Sensors and Actuators
Sensor Physics

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PIEZOELECTRIC AND PYROELECTRIC SENSORS

(Chapter 3.6, 3.7)
Piezoelectric and pyroelectric sensor applications
Piezoelectric effect

- crystalline materials generate electric charge when subjected to stress (piezoelectric effect)
- pyroelectric effect closely related to piezoelectric effect
- both effects are reversible

![Energy Conversion Diagram]

piezoelectric effect

- piezoelectric effect exists in
  - natural crystals (e.g. quartz - SiO₂)
  - artificially polarized (poled) ceramics and polymers
Piezoelectric effect – explanatory model

- quartz crystal model as helix
  - one silicon and two oxygen atoms alternating around helix
  - single cell (slice of helix) contains 3 Si atoms and 6 O atoms
- Si has 4 positive charges, O has 2 negative charges
- cell is electrically neutral
- compressing force in X direction leads to positive charge at top
- stretching force in Y direction leads to negative charge at top
Thermal poling of piezoelectric material

- Crystal cells can be considered electrical dipoles
  - Cells may be naturally oriented along crystal axes (e.g. quartz)
  - Dipoles may be oriented randomly, but dipoles can be “poled” into required orientation

- Thermal poling is most commonly used technique for poling
  - Warm up crystalline material till just below Curie temperature
  - Apply strong electrical field to align dipoles
  - Cool material down
  - Remove electrical field
  - Orientation of dipoles is “frozen” in direction of the electrical field
Piezoelectric sensor

- thermal poling creates small charge on the plates
  - quickly dissipated by free charges from the surrounding atmosphere which are attracted to the plates
  - after a very short time, there will be no charge on the plates

- stress disturbs balanced state
  - charge will appear on the plates

- internal leakage will neutralize charge when stress is maintained
  - piezoelectric sensor is sensitive to change, not to steady-state
Piezoelectric sensor

- charge on electrodes due to force $F$
  
  $$ Q = d \frac{F}{l \cdot h} (w \cdot l) $$

  - $d$ – piezoelectric charge constant (pC/N)

- charge constant depends on position of force and electrodes

- capacitor relates charge and voltage
  
  $$ Q = CV \Rightarrow V = \frac{Q}{C} \left\{ \Rightarrow V = d \frac{F}{l \cdot h} (w \cdot l) \frac{h}{\varepsilon_0 \varepsilon_r \cdot w \cdot l} = d \frac{F}{l \cdot \varepsilon_0 \varepsilon_r} \right\} $$

- crystal has conductive properties

- resistive path between electrodes
  
  $$ R = \rho \frac{h}{w \cdot l} $$
Piezoelectric sensor

- electrical equivalent circuit for sensor

1) force generates voltage

\[ V = d \frac{F}{l \cdot \varepsilon_0 \varepsilon_r} \]

2) charge collects on plates

\[ C_s = \varepsilon_0 \varepsilon_r \frac{w \cdot l}{h} \]

3) charge leaks through internal resistance

\[ R_s = \rho \frac{h}{w \cdot l} \]

- capacitor and resistor form HPF

\[ \left| \frac{v_o}{v_s} \right| = \frac{j \omega R_s C_s}{1 + j \omega R_s C_s} = \frac{\omega R_s C_s}{\sqrt{1 + (\omega R_s C_s)^2}} \]

- cut-off frequency

\[ \omega_c = \frac{1}{R_s C_s} \]
Piezoelectric sensor

- electrical equivalent circuit for sensor
  - 1) force generates voltage
    \[ V = d \frac{F}{l \cdot \varepsilon_0 \varepsilon_r} \]
  - 2) charge collects on plates
    \[ C_s = \varepsilon_0 \varepsilon_r \frac{w \cdot l}{h} \]
  - 3) charge leaks through internal resistance
    \[ R_s = \rho \frac{h}{w \cdot l} \]

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- cut-off frequency
  \[ \omega_c = \frac{1}{R_s C_s} \]

- sensor only sensitive to changing force

- sensor has no DC response
Piezoelectric sensor

example – piezoelectric sensor

- $h = 52 \, \mu m$, $l = 10 \, cm$, $w = 10 \, cm$
- $d = 23 \, pC/N$, $\varepsilon_r = 12$, $\varepsilon_0 = 8.85 \, pF/m$, $\rho = 10 \, T\Omega \cdot m$

what is the output voltage when a weight of 40 kg is applied to the sensor?

what is the minimal frequency of a dynamic compression for an allowed amplitude error of 5%?
Piezoelectric sensor

example – piezoelectric sensor

- \( h = 52 \ \mu m, \ l = 10 \ \text{cm}, \ w = 10 \ \text{cm} \)
- \( d = 23 \ \text{pC/N}, \ \varepsilon_r = 12, \ \varepsilon_0 = 8.85 \ \text{pF/m}, \ \rho = 10 \ \text{T}\Omega\cdot\text{m} \)

what is the output voltage when a weight of 40 kg is applied to the sensor?

- output voltage of the sensor

\[
V = d \frac{F}{l \cdot \varepsilon_0 \varepsilon_r} = (23 \text{ pC} / \text{N})(\frac{40 \cdot 9.8 \text{ N}}{0.1 \text{ m} \cdot (12 \cdot 8.85 \text{ pF/m})}) = 849 \text{V}
\]

what is the minimal frequency of a dynamic compression for an allowed amplitude error of 5%?

\[
\left| \frac{v_o}{v_s} \right| = \frac{\omega R_s C_s}{\sqrt{1 + \left( \frac{\omega R_s C_s}{\omega} \right)^2}} = \frac{1}{\sqrt{1 + \left( \frac{\omega_c}{\omega} \right)^2}}
\]

requirement: \[
\frac{1}{\sqrt{1 + \left( \frac{\omega_c}{\omega} \right)^2}} > 0.95
\]
Piezoelectric sensor

example – piezoelectric sensor

- $h = 52 \, \mu m$, $l = 10 \, cm$, $w = 10 \, cm$
- $d = 23 \, pC/N$, $\varepsilon_r = 12$, $\varepsilon_0 = 8.85 \, pF/m$, $\rho = 10 \, T\Omega \cdot m$

what is the minimal frequency of a dynamic compression for an allowed amplitude error of 5%?

$$R_s = \rho \frac{h}{w \cdot l} = (10 \cdot 10^{12} \Omega \cdot m) \frac{52 \, \mu m}{0.1 \, m \cdot 0.1 \, m} = 52G\Omega$$

$$C_s = \varepsilon_0 \varepsilon_r \frac{w \cdot l}{h} = 12 \cdot 8.85 \, pF/m \cdot \frac{0.1 \, m \cdot 0.1 \, m}{52 \, \mu m} = 20.4nF$$

constraint:

$$\frac{1}{\sqrt{1 + \left( \frac{\omega_c}{\omega} \right)^2}} > 0.95$$

$$\Rightarrow \omega > 3227.4 \, rad / s$$

$$\Leftrightarrow f > 20278.4Hz$$
Signal processing

- Charge amplifier circuit
  - $R$ provides bias current path
  - Output voltage
    \[ v_o = -\frac{C_x}{C} v_e \]

- Charge amplifier can be used to get charge of piezoelectric sensor
  \[
  v_o = -\frac{C_s}{C} v_s \quad \Rightarrow \quad v_o = -\frac{C_s}{C} \frac{Q_s}{C_s} = -\frac{Q_s}{C}
  \]
  \[
  v_s = \frac{Q_s}{C_s} \quad \Leftrightarrow \quad v_o = -\frac{Q_s}{C}
  \]
  \[
  Q_s = d \frac{F}{l \cdot h} (w \cdot l) \quad \Rightarrow \quad v_o = -d \frac{F}{l \cdot h} (w \cdot l) \frac{1}{C}
  \]
example – piezoelectric sensor

- $h = 52 \, \mu m, \, l = 10 \, cm, \, w = 10 \, cm$
- $d = 23 \, pC/N, \, \varepsilon_r = 12, \, \varepsilon_0 = 8.85 \, pF/m, \, \rho = 10 \, T\Omega \cdot m$
- $C_s = 20.4 \, nF, \, R_s = 52 \, G\Omega$

what value should the capacitor $C$ have to get an output sensitivity of $-10 \, mV/Pa$?

$$v_o = -d \frac{F}{l \cdot h} (w \cdot l) \frac{1}{C} \Rightarrow -10 mV = -23 pC/N(1N/m^2)(0.1m \cdot 0.1m) \frac{1}{C} \Rightarrow C = 23 pF$$
Tactile sensors

- Tactile sensors are often built with piezoelectric films.
- Piezoelectric film can be used in active or passive mode.

- Active piezoelectric tactile sensor
  - Two layers of piezoelectric film are laminated to a compression film in the center.
  - Center film is used for acoustic coupling between outer layers.
  - Piezoelectric films respond with an electrical signal to a deformation.

*Note: Thickness of sensor is greatly exaggerated for clarity.*
Tactile sensors

- passive piezoelectric tactile sensor
  - PVDF film strips embedded in rubber skin
  - no excitation signal needed since sensor is passive
  - sensor response is proportional to rate of stress
  - magnitude of stress cannot be measured directly

- operation
  - force applied to piezoelectric strip leads to output voltage
  - polarity of voltage depends on direction of force
  - amplitude of voltage depends on speed of vibration
Piezoelectric sensor/actuator

- **piezoelectric speakers**
  - used in many electronics devices (e.g., computer, watch)
  - piezoelectric speakers are resistant to overloads
  - provide direct conversion of electrical to mechanical energy
    - other speaker use magnetic field to move cone
  - their frequency response is inferior to that of other technologies
    - generally used in single frequency (beeper) applications

- piezoelectric speaker can also be used to convert mechanical energy (sound) to electrical energy
- **actuator** (speaker) can be used as **sensor** (microphone)
Pyroelectric effect

- **pyroelectricity** is the ability of certain materials to generate an electrical charge in response to heat flow.

- pyroelectric effect is closely related to piezoelectric effect.

![Diagram showing energy conversion between pyroelectric and piezoelectric effects]

- Electrical energy
- Thermal energy
- Kinetic energy
- Piezoelectric effect
- Pyroelectric effect
Pyroelectric material

- material has center of symmetry when each atom in an imaginary unit cell has an exact twin opposite to it on a line through an imaginary center point

![Symmetric cell and non-symmetric cell](image)

- force on symmetric cell will never cause a dipole to appear
- piezoelectric materials have no center of symmetry
  - some piezoelectric materials show temperature dependent polarization
  - these materials are called pyroelectric
Operation of a pyroelectric sensor

- pyroelectric sensor
  - same construction as piezoelectric sensor
  - passive (self-generating) sensor
  - responds to change in temperature (dynamic)
  - no response to temperature (steady-state)
pyroelectricity is the ability of certain materials to generate an electrical charge in response to heat flow

pyroelectricity caused by two mechanisms
  - mechanism 1: temperature changes cause shortening or elongation of individual dipoles
  - randomness of dipole orientation changes due to thermal agitation
Operation of a pyroelectric sensor

- Pyroelectricity is the ability of certain materials to generate an electrical charge in response to heat flow.

- Pyroelectricity caused by two mechanisms:
  - Mechanism 2: strain due to thermal expansion creates piezoelectric effect.
    - Thermal radiation absorbed by sensor as heat.
    - Heat propagates to pyroelectric material.
    - Creates thermally induced stress.
Pyroelectric sensor

- pyroelectric sensor connected to a resistor $R_b$
- ignore internal leakage since $R_b << R_s$
- capacitor discharged through $R_b$
- measure output of sensor as
  - current through $R_b$ (flow of charge)
  - voltage across $R_b$ (charge build-up)

$R_b$ $i_s$ $C_s$ $R_b$ $V_o$

heat induced current
current response
relative output

charge collected on plates
voltage response
Pyroelectric sensor

- pyroelectric sensor exposed to step function of heat
- electric charge \((Q)\) reaches peak value instantaneously
- thermal induced polarization occurs initially only at outermost layers
  - outer layers reach maximal temperature instantaneously
  - creates highest thermal gradient and maximal polarization
- electric charge decays as heat propagates through material
- part of heat lost to surrounding environment
  - result in voltage \(V_0\)
  - use sensor to measure (constant) heat flow
Construction of pyroelectric sensors

- Pyroelectric sensors belong to class of **passive infrared sensors**
- Thermal energy reaches sensor element through window
- Often two sensor elements for compensation of mechanical stress
Signal processing

- solution 1: voltage follower
  - voltage across bias resistor $R_b$ is followed by voltage $V_{out}$
  - response time depends on electrical time constant ($\tau_e = C \cdot R_b$)
    - typically 2 seconds
    - upper cut-off frequency around 0.08Hz
    - only suitable for slow moving objects (e.g. people)
  - offset voltage at output due output resistor
Signal processing

- solution 2: **current-to-voltage converter**
  - output voltage follows shape of current
  - faster response
  - insensitive to sensor capacitance
  - feedback forces output voltage of sensor to zero