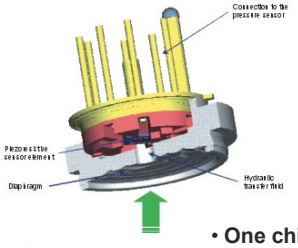
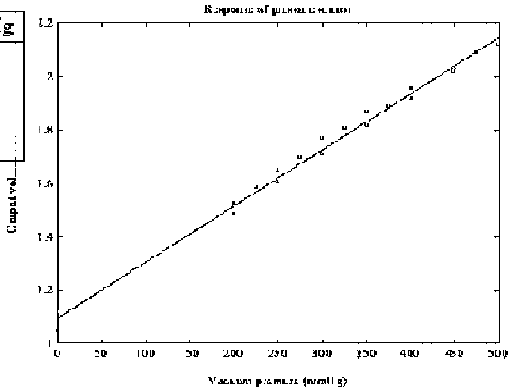
Piezoresistive Transduction - Circuit

Resistor	R at STP	R at 500 mmHg
R_a	151.8	153.8
R_b	148.7	147.7
R_c	151.4	152.4
R_d	151.1	150.9







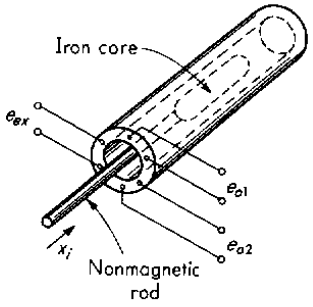
- One chip Si-Piezoresistive sensor and signal conditioning
- Pressure range: up to 5,2 bar Absolute
- Operating temperature: -40 to 125 °C
- Supply voltage: 5 V ± 0.25 V
- Transfer function: linear, ratiometric
- Accuracy over full-scale: 1 % full span (10 to 85 °C)

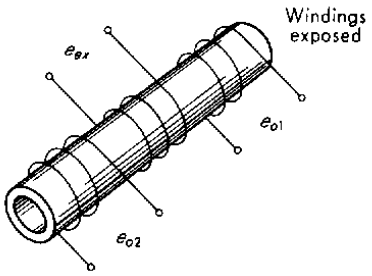
Position, Displacement, and Level

- Potentiometric Sensors
- Gravitational Sensors
- Capacitive Sensors
- Inductive and Magnetic Sensors
  - LVDT and RVDT
  - Eddy Current Sensors & Transverse Inductive Sensor
  - Hall Effect Sensors & Magnetoresistive Sensors
- Optical Sensors
  - Optical Bridge & Proximity Detector with Polarized Light
  - Fiber-Optic Sensors & Fabry–Perot Sensors
  - Grating Sensors & Linear Optical Sensors (PSD)
- Ultrasonic Sensors
- Radar Sensors :
  - Micropower Impulse Radar & Ground-Penetrating Radar
- Thickness and Level Sensors :
  - Ablation & Thin-Film & Liquid-Level Sensors

Displacement Sensor

Linear Variable Differential Transformer (LVDT)





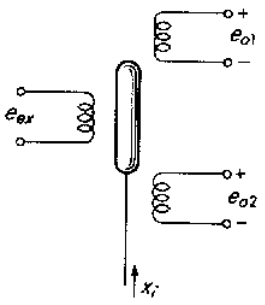
Basic Principles:

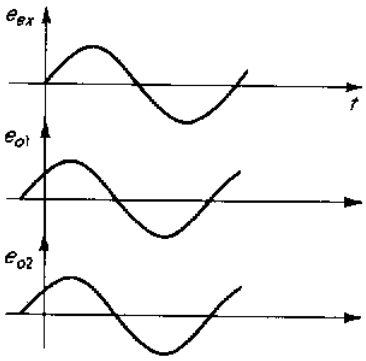
a. **AC current flows through "primary" coil, due to excitation voltage e_{ex}.**
b. **Current is "induced" through a pair of secondary coils (e_{o1}, e_{o2}).**
c. **The frequency of the induced AC current is the same as the excitation frequency.**
d. **The amplitude of the induced current in each secondary coil depends upon the location of the movable "core".**

Displacement Sensor

Linear Variable Differential Transformer (LVDT)

If core is located in "null" position then secondary voltages are equal, as illustrated below.



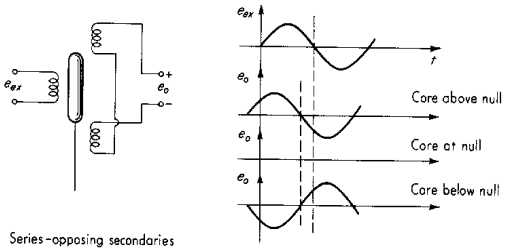


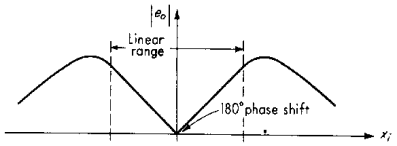
Core in null position

Linear Variable Differential Transformer (LVDT)

If the two secondary coils are connected in anti-series (+ → + and - →-) then the resulting output is the difference between the outputs of the individual seconary coils. The amplitude depends upon the position of the rod.

(There is also a Phase shift between e_{ex} and e_o as we will show later)





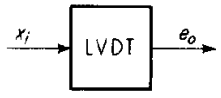
Linear Variable Differential Transformer (LVDT)

The input, x_i, is the MOTION of the rod to which the core is connected.

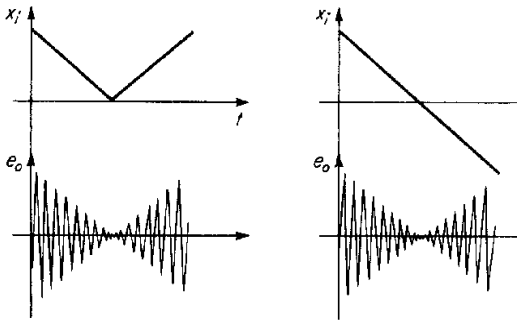
The output, e_o, is the voltage difference between the induced voltages in the two secondary loops.

Note: The output is inherently AM modulated

(The "carrier" is AC excitation of the primary loop).



e_o record is "visually" the same for two very different x_i records



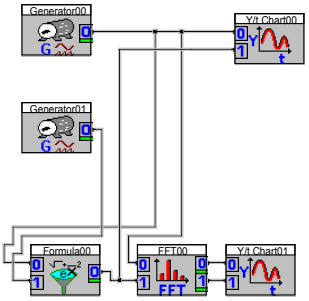
Note: Phase Shift occurs as x_i crosses "null" point

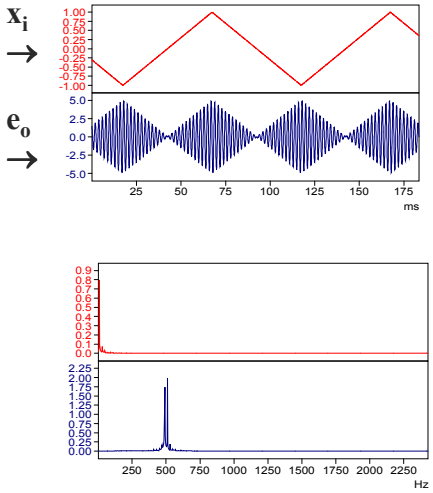
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PRINSIP DASAR

Linear Variable Differential Transformer (LVDT)

Simulated Output



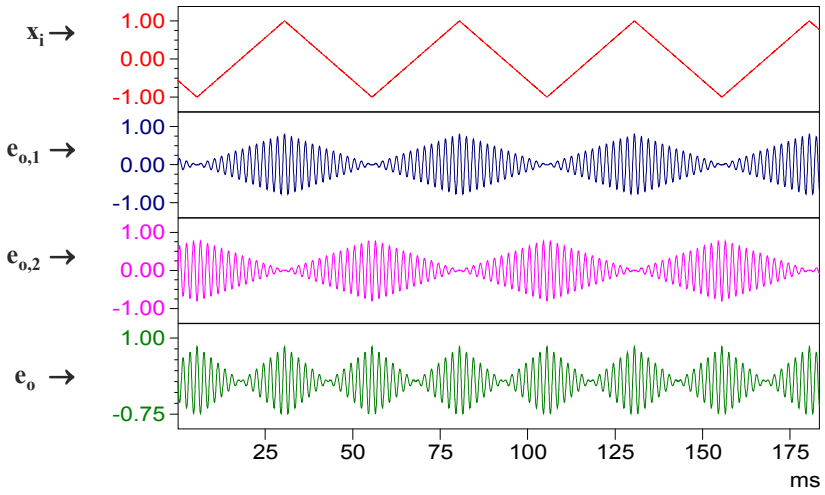


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SISTEM PENGUKURAN

PRINSIP DASAR

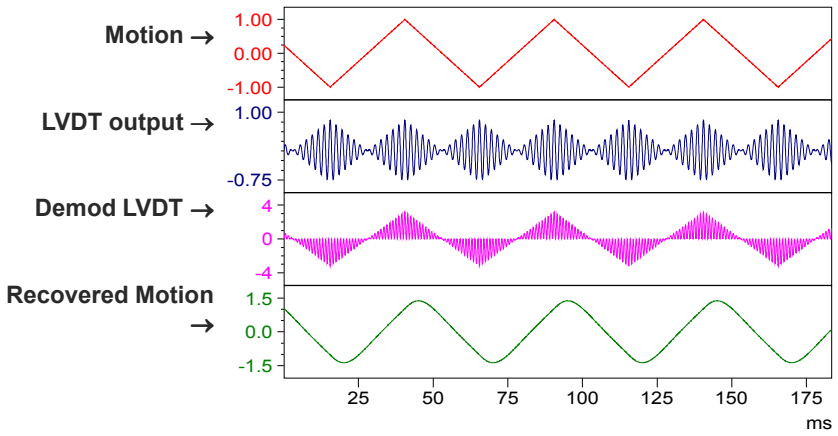
Linear Variable Differential Transformer (LVDT)



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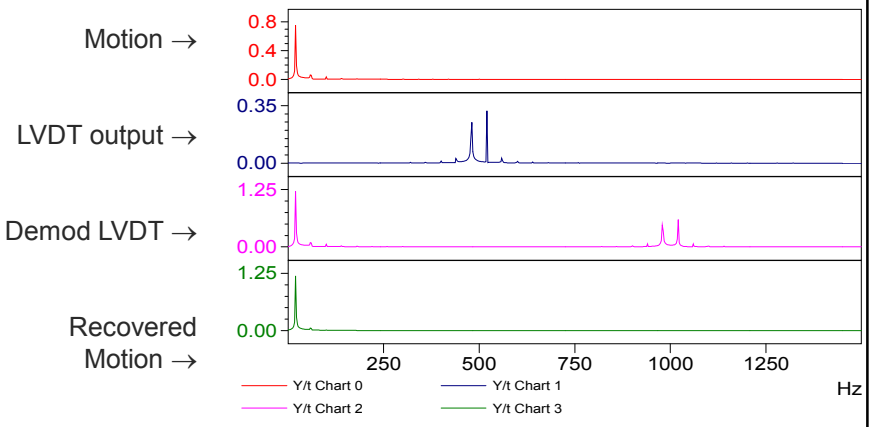
Linear Variable Differential Transformer (LVDT)

How Do We Recover the LVDT Signal?



Linear Variable Differential Transformer (LVDT)

LVDT Signal Recover – Frequency Domain



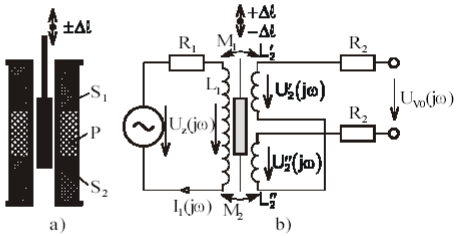
LVDT = Linear Variable Differential Transformer

$$U_2'(j\omega) = j\omega M_1 I_1(j\omega), U_2''(j\omega) = j\omega M_2 I_1(j\omega)$$

$$I_1(j\omega) = \frac{U_Z(j\omega)}{R_1 + j\omega L_1}$$

for $R_1 << j\omega L_1$ (voltage driven):

$$U_V(j\omega) = (M_1 - M_2)\frac{U_Z}{L_1}$$



Synchronnous detector:

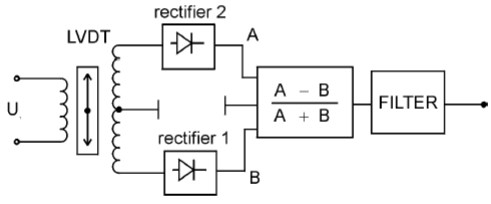
☺ elimination of feed-through via parasitic capacitances

☺ indicates the direction of displacement by polarity of O/P voltage

LVDT

Ratiometric signal conditioning circuit for LVDT

=> suppression of excitation amplitude variations, etc…



Typical example ... AD698 (Analog devices)

Displacement Sensor

Sensors of displacement with variable inductance

$$Z(j\omega) = R + j\omega\frac{N^2}{Z_m} = R + j\omega\frac{N^2}{R_m + jX_m}$$

Z_m... magnetic reluctance ($L = N^2/Z_m$, complex variable)

R_m ... Magnetic resistance $R_m = l/\mu S$
X_m ... Losses caused by eddy currents and hysteresis

$$Z(j\omega) = R + \frac{N^2\omega X_m}{|Z_m(j\omega)|^2} + j\frac{N^2\omega R_m}{|Z_m(j\omega)|^2}$$

For small f: $R_m >> X_m$ … eddy currents affect Re(Z), for high f: … Im(Z)

- self induction / transformer
- open / closed magnetic circuit
- single / differential

Displacement Sensor

Inductance sensors with variable air gap

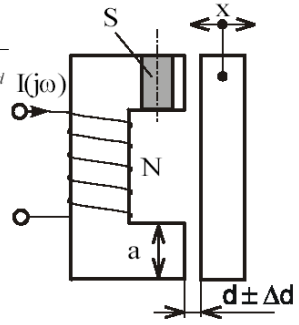
$$Z(j\omega) = R + j\omega\frac{N^2}{Z_m} = R + j\omega\frac{N^2}{(R_m) + \cancel{jX_m}}$$

R_m ... Magnetic resistance $R_m = l/\mu S$

$$R_m = \sum_i \frac{l_i}{\mu_i S_i} = \frac{l_{Fe}}{\mu_0\mu_r S_{Fe}} + \frac{2d}{\mu_0 S_d} \rightarrow \frac{2d}{\mu_0 S_d}$$

$$L = \frac{N^2}{R_m} = \frac{N^2}{2d}\mu_0 S_d$$

(stray field neglected)



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Displacement Sensor

Inductance sensors with variable air gap

$$\Delta L = \frac{N^2 \mu_0 S_d}{2}\left(\frac{1}{d+\Delta d}-\frac{1}{d}\right) = Ld\left(\frac{1}{d+\Delta d}-\frac{1}{d}\right) = L\frac{-\frac{\Delta d}{d}}{1+\frac{\Delta d}{d}}$$

$$\frac{\Delta L}{L} = \frac{-\frac{\Delta d}{d}}{1+\frac{\Delta d}{d}} \qquad y = f(x) = f(x_0) + x\left[\frac{\delta f}{\delta x}\right]_{x_0} + \frac{1}{2!}x^2\left[\frac{\delta^2 f}{\delta x^2}\right]_{x_0} + \frac{1}{3!}x^3\left[\frac{\delta^3 f}{\delta x^3}\right]_{x_0} + \ldots.$$

Taylor series

$$x = \frac{\Delta d}{d} \qquad f(x) = -\frac{x}{1+x} \qquad f(0) = 0, \frac{\delta f}{\delta x} = \frac{1}{(1+x)^2}, \frac{\delta^2 f}{\delta x^2} = -\frac{2}{(1+x)^3}, \frac{\delta^3 f}{\delta x^3} = \frac{3\cdot 2}{(1+x)^4}$$

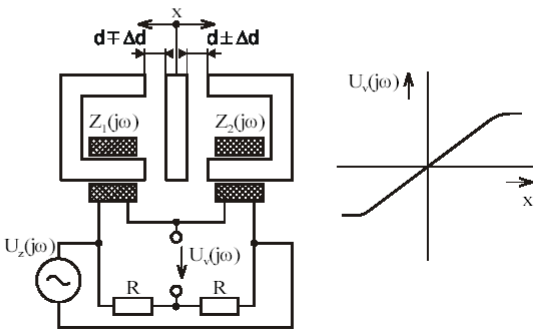
$$\frac{\Delta L}{L} = -\frac{\Delta d}{d} + \left(\frac{\Delta d}{d}\right)^2 - \left(\frac{\Delta d}{d}\right)^3 + \ldots.$$

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SISTEM PENGUKURAN

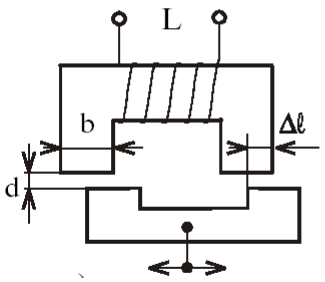
Differential sensor with variable inductance

$$\frac{\Delta L}{L} = -\frac{\Delta d}{d} + \left(\frac{\Delta d}{d}\right)^2 - \left(\frac{\Delta d}{d}\right)^3 + \ldots.$$

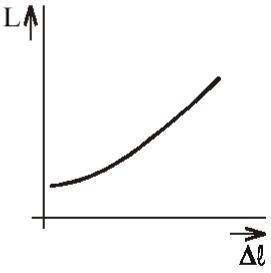


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Inductance sensor of motion with variable area of air gap



$$L \doteq \frac{\mu_0 S N^2}{2d} \cdot \frac{\Delta \ell}{b}$$



d = const.!

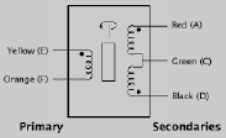
RVDT Sensors AC/AC

Rotary Variable Differential Transformer

SENTECH INC.



SCHEMATIC

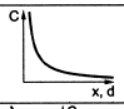
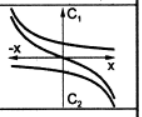
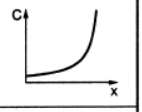
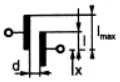
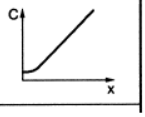


Technical Specifications @ 10 kHz (call for specific model drawings)

PERFORMANCE		*ELECTRICAL*	
Non-Linearity	< ±0.5% of Full Scale @ -45° to +45° < ±1.0% of Full Scale @ -60° to +60°	Input Voltage	3 Volts AC RMS (Nominal)
Angular Displacement	up to ±70°	Input Frequency	2.5 kHz to 20 kHz
Mechanical Rotation	360°	Sensitivity	3.6 mVout/deg/Vin
Operating Temperature Range	-55°F to 275°F (-50°C to 135°C) Wider range available	Null Voltage	Less than 0.5% of Full Scale Output

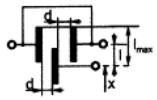
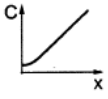
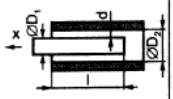
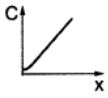
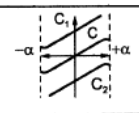
Capacitive sensors

$$C = \frac{\varepsilon S}{d}$$

Type	Layout	Formula	Graph
variable air gap		$C = \varepsilon\frac{S}{d(x)}$; $\frac{\Delta C}{\Delta d} \doteq -\frac{C}{d}\left(1-\frac{\Delta d}{d}\right)$	
variable air gap differential		$C_1 = \varepsilon\frac{S}{d+\Delta d}$; $C_2 = \varepsilon\frac{S}{d-\Delta d}$; $\frac{\Delta C}{\Delta d} \doteq -\frac{C}{d}\left[1+2\left(\frac{\Delta d}{d}\right)^2\right]$	
variable thickness of dielectric pad		$C = \frac{\varepsilon_1 S}{d_0 - d_1(x)\left(1-\frac{\varepsilon_1}{\varepsilon_2}\right)}$	
variable overlapping area		$C = \varepsilon\frac{S(x)}{d}$; $\frac{\Delta C}{\Delta \ell} \doteq -\frac{C_{max}}{\ell_{max}}\left(1+\frac{\Delta d}{d}\right)$	

Capacitive sensors – cont'd

$$C = \frac{\varepsilon S}{d}$$

Type	Layout	Formula	Graph
variable overlapping differential		$C = \varepsilon\frac{S(x)}{d}$; $\frac{\Delta C}{\Delta \ell} \doteq -\frac{C_{max}}{\ell_{max}}\left[1+\left(\frac{\Delta d}{d}\right)^2\right]$	
cylindrical variable overlapping		$C = \varepsilon\frac{2\pi\cdot\ell(x)}{\ln\frac{D_1}{D_2}}$; $\frac{\Delta C}{\Delta \ell} \doteq -\frac{C_{max}}{\ell_{max}}\left[1-\frac{1}{2}\left(\frac{\Delta d}{d}\right)^2\right]$	
angular variable overlapping		$C = \varepsilon\frac{S(\alpha)}{d}$	

Capacitive sensor with variable air gap

$$C = \frac{\varepsilon S}{d}, \qquad \Delta C = \varepsilon S\left(\frac{1}{d+\Delta d} - \frac{1}{d}\right) = Cd\left(\frac{1}{d+\Delta d} - \frac{1}{d}\right) = C\frac{-\frac{\Delta d}{d}}{1+\frac{\Delta d}{d}}$$

$$\frac{\Delta C}{C} = \frac{-\frac{\Delta d}{d}}{1+\frac{\Delta d}{d}} \qquad y = f(x) = f(x_0) + x\left[\frac{\delta f}{\delta x}\right]_{x_0} + \frac{1}{2!}x^2\left[\frac{\delta^2 f}{\delta x^2}\right]_{x_0} + \frac{1}{3!}x^3\left[\frac{\delta^3 f}{\delta x^3}\right]_{x_0} + \ldots.$$

Taylor series

$$x = \frac{\Delta d}{d} \qquad f(x) = -\frac{x}{1+x} \qquad f(0) = 0, \frac{\delta f}{\delta x} = \frac{1}{(1+x)^2}, \frac{\delta^2 f}{\delta x^2} = -\frac{2}{(1+x)^3}, \frac{\delta^3 f}{\delta x^3} = \frac{3\cdot 2}{(1+x)^4}$$

$$\frac{\Delta C}{C} = -\frac{\Delta d}{d} + \left(\frac{\Delta d}{d}\right)^2 - \left(\frac{\Delta d}{d}\right)^3 + \ldots.$$

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Capacitive sensor with variable air gap

$$\frac{\Delta C}{C} = -\frac{\Delta d}{d} + \left(\frac{\Delta d}{d}\right)^2 - \left(\frac{\Delta d}{d}\right)^3 + \ldots.$$

$$d_1 = d + \Delta d \quad \ldots \quad \frac{\Delta C_1}{C} = -\frac{\Delta d}{d} + \left(\frac{\Delta d}{d}\right)^2 - \left(\frac{\Delta d}{d}\right)^3 + \ldots.$$

$$d_2 = d - \Delta d \quad \ldots \quad \frac{\Delta C_1}{C} = -\frac{-\Delta d}{d} + \left(\frac{-\Delta d}{d}\right)^2 - \left(\frac{-\Delta d}{d}\right)^3 + \ldots.$$

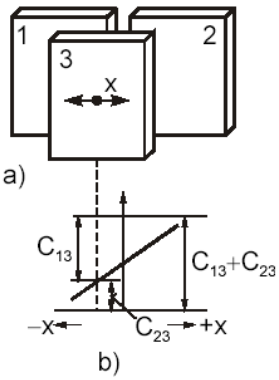
$$C_1 = C + \Delta C_1, \quad C_2 = C + \Delta C_2 \qquad C_1 - C_2 = \Delta C_1 - \Delta C_2$$

$$\frac{C_1 - C_2}{C} = \frac{\Delta C_1}{C} - \frac{\Delta C_2}{C} = -2\frac{\Delta d}{d} - 2\left(\frac{\Delta d}{d}\right)^3 - \ldots.$$

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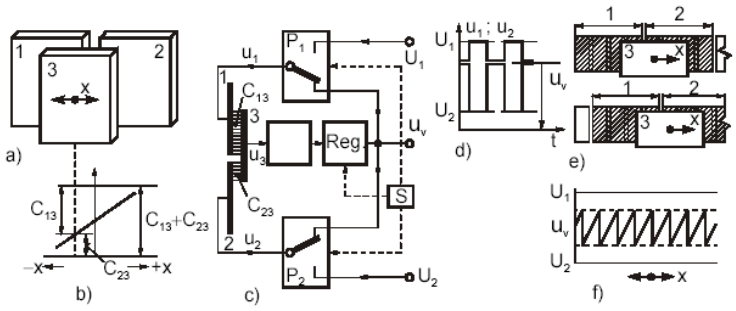
Capacitive sensor with variable area of electrodes overlapping

$$C = \frac{\varepsilon S}{d}$$



ratiometric measurement: $\frac{C_{23} - C_{13}}{C_{23} + C_{13}}$ influence of d,ε eliminated

Capacitive sensor with variable area of electrodes overlapping



$$U_1(j\omega)j\omega C_{13} + U_2(j\omega)j\omega C_{23} = 0 \Rightarrow U_1(j\omega)C_{13} = -U_2(j\omega)C_{23}$$

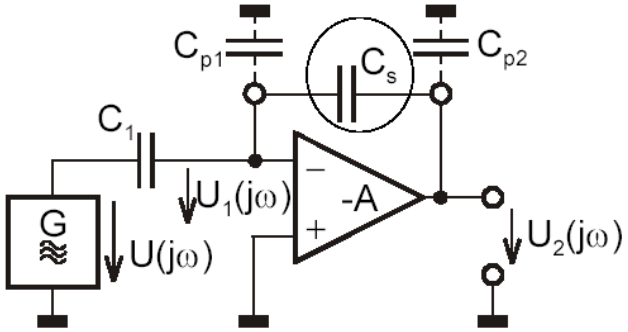
$$(u_V - U_1)C_{13} = -(u_V - U_2)C_{23}$$

if $U_1 = U$, $U_2 = -U$

$$(u_V - U)C_{13} = -(u_V + U_2)C_{23} \Rightarrow u_V = U\frac{C_{13} - C_{23}}{C_{13} + C_{23}}$$

resolution: 1 μm, uncertainty 5 μm

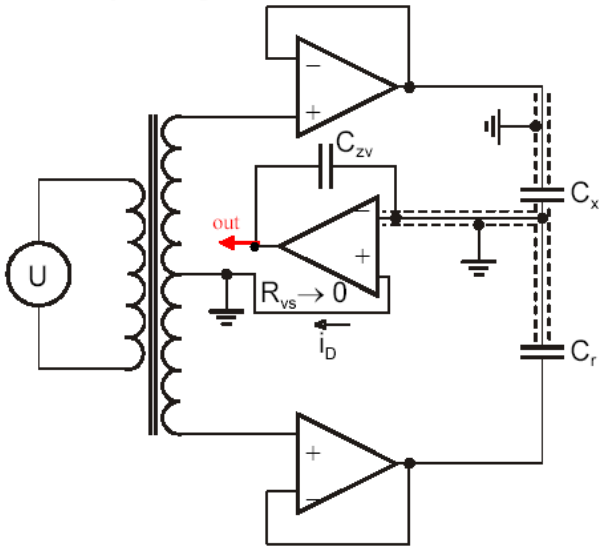
Amplifier for capacitive sensors:



Parasitic capacitances of the cable to C_S will not apply:
C_{p1} is on virtual zero, C_{p2} is on low output impedance of the OpAmp

Linearity even for variable air gap sensor (vibration measurement),
$U_2 \sim d$

Transformer bridge for capacitive sensors:



Transformer bridge for capacitive sensors:

