IN 221 (AUG) 3:0
Sensors and Transducers
Electromagnetic Sensors and Transducers
Lecture 1

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Scope

Sensors and transducers

- Sensors and transducers which can be studied using concepts from *electromagnetics*.
- Sensors and transducers that use electric or magnetic fields.

Interfacing Electronics

- Analogue signal conditioning
- Conversion to digital form

Two textbooks

Ian Sinclair

Sensors and Transducers

H. K. Tönshoff and I. Inasaki (Editors)

Sensors in Manufacturing

Example Electromagnetic Sensors

- Microphone
- Capacitive touch sensor
- LVDT
- Piezoelectric sensors
- Coil
- Resistance thermometer
- Hall sensor
- Strain gauge
- MEMS Sensors
- Antenna

Example Electromagnetic Transducers

- Loudspeakers
- Motors
- Solenoids and relays
- Piezoelectric actuators
- MEMS actuators
- Coil for producing magnetic field
- Antenna
- Electric heater

Sensors Based on Change in Resistance

- Strain Gauge
- Load Cell
- Platinum Resistance Thermometer
- Thermistor
- Light Dependent Resistor (LDR)
- Some types of MEMS accelerometers

Sensors Based on Change in Inductance

- Proximity sensors using coils
- Some types of pressure sensors
- Linear Variable Differential Transformer (LVDT)

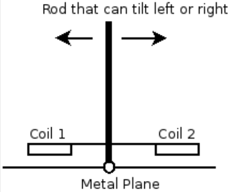
Sensors Based on Change in Capacitance

- MEMS accelerometers
- Pressure sensors
- Angle sensors
- Capacitor microphone

Usually there is no simple formula

No simple formula

Inductive tilt sensor:



Simple formula

Small air-core coil sensing a changing magnetic field.

- Coil area is known.
- Number of turns is known.

Note: Putting an iron core would make the sensor more sensitive, but now the calculations will be harder.

Calibration and Characterization

Whether the sensor or transducer output can be given by a formula or not, we always need to *calibrate* and characterize the device.
Output vs. input measurements for …

- …a number of different input values,
- …a number of different environmental conditions,
- …a number of different device samples, …

Miniaturization: Advantages and challenges

- Miniaturization: Making sensors smaller in size
- Simplification: Make the construction as simple as possible

Advantages

Miniaturization makes sensors:

- More precise in location
- Faster in response
- Cheaper
- More reliable
- More durable

Challenges

The output signal amplitude usually becomes smaller.

Electronics: Signal conditioning concepts

- Amplification
- Filtering
- Bridge or differential arrangement
- Modulation and synchronous or phase sensitive detection, also known as *lock-in amplifier*

Amplification and Filtering

Amplification

- DC vs. AC: AC amplifier is easier to build.
- Broadband vs. Tuned: Tuned amplifiers are less affected by noise.
- Chopper: Converts DC to AC.
- Single input vs. Differential input
- Can often be integrated with the sensor.

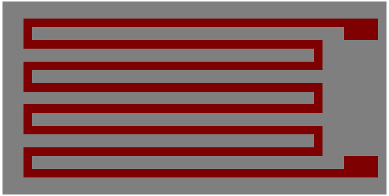
Filtering

- Removes unwanted noise.
- Even simple RC lowpass filter or LC bandpass filter can be quite effective.

Differential or Bridge Arrangement

- Two identical sensors as arms of a bridge circuit.
- Of course no two sensors are exactly identical.
- Bridge with nearly identical sensors is better than no bridge.
- Removes common mode signal.
- Examples: Strain gauge, LVDT

Strain Gauge



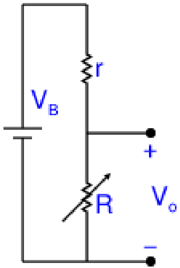
Metal Foil Strain Gauge
Change in resistance is proportional to strain.

Gauge Factor

$$\mathrm{GF} = \frac{\Delta R / R_{\mathrm{G}}}{\epsilon} \tag{1}$$

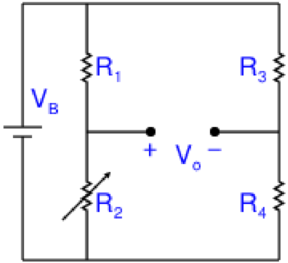
ΔR: Change in resistance caused by strain
R_{G}: Resistance of the strain gauge when there is no deformation
ϵ: Strain = (Change in length) / (Length)
For metallic foil gauges, GF is a little over 2.

Strain Gauge: Voltage Divider Arrangement



Disadvantages: Too much offset!
Let the battery voltage be 5 V, and both *R* and *r* be 100 ohms. The change in *R* may at most be 1 ohm. Then the change in output is 12.44 mV over a base value of 2.5 V. Very hard to use.
Not used.

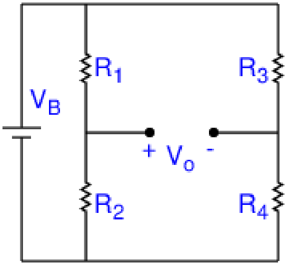
Strain Gauge: Bridge Arrangement



Advantage: No offset output. With minor adjustment, one can make the output nearly proportional to the input.

Much used.

Wheatstone Bridge Arrangement



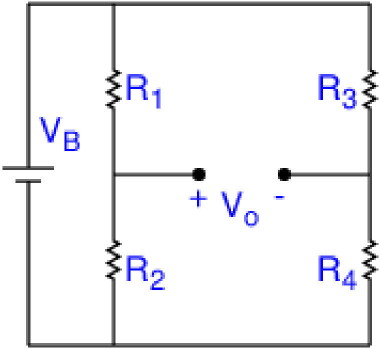
One or more of the bridge arms can be a strain gauge.

Example Usage with a Beam:

R_1, or R_4, or both can be mounted above the beam. R_2, or R_3, or both can be mounted below the beam.

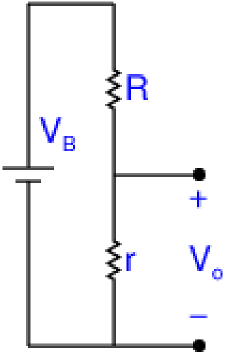
If all resistors in this diagram are strain gauges, then the output will not be affected by a change in the temperature.

Wheatstone Bridge Output



$$V_o = V_B\left(\frac{R_2}{R_1+R_2} - \frac{R_4}{R_3+R_4}\right) \tag{2}$$

Voltage Divider



$$V_o = V_B \frac{r}{R + r}$$

Voltage Divider Analysis

$$V_o = V_B \frac{r}{R + r} \tag{3}$$

- The resistance *r* is a function of some physical input such as temperature or strain.
- The change in *r* is small and is usually proportional to the reference value of *r*.
- So it is the fractional change in *r* that is determined by the change in the physical quantity that is being sensed.
- Fractional change in common language: Percentage change or per unit change

Question: What value of *R* maximizes the change in the output for a given fractional change in *r*?

Rates of Change

Rate of change of V_o with respect to r:

$$\frac{\partial V_o}{\partial r} = \frac{\partial \left(V_B \frac{r}{R+r} \right)}{\partial r} = V_B \frac{R}{(R+r)^2} \tag{4}$$

Rate of change of V_o with respect to fractional change in r:

$$\frac{\partial V_o}{\frac{1}{r}\partial r} = r \frac{\partial V_o}{\partial r} = V_B \frac{Rr}{(R+r)^2} = \frac{1}{4} V_B \left[1 - \frac{(R-r)^2}{(R+r)^2} \right] \tag{5}$$

This is maximized when $R = r$.

Best Operating Conditions

- So the best value of R is the nominal reference value of r.
- Note that even though the output is proportional to V_B, to keep the components safe, V_B cannot be made too high.
- Using higher values may cause heating of the strain gauge elements.

Processing small AC signals

- In many sensors, a change in the physical quantity to be measured is converted to a change of either capacitance or inductance.
- The capacitance or inductance is then made part of an AC bridge.
- The output is a small AC signal.

Accelerometer: Sensing the Displacement

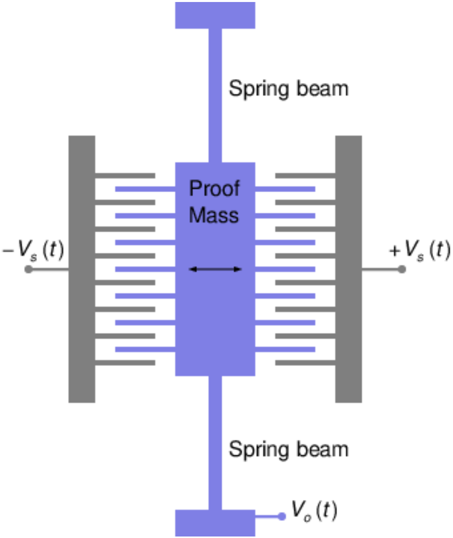
Differential Capacitance Arrangement

- The proof mass acts as an electrode that moves between two other electrodes.
- It forms two capacitances that are equal when there is no displacement.
- The difference between the capacitances is proportional to the displacement, provided the displacement is small.

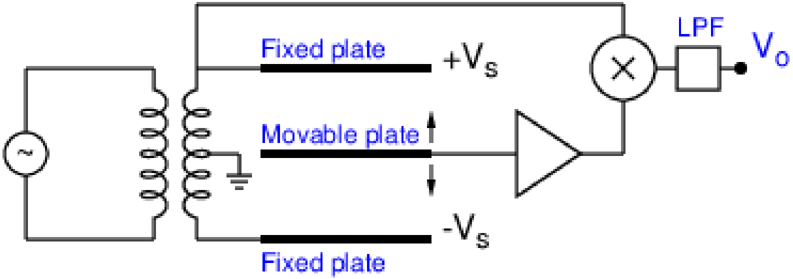
Challenge

- The devices are very small.
- The change in capacitance is very small.
- How do we reliably detect this small change?

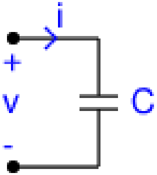
Accelerometer: Interdigitated Structure



Capacitive Sensor: Block Diagram



Capacitance



Q is the stored charge in the capacitor. $Q = Cv$.

$$C = \frac{Q}{v}$$

$$i = \frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{\mathrm{d}(Cv)}{\mathrm{d}t} = C\frac{\mathrm{d}v}{\mathrm{d}t} + v\frac{\mathrm{d}C}{\mathrm{d}t}$$

If C is constant, $i = C\frac{\mathrm{d}v}{\mathrm{d}t}$.

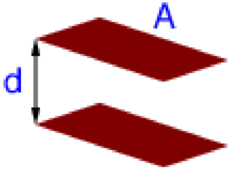
Sinusoidal Excitation

Let C be constant, and $v(t) = V_p \cos(2\pi ft) = V_p \cos(\omega t)$.
Here V_p is the *peak value* of the applied sinusoidal voltage. f is the *frequency* of the source, and ω is its *angular frequency*.
Then

$$i(t) = -2\pi fCV_p \sin(2\pi ft) = -\omega CV_p \sin(\omega t) \tag{6}$$

Peak value of the current is ωCV_p. It leads the voltage by a right angle.

Parallel Plate Capacitor

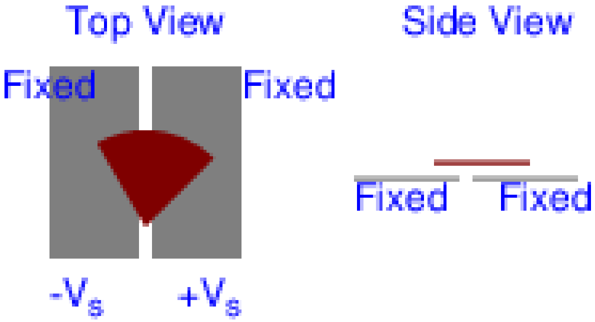


Capacitance

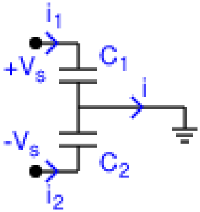
$$C = \frac{\epsilon A}{d} = \frac{\kappa \epsilon_0 A}{d} \tag{7}$$

Electric constant: $\epsilon_0 = 8.854\,187\,82 \times 10^{-12}\,\mathrm{F\,m^{-1}}$
κ: Dielectric constant of the medium separating the plates.
κ is 1 for free space and air.
This formula neglects fringing field effects.

Capacitive Angle Sensor Electrodes



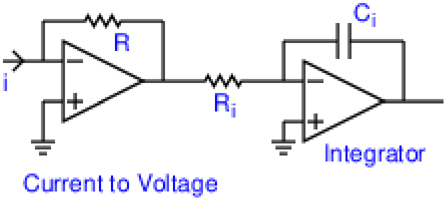
Output Current is Proportional to ΔC



$$i = i_1 + i_2 = C_1 \frac{\mathrm{d}V_s}{\mathrm{d}t} + C_2 \frac{\mathrm{d}(-V_s)}{\mathrm{d}t} = (C_1 - C_2)\frac{\mathrm{d}V_s}{\mathrm{d}t} = \Delta C \frac{\mathrm{d}V_s}{\mathrm{d}t} \tag{8}$$

Note: The movable plate output is usually connected to a current to voltage converter.
The output is proportional to ΔC, which in turn is proportional to (i) the angle in case of the angle sensor, or (ii) the displacement of the proof mass in case of the MEMS accelerometer.

Circuit for Amplifier

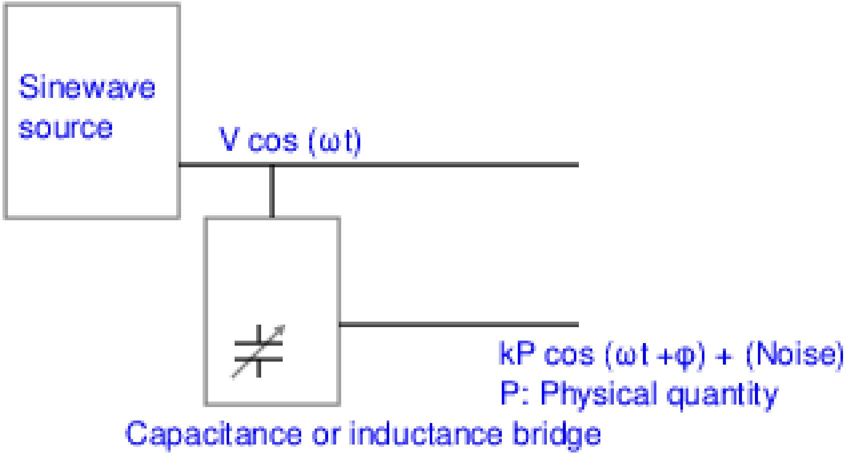


The integrator is optional.

Accelerometer or Pressure sensor

- A flexible electrode moves a small distance that is proportional to the acceleration or the pressure difference to be measured.
- This small movement changes a capacitance or an inductance.
- With a bridge arrangement, this sensor can be . . .
  - . . . sensitive,
  - . . . reliable,
  - . . . and quite linear.

How do we measure *P*?



Sinewave source

V cos (ωt)

kP cos (ωt +φ) + (Noise)

P: Physical quantity

Capacitance or inductance bridge

How do we measure P?

Physical quantity to be measured: P
Output: (Signal) + (Noise)
Signal: $kP\cos(\omega t + \phi)$

$$v_o = kP\cos(\omega t + \phi) + \text{(Noise)}$$

- The signal output may be quite small.
- It is still proportional to P.
- Here, ϕ is a constant phase shift that is specific to the bridge instrumentation.

Trouble with simple amplification

- In industrial settings, the noise strength may be comparable to the signal. It may sometimes be greater.
- If we simply amplify the output, the noise will also be amplified.
- Filtering will decrease the noise, but that may not be enough.
- Cases like this are very common.

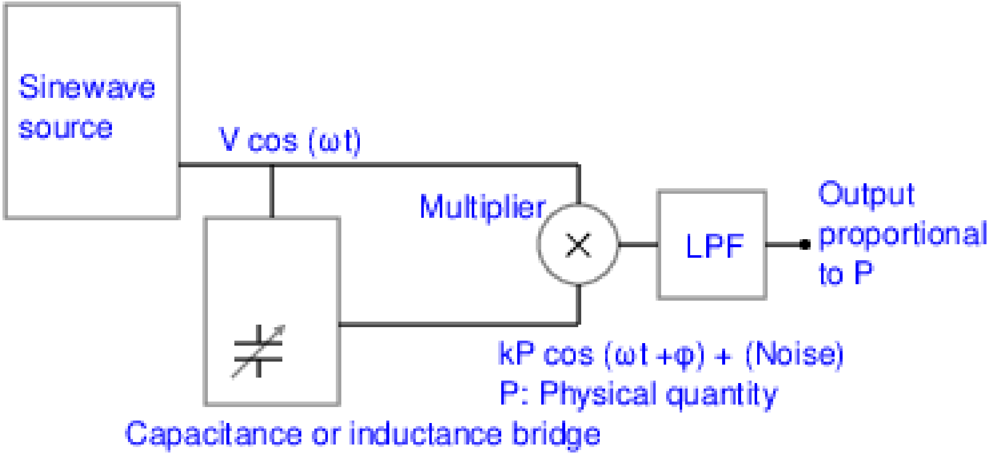
Lock-in Amplifier

- Solution: Use a *lock-in amplifier*.
- Other names:
  - Synchronous detection
  - Phase-sensitive detection
- Implementation: Multiply the bridge output v_o with the reference sinewave and average (low-pass filter) it.
- What is the resulting output?

Lock-in Amplifier Mathematics

Product is $V\cos(\omega t) \times kP\cos(\omega t + \phi)$.
Same as $kVP\cos(\phi)\cos^2(\omega t) - kVP\sin(\phi)\sin(\omega t)\cos(\omega t)$.
Average of $\cos^2(\omega t)$ is $\frac{1}{2}$.
Average of $\sin(\omega t)\cos(\omega t)$ is 0.
So the average of the product is $\frac{1}{2}kVP\cos(\phi)$.
The output is proportional to P.

Lock-in Amplifier: Block diagram



Sinewave source

V cos (ωt)

Multiplier

×

LPF

Output proportional to P

kP cos (ωt +φ) + (Noise)

P: Physical quantity

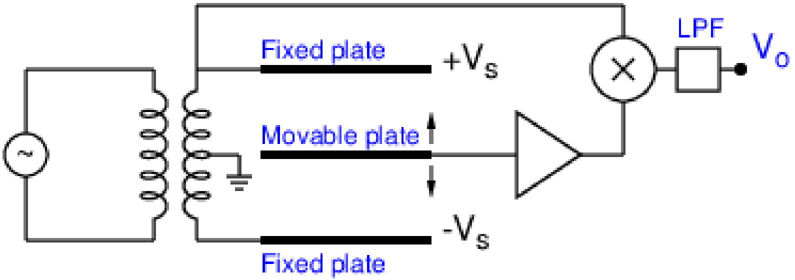
Capacitance or inductance bridge

Essential electronics for sensors

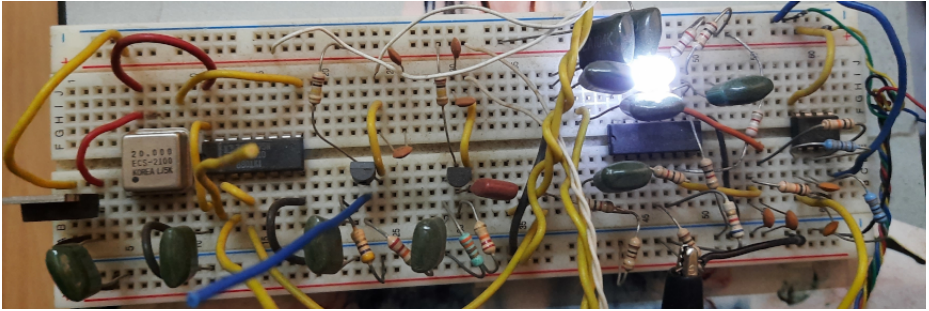
Many sensors owe their success to the use the following electronic subsystems.

- Amplifier
- Filter
- Bridge or differential arrangement
- Lock-in amplifier

Capacitive Sensor: Block Diagram



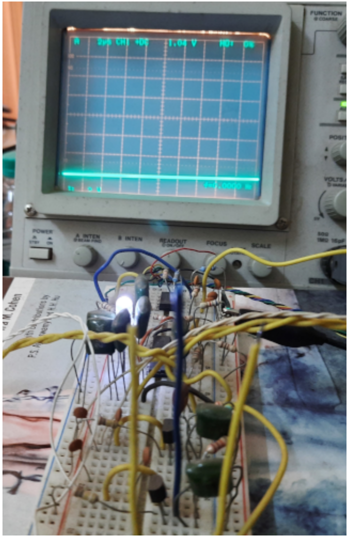
Example Differential Capacitive Sensor



Capacitive Sensor: Circuit Details

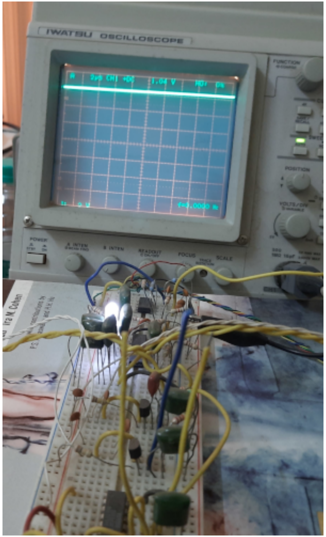
- 20 MHz crystal oscillator output given to a divide by 2 counter.
- 1/4 of 74LS175 D flip-flop used to implement the divide by 2 counter.
- Q_0 output is $+V_s(t)$, $\overline{Q}_0$ output is $-V_s(t)$
- The two yellow wires sticking out are the fixed plates.
- The blue wire sticking out is the movable plate.
- The amplifier is a two-transistor tuned amplifier.
- MC1496 is used as the multiplier.
- Uses RC LPF.
- NE5532 is the final amplifier after the LPF.

Blue Wire Closer to the Left Yellow Wire



Blue Wire Equidistant from the Yellow Wires

Blue Wire Closer to the Right Yellow Wire



Doubts and Questions

- Ask in class
- Write to `amohanty@iisc.ac.in`
- Inform any of the TAs