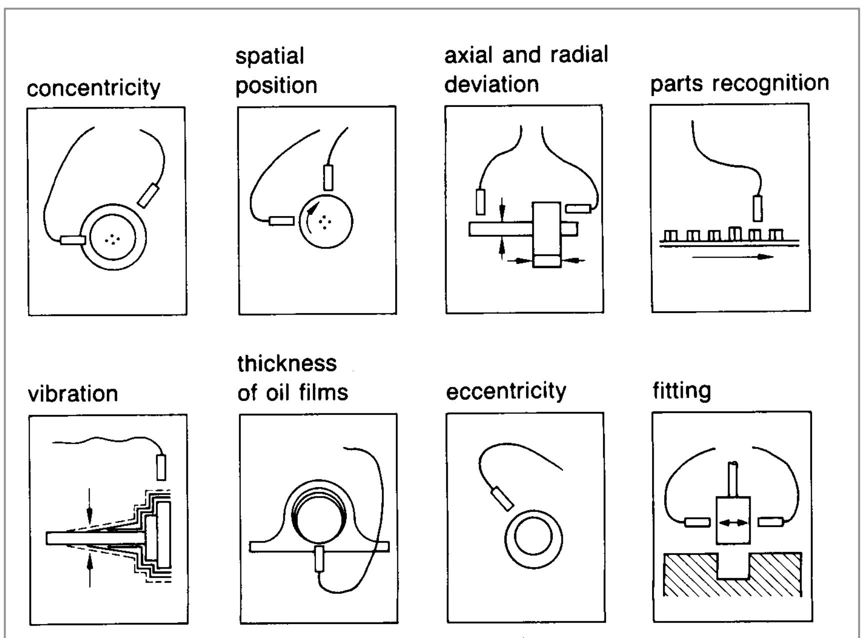
Example: Ultrasonic distance measurement

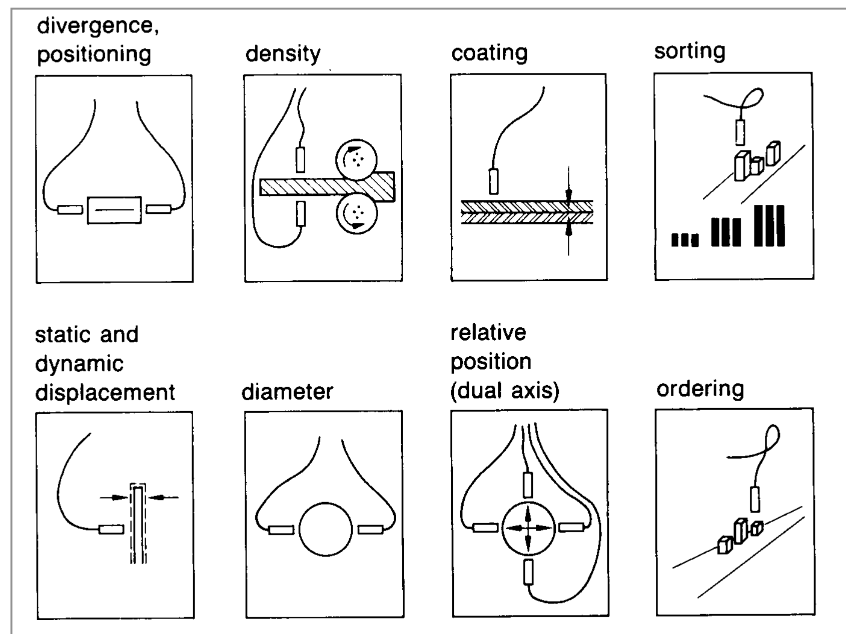


SENSORS and TRANSDUCERS

One form of energy can be used for measuring different quantities

Example: Applications of inductive sensors



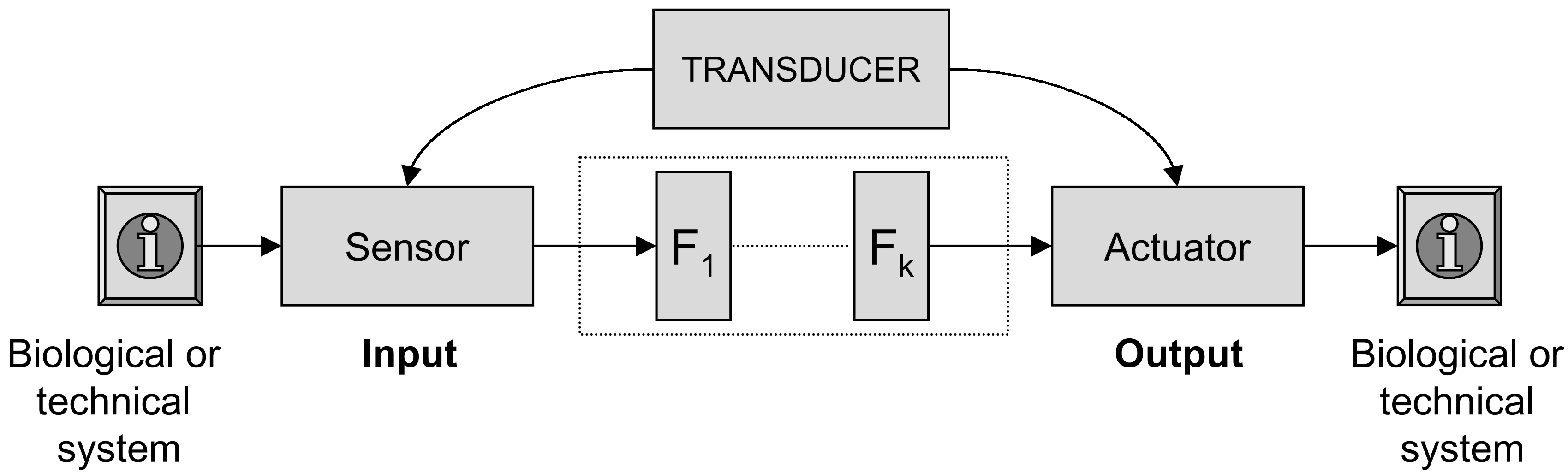


SENSORS and TRANSDUCERS

TRANSDUCER - *latin tranducere* - ‘to convert’

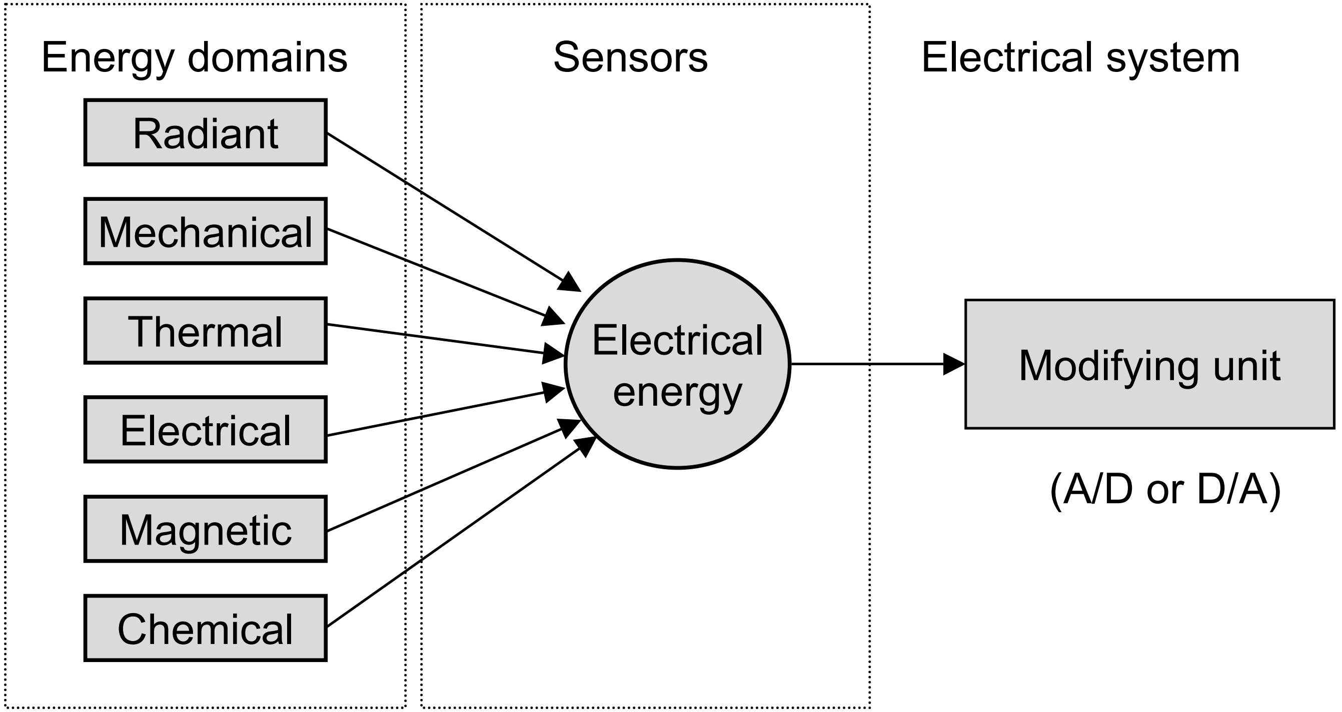
Input transducer - sensor

Output transducer - actuator



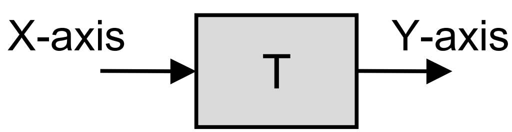
Classification of transducers

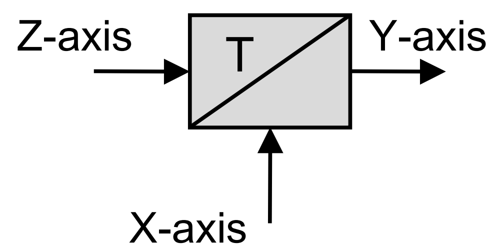
* Types of energy form



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] $\Rightarrow$ [*input energy, output energy, modulating energy*]

Transducer	Miller index [x y z]	Type description
Transistor	[el, el, el]	Modulating shape transducer
Thermocouple	[th, el, 00]	Self-generating input transducer
pH meter	[ch, el, 00]	Self-generating input transducer
LED display	[el, ra, 00]	Self-generating output transducer
LCD display	[ra, ra, el]	Modulating output transducer
Coil	[ma, el, 00]	Self-generating output transducer
Magnetoresistor	[ma, el, el]	Modulating input transducer
Photoconductor	[ra, el, el]	Modulating input transducer

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 d*V* in which transducer is placed

The energy content d*W* 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 curry power, e.g.,displacement, resistance)

σ - mechanical force

P - pressure

V - voltage

E - electrical field

H - magnetic field

T - absolute temperature

dl - displacement

dρ - 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

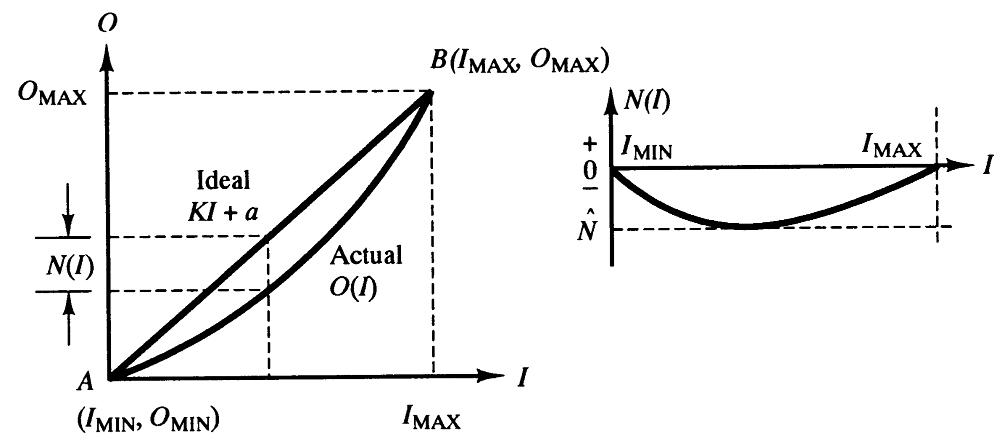
Static Characteristics

- 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

$$O_{ideal} = KI + a \qquad K = \frac{O_{\max} - O_{\min}}{I_{\max} - I_{\min}}$$

  - Nonlinearity

$$N(I) = O(I) - (KI + a)$$



Dynamic Characteristics

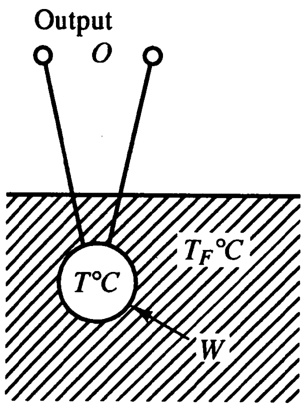
- Transfer functions
  - First order elements
    - Example: *Temperature sensor is described by heat balance equation*

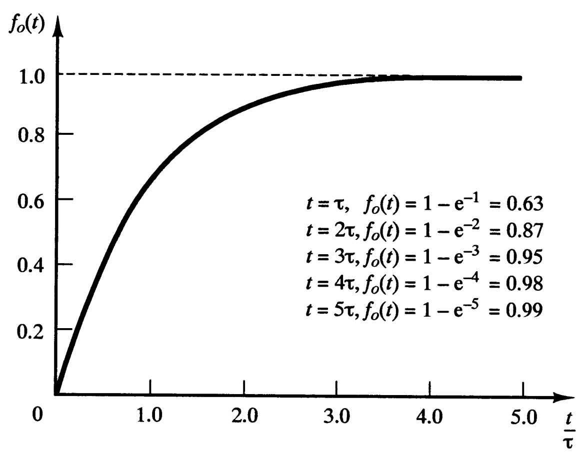
$$\tau \frac{dT}{dt} + T = T_F \quad \Rightarrow \quad G(s) = \frac{1}{1+\tau s}$$

where: τ - time constant

T- sensor temperature

T_F- ambient temperature





Dynamic Characteristics

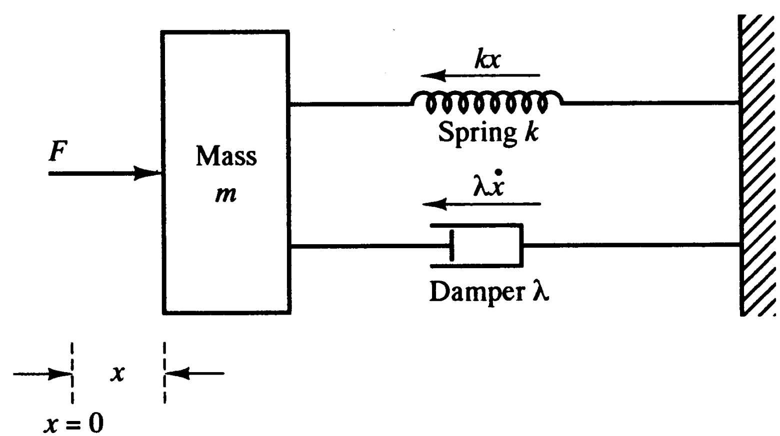
- Transfer functions
  - Second order elements
    - Example: *Mass-spring-damper (accelerometer)*

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

where:

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

$\xi=\frac{\lambda}{2\sqrt{km}}$ - damping ratio



Transducer parameters

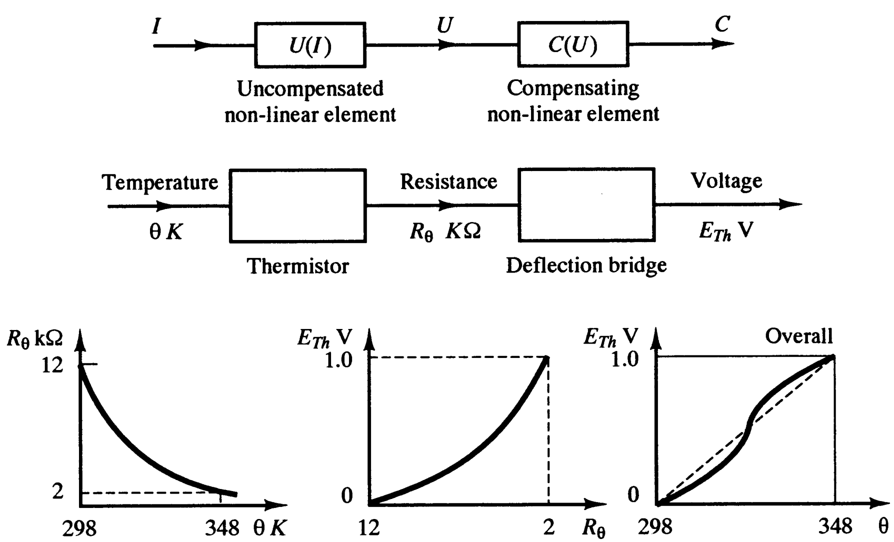
* *The state description - Example*

Parameter	Unit	Description
Settling (response) time	s	Time for signal to respond to step input signal within a rated accuracy
Rise time	s	Time for signal to change from 10% to 90% of its p-p value
Excitation	V or A	Power supply voltage/current required for normal operation
Sensitivity	dV/dx_i	The rate of change at the output at the change at the input
Hysteresis	any	Permanent deviation from zero for zero input
Offset voltage	mV	Output voltage obtained for zero (reference) input conditions
Temperature coefficient	ppm K^{-1}	The rate of change of reading as a function of temperature
Repeatability	%	Measure of agreement between successive measurement (same conditions)
Reproducibility	%	Measure of agreement between successive measurement (changed conditions)
Temperature range	T(K)	Operating span for specified accuracy

Static errors - error reducing techniques

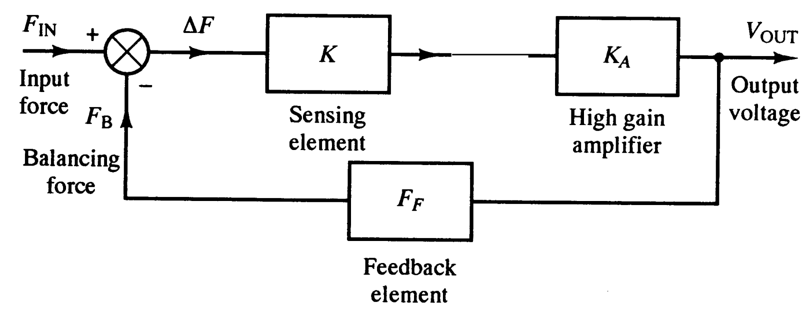
Compensating non-linear element

$$V_{out} = Kk_{cor}F_{in}$$



High gain negative feedback

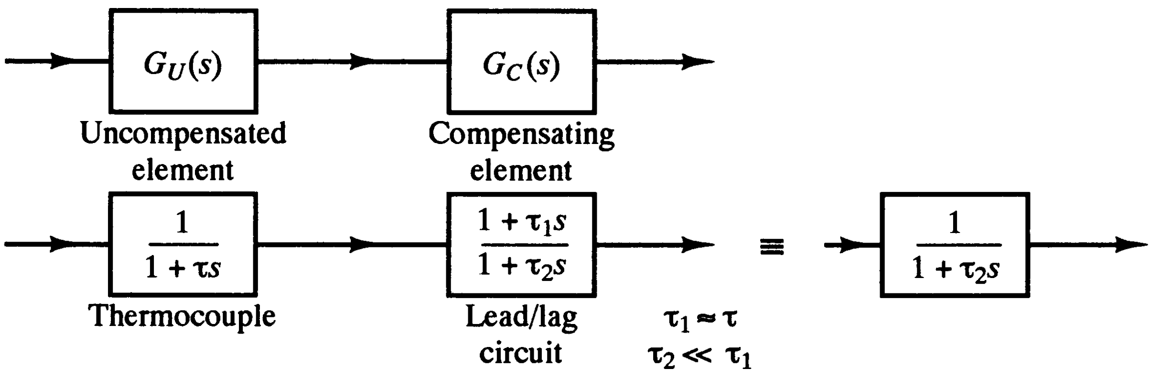
$$V_{out} = \frac{Kk_A}{1+Kk_Ak_F}F_{in} \approx \frac{1}{k_F}F_{in} \qquad if \quad Kk_Ak_F >> 1$$



Dynamic errors - Compensating techniques

⁕ Open-loop dynamic compensation

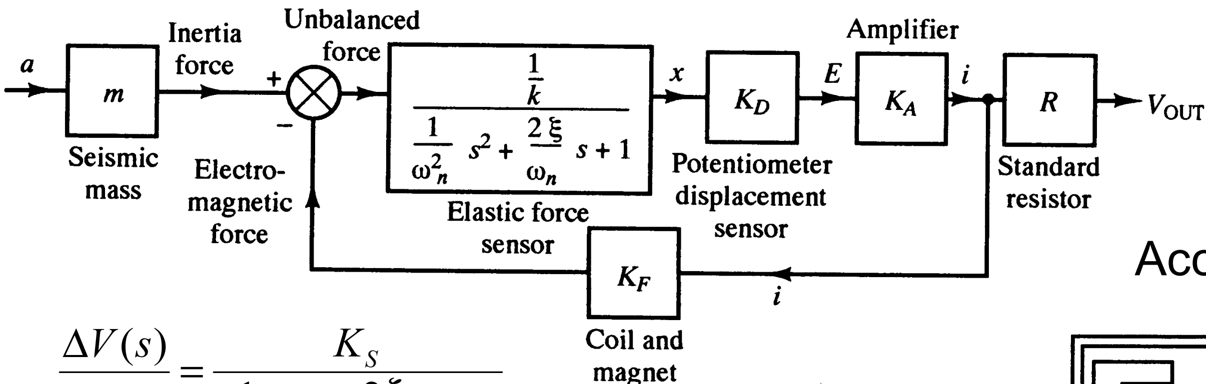
$$V_{out}(\omega) = G_u(\omega) G_c(\omega) F_{in}(\omega)$$



Dynamic errors - Compensating techniques

* High gain negative feedback

$$V_{out}(\omega) = \frac{G(\omega)G_A(\omega)}{1+G(\omega)G_A(\omega)G_F(\omega)} F_{in}(\omega) \approx \frac{1}{G_F(\omega)} F_{in}(\omega) \quad for \quad \omega_{\min} < \omega < \omega_{\max} \quad |G(\omega)G_A(\omega)G_F(\omega)| >> 1$$

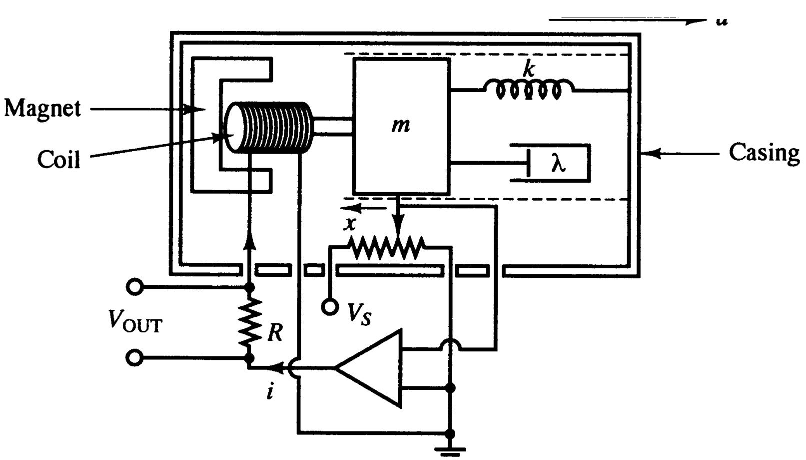


$$\frac{\Delta V(s)}{\Delta a(s)} = \frac{K_S}{\frac{1}{\omega_{ns}^2}s^2 + \frac{2\xi_S}{\omega_{ns}}s + 1}$$

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

$$\xi_S = \xi \sqrt{\frac{k}{K_A K_D K_F}}$$

Accelerometer



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 al 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*

I/Out		Modulating			
Energy domain	Self-generating	Resistor, inductance, capacitive	Diode	Transistor	Examples of smart transducers
Radiation	Volta effect, solar cell	Photoconductor	Photodiode	Phototransistor	Photo-IC CCD
Mechanical	Not known	Piezoresistivity	Piezojunction	Piezotransistor	Accelerometer Piezo IC
Thermal	Seebeck effect, thermocouple	R = f(T)	Reverse biased I_{rev}= f(T)	Forward biased U_{BE}= f(T)	Temeperature IC
Electrical	Thermal energy, resistance	Electric field MOSFET	Electric field FET	Dual gate MOSFET	All types of IC
Magnetic	Maxwell diffused coil	Magnetoresistor	Magnetic diode	Hall effect	Hall IC
Chemical	Galvanic	Ion concentration	Not known	ISFET	Smart nose

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