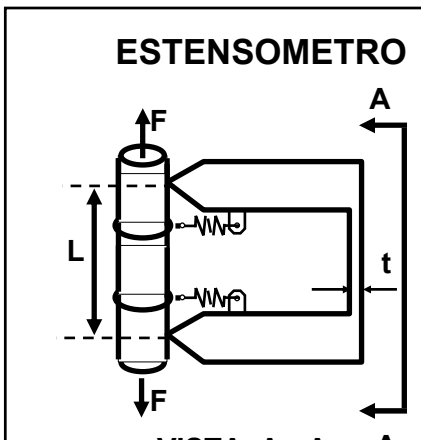
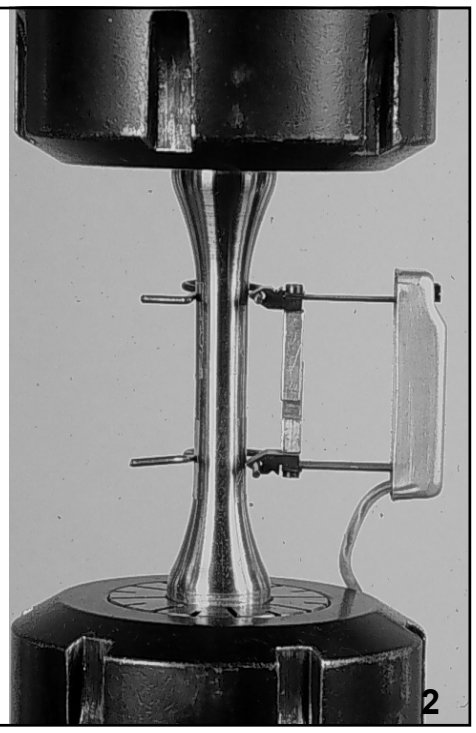
MISURE DI SPOSTAMENTO





Misure di spostamento :
- **lineare**
- **angolare**

Misure di spostamento :

- **Quasi statiche (allineamento di un rotore con comparatori)**
- **Tempovarianti (posizione del perno nel cuscinetto)**

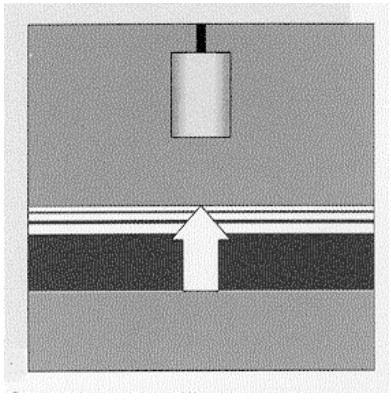
Trasduttori:

- Analogici:

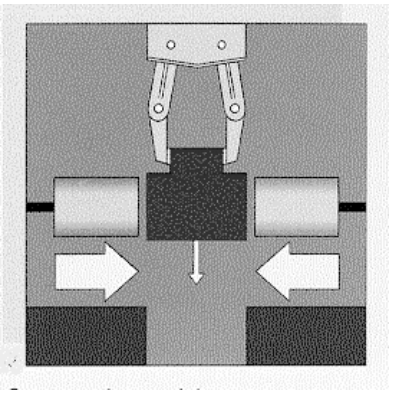
  - a contatto (effetto di reazione)

  - senza contatto

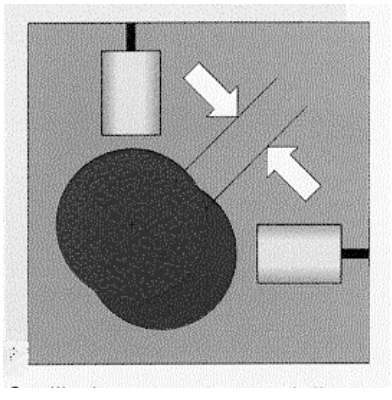
- Digitali



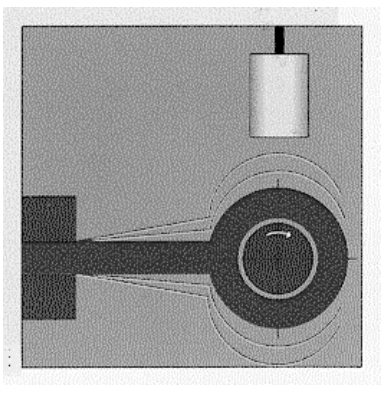
spostamento, dilatazione



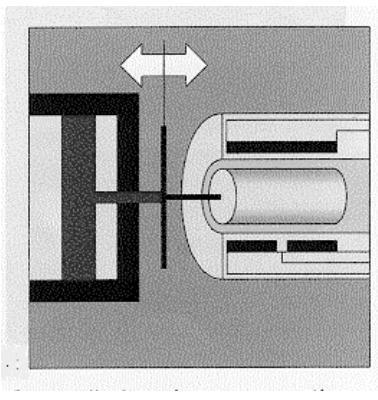
centraggio, posizionamento



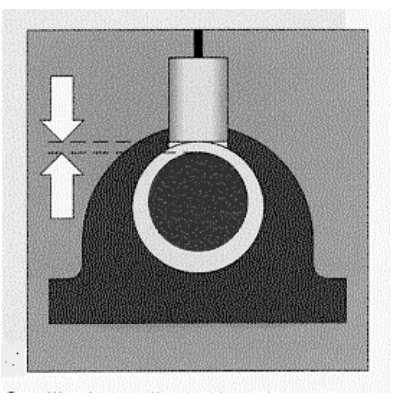
vibrazioni di alberi, eccentricità



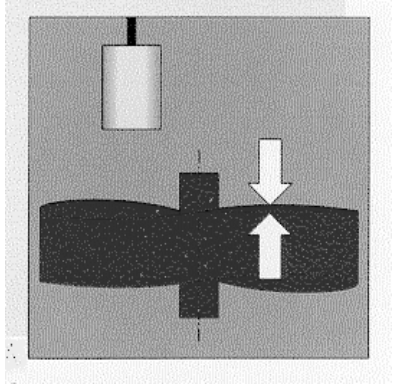
vibrazione di organi di macchine



corsa di pistoni



spostamenti relativi perno - cuscinetto



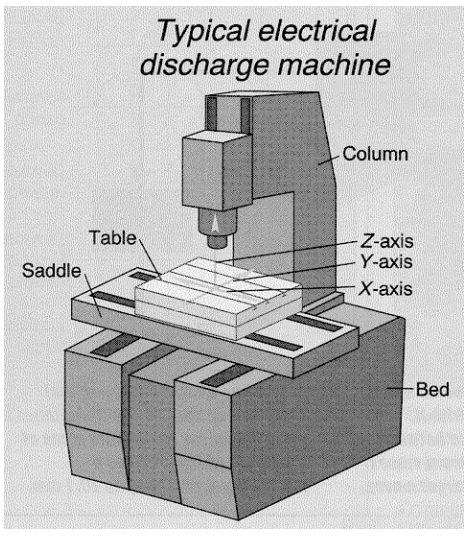
**vibrazioni assiali,
usura e deformazione
pale rotori**

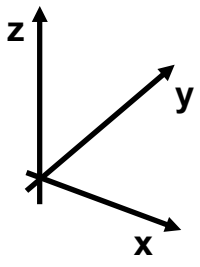
Esempi:

- **Controllo in posizione di:**

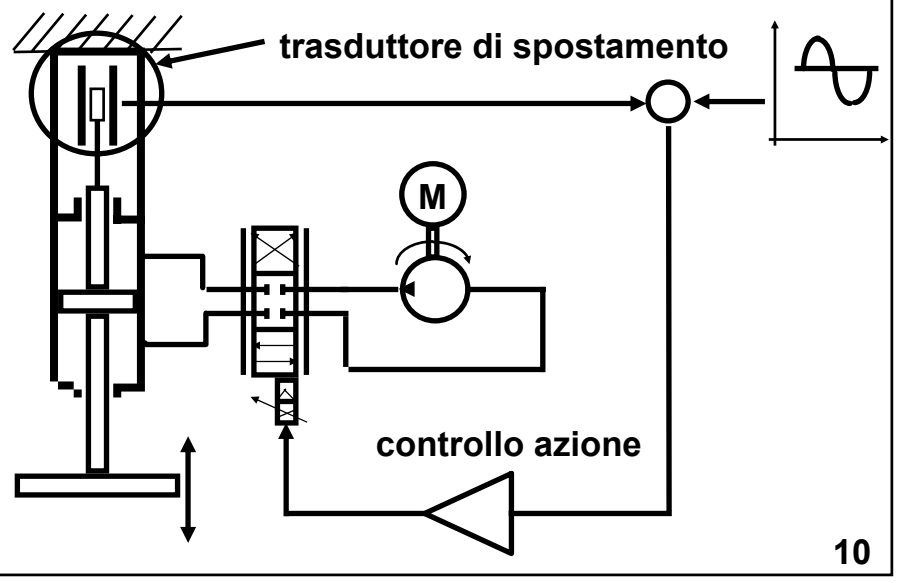
  - **macchine utensili**
  - **attuatori di macchine di prova**
  - **apertura di una valvola**

- **Controllo in posizione di macchine utensili**

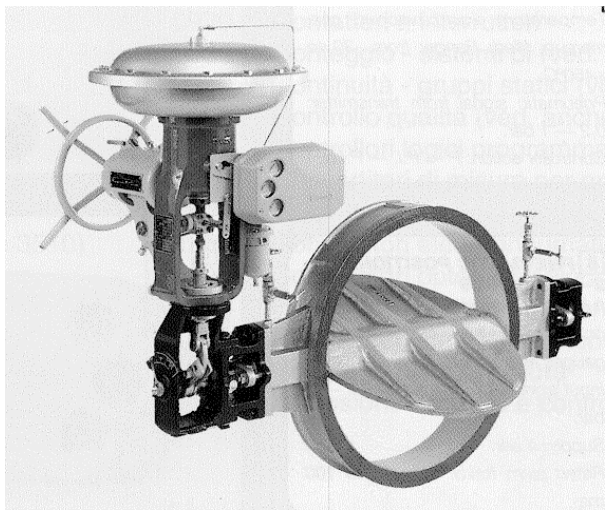




- **Controllo in posizione di attuatori di macchine di prova**



- **Controllo dell'angolo di apertura di una valvola**

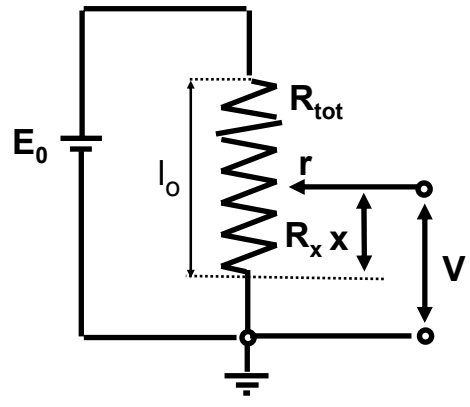


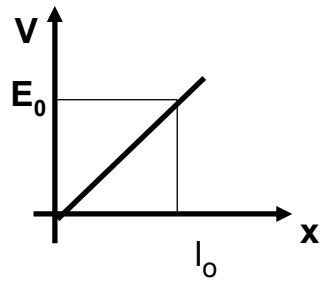
TRASDUTTORI DI SPOSTAMENTO A CONTATTO

**Misurano lo spostamento RELATIVO
tra lo statore e il tasto sonda**

TRASDUTTORI DI SPOSTAMENTO RESISTIVI

$V = R_x\, i$

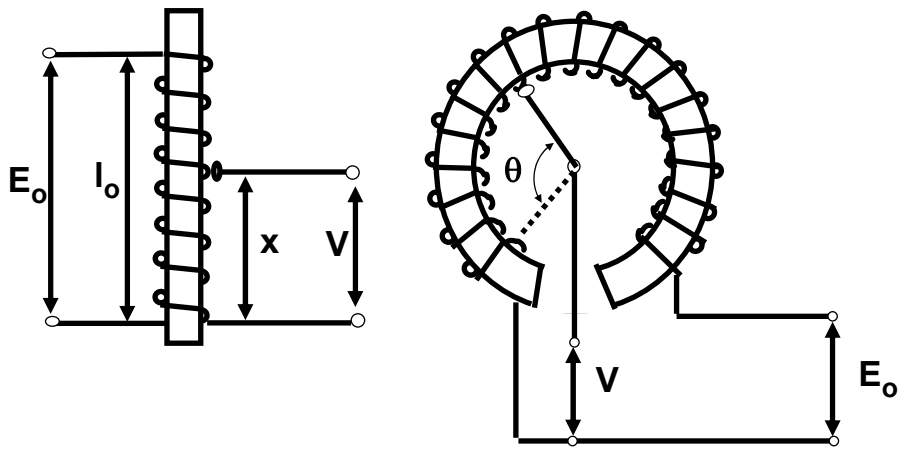




$V = \frac{x}{l_o} E_o$

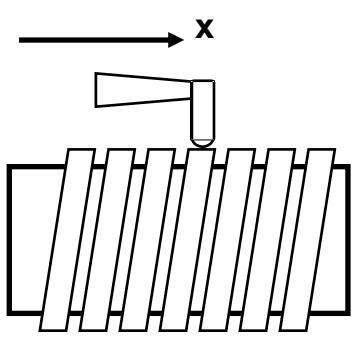
$x = \frac{V}{E_o} l_o$

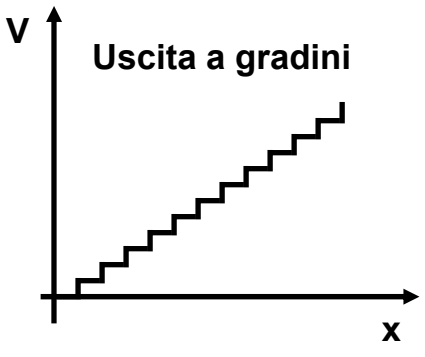
strumento di ordine 0 (teorico)



lineare **angolare**

POTENZIOMETRI RESISTIVI A SPIRE

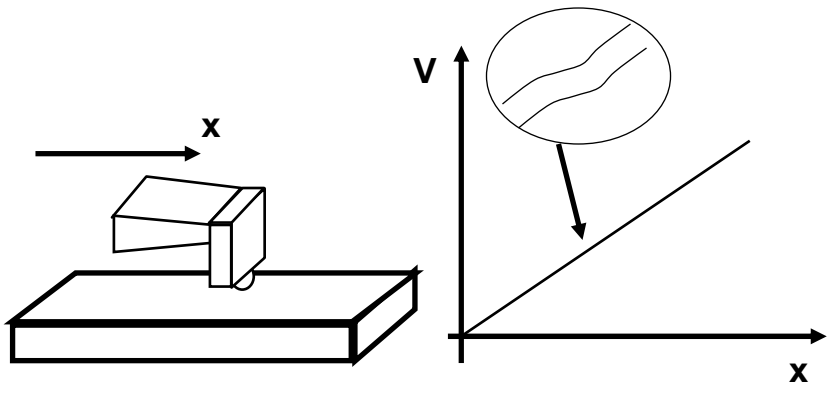




Risoluzione: $\frac{l_o}{n}$

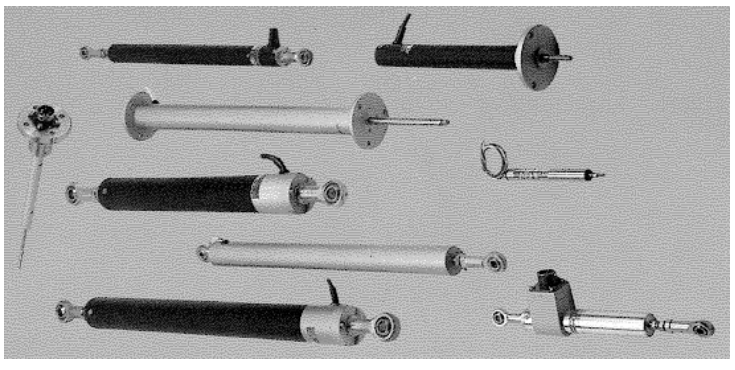
n: numero di spire

POTENZIOMETRI RESISTIVI A STRATO



Risoluzione: infinita (teorica)

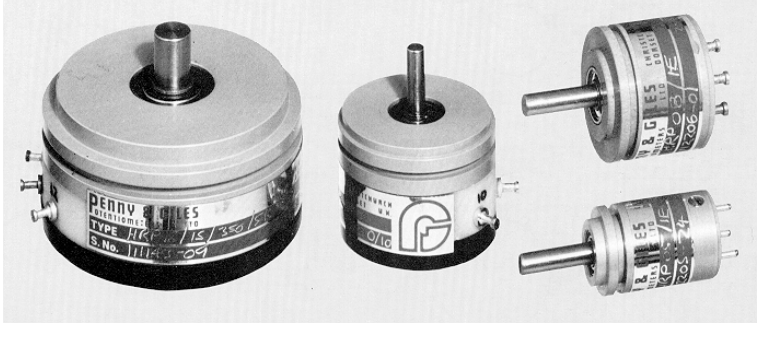
Trasduttori lineari



VALORI TIPICI:

- **Portata:** 2 ÷ 2000 mm
- **Risoluzione:** infinita ??? (se a strato)
  0,1% ÷ 1% f.s. (se a filo)
- **Linearità:** ± 0,1% ÷ 0,3%
- **Resistenza:** 0,5 ÷ 10 KΩ / 25 mm
- **Vita a fatica:** 10^8 cicli
- **Velocità massima:** 1 m/s

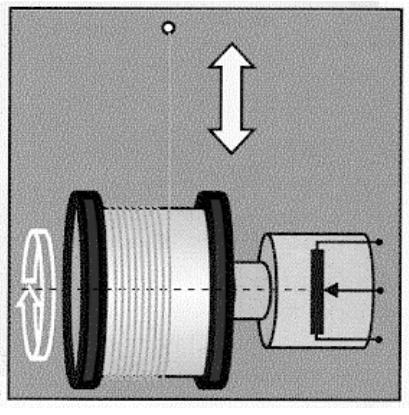
Trasduttori angolari

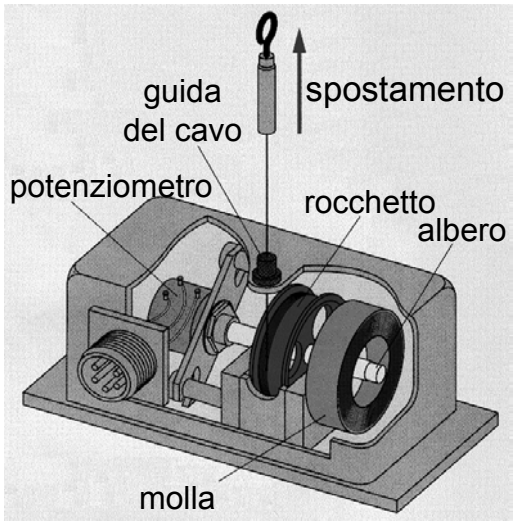


VALORI TIPICI:

- **Portata:** 10° ÷ 60giri
- **Risoluzione:** infinita (se a strato)
  0,05% ÷ 1% f.s. (se a filo)
- **Linearità:** ± 0,1% ÷ 0,5%
- **Resistenza:** 0,5 ÷ 20 kΩ
- **Vita a fatica:** 10^8 cicli
- **Coppia di spunto:** 10^{-4} Nm
- **Velocità massima:** 3000°/s

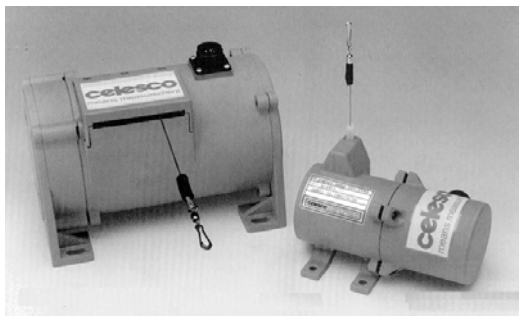
E' possibile utilizzare un trasduttore angolare per eseguire misure lineari





spostamento = $\alpha \frac{D}{2}$

essendo:
- α: angolo di rotazione dell'albero;
- D: diametro del rocchetto



VALORI TIPICI:

- **Portata:** 50 ÷ 2500 mm
- **Sensibilità:** 0,1 ÷ 20 mV/V/mm
- **Resistenza:** 0,5 ÷ 1 kΩ
- **Accuratezza:** ± 0,1% ÷ 0,25% f.s.

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LIMITI

- **Tensione cavo:** 2 ÷ 10 N
- **Velocità max.:** < 10 m/s
- **Accelerazione max:**
  - **estrazione:** < 35 g
  - **avvolgimento:** < 25 g

VANTAGGI

- **Il filo disaccoppia l'oggetto dal trasduttore nella direzione perpendicolare al filo**

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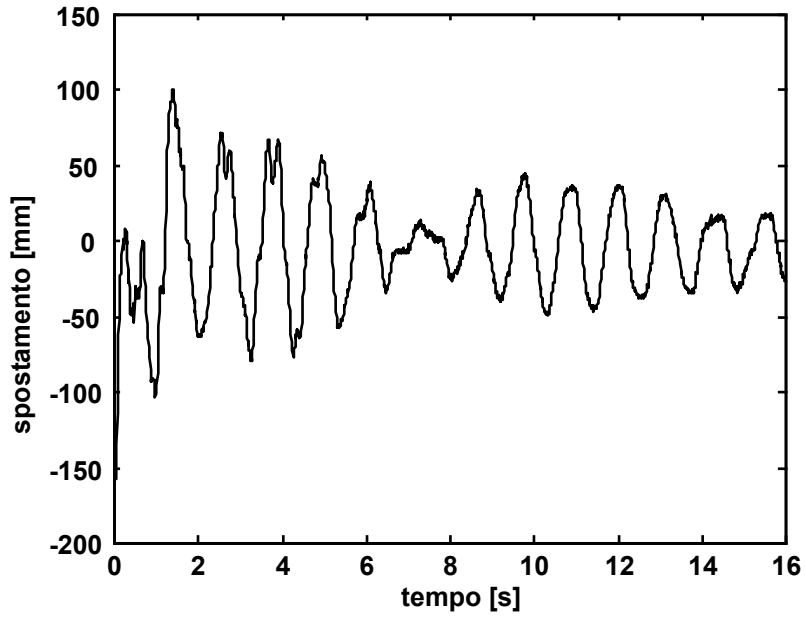
Spostamento della Fune di Contatto



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TRASDUTTORI DI SPOSTAMENTO INDUTTIVI

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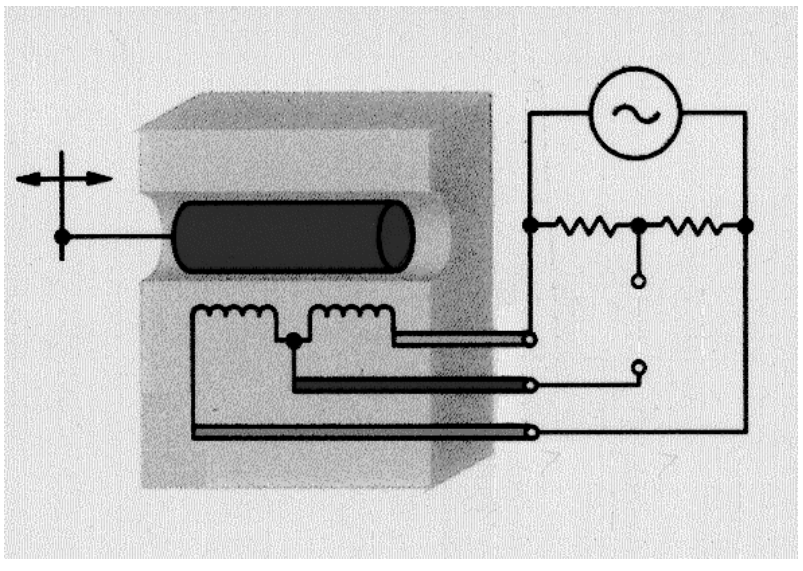
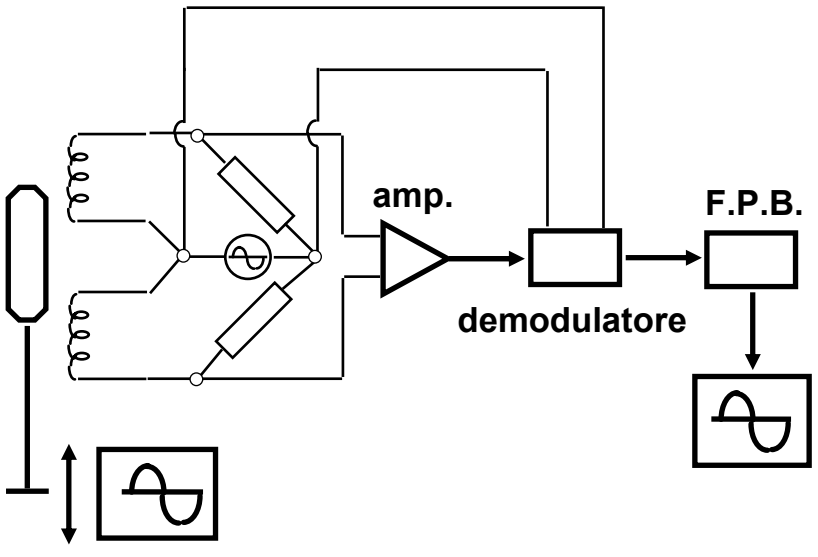


30



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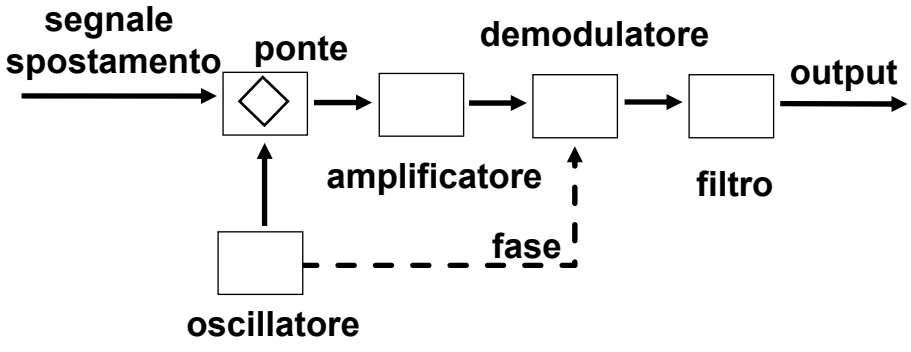
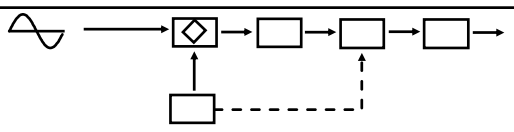
MODULAZIONE IN AMPIEZZA



32



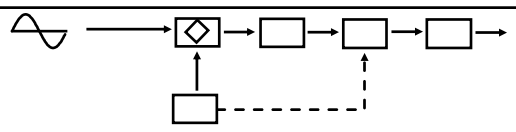
- **Segnale del generatore ("carrier"):**
  -ampiezza: A_C
  -frequenza: ω_C

- **Segnale di spostamento armonico:**
  - ampiezza: A_S
  - frequenza: ω_S

- **Ipotesi:** $Z_1 = Z_2 = Z_3 = Z_4$

$$\Rightarrow \Delta V = \frac{V}{4}\frac{\Delta Z}{Z}$$

33



- $V_{\Delta R} = (A_S \sin\omega_S t)(A_C \sin\omega_C t) =$

$$= \frac{A_S A_C}{2}\sin[(\omega_C - \omega_S)t + 90°] + \frac{A_S A_C}{2}\sin[(\omega_C + \omega_S)t - 90°]$$

- **Lo spettro del segnale modulato è discreto con contenuto armonico alle frequenze** $\omega_C - \omega_S$ **e** $\omega_C + \omega_S$

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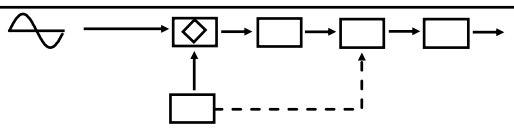

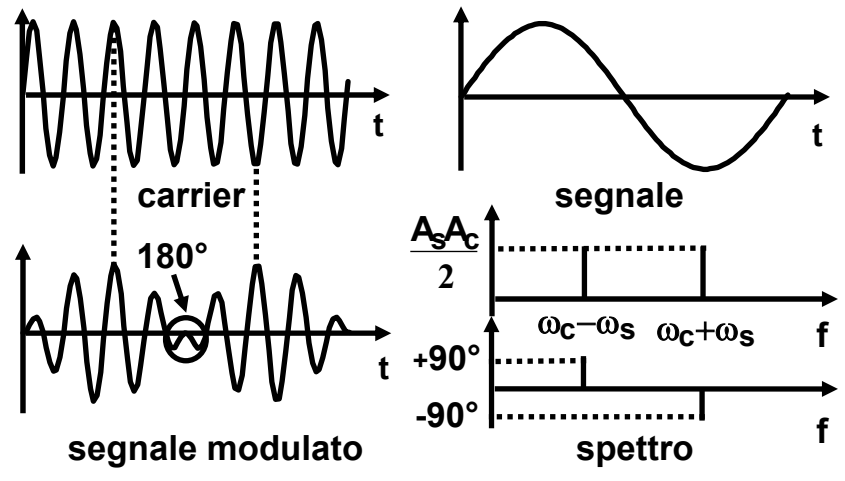

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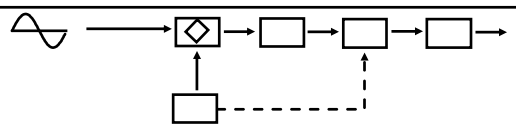
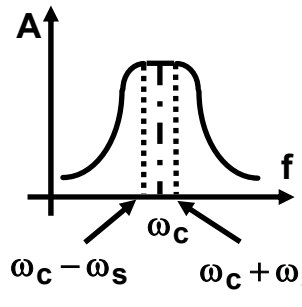


- **AMPLIFICAZIONE DEL SEGNALE:**

amplificazione costante se $2\omega_S / \omega_C$ è piccolo, cioè se $\omega_C >> \omega_S$



ESEMPIO:
$\omega_C = 1000$ **Hz**
$\omega_S = 10$ **Hz**
banda amplifacazione:
990 - 1010 Hz

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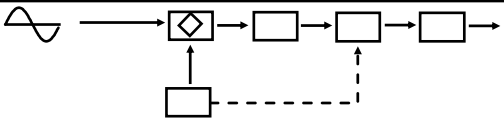
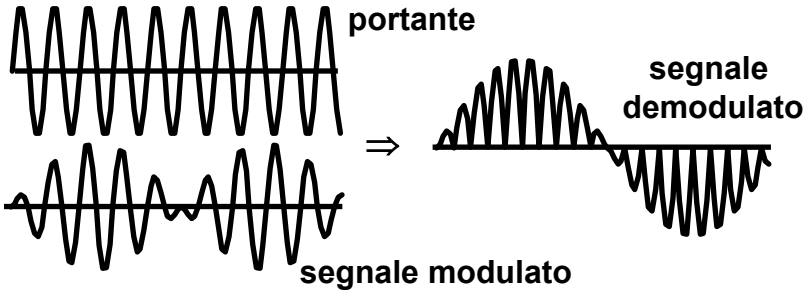
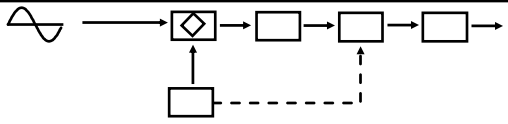


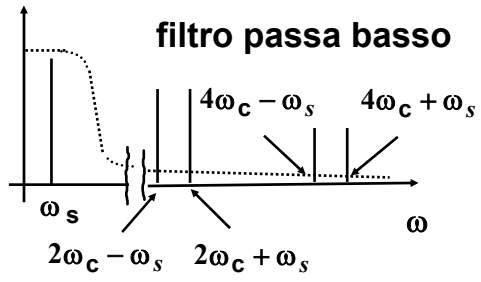
◆ **DEMODULAZIONE DEL SEGNALE:**

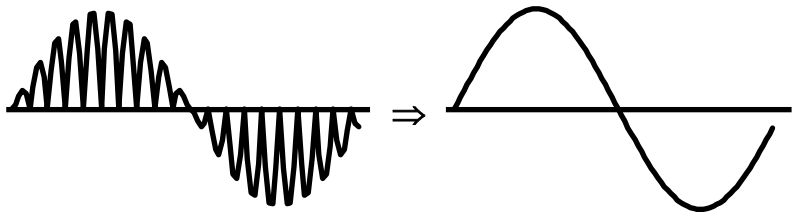
si confronta la fase del segnale modulato con la fase della portante

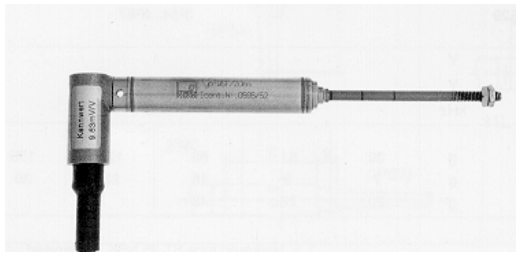




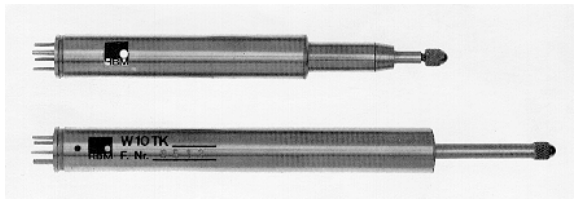
◆ **FILTRAGGIO DEL SEGNALE:**







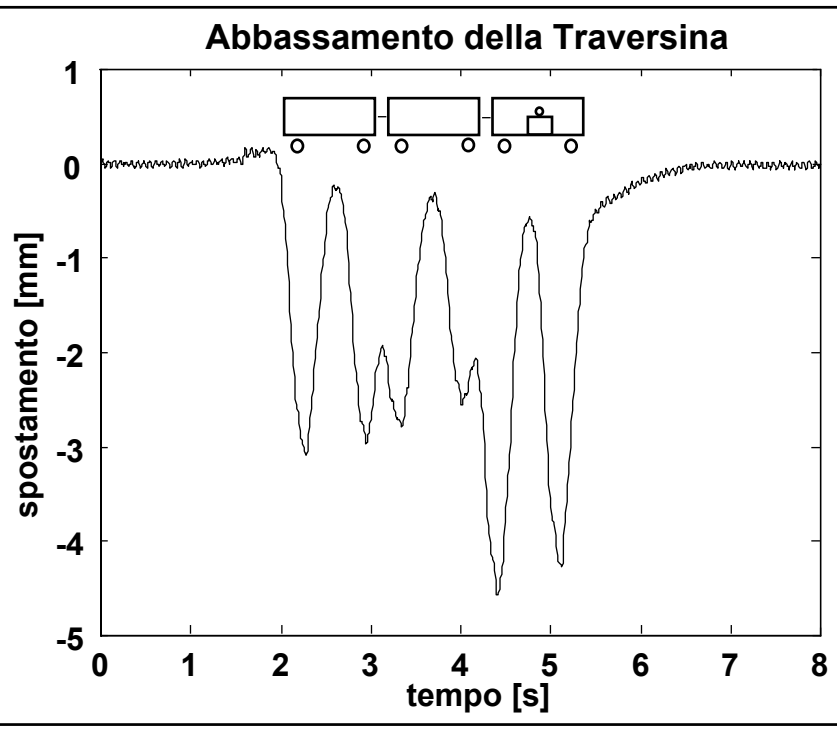
Tasto sonda libero



Tasto sonda a molla

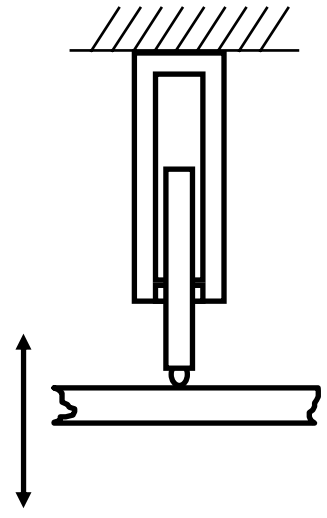
VALORI TIPICI:

- **portata (sonda a molla): 4 ÷ 100 mm**
- **(sonda libera): 20 ÷ 500 mm**
- **sensibilità (al f.s.): 10 ÷ 80 mV/V**
- **scostamento dalla linearità: < ± 0,4%**



PROBLEMI DI MONTAGGIO

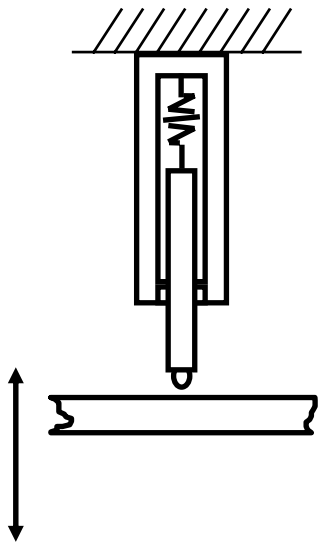
TASTO SONDA SEMPLICEMENTE APPOGGIATO



- Effetto di reazione basso
- Saltellamento del tasto sonda se l'accelerazione dell'elemento vibrante è maggiore di quella di gravità

Esempio
- Ampiezza: 1 mm
- Frequenza max: 16 Hz

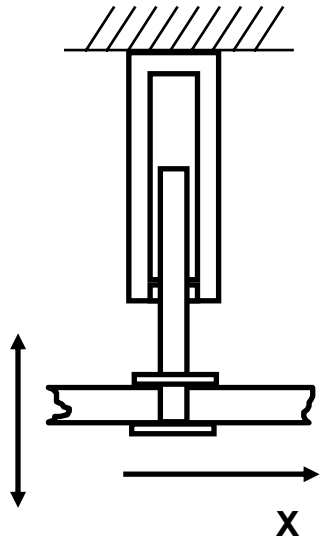
TASTO SONDA CON MOLLA



- Effetto di reazione causato dalla molla
- Saltellamento del tasto sonda dipende dalla massa della sonda, dalla rigidezza della molla e dal precarico

Esempio
- Precarico: 2 N
- Massa sonda: 0,01 Kg
- Rigidezza Molla: 0,1 N/mm
- Ampiezza: 1 mm
- Frequenza max: 70 Hz

TASTO SONDA RIGIDAMENTE COLLEGATO ALL'ELEMENTO VIBRANTE

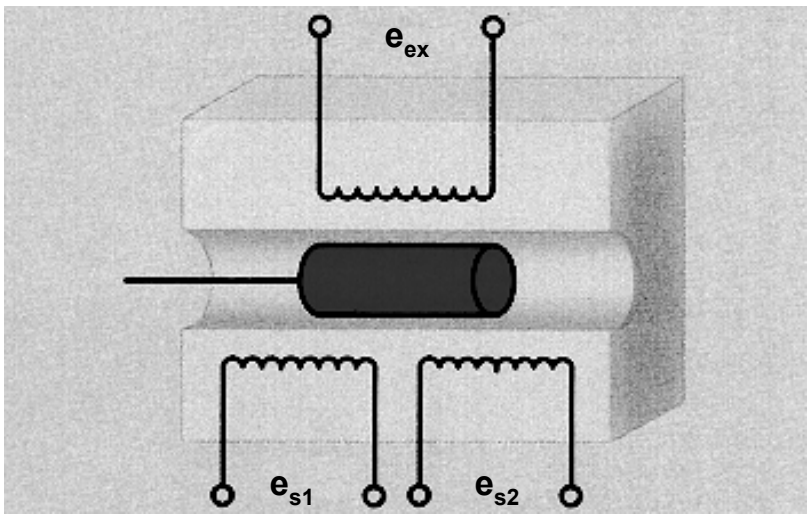


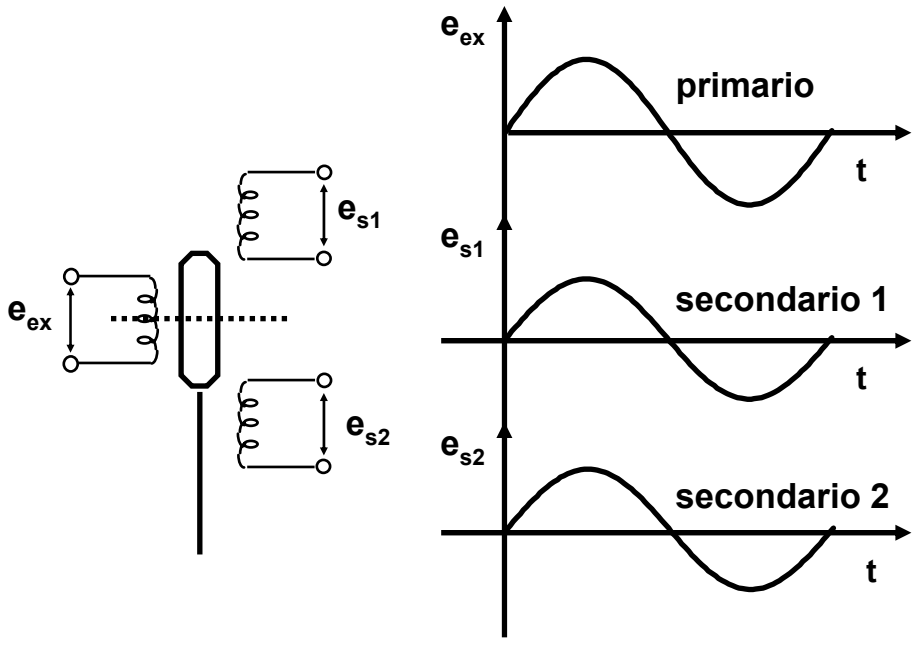
- Non si ha il saltellamento del tasto sonda alle alte frequenze
- Impediti eventuali moti relativi tra il tasto sonda e l'elemento vibrante lungo l'asse X

Trasduttori di spostamento a trasformatore differenziale

LVDT

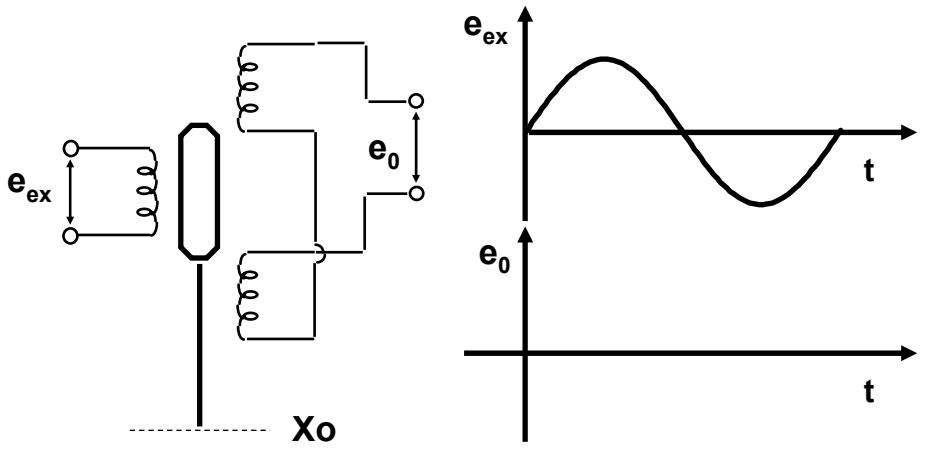
Linear Variable Differential Transformer





49

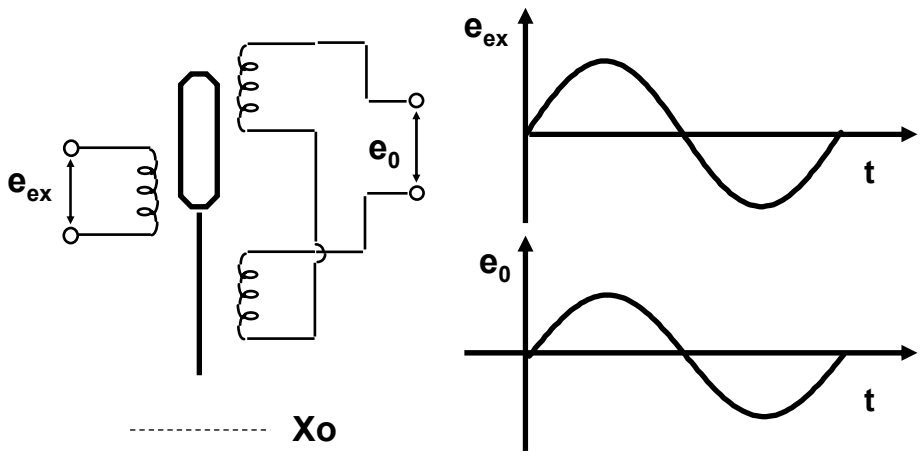
SECONDARI COLLEGATI IN SERIE IN OPPOSIZIONE



Esiste una posizione in cui $e_o = 0$ (posizione di 0 elettrico)
In questa posizione viene fissato lo 0 meccanico X_0

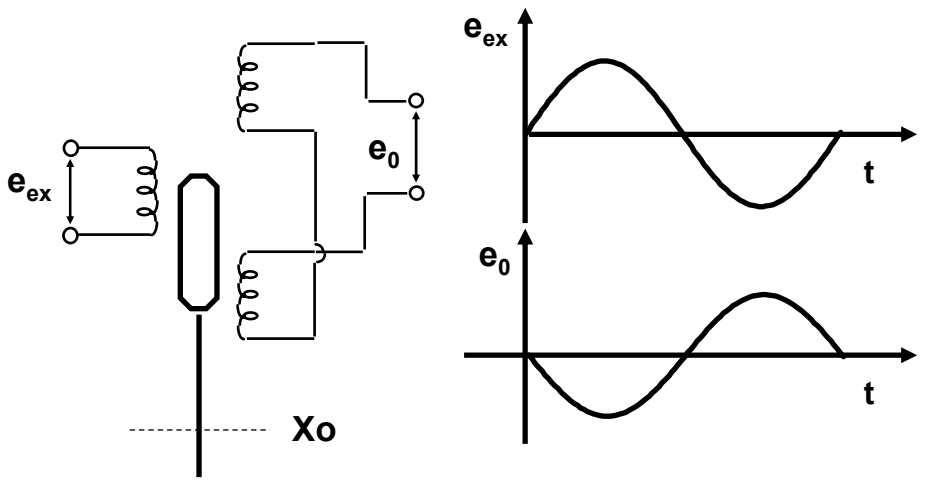
50

SECONDARI COLLEGATI IN SERIE IN OPPOSIZIONE



51

SECONDARI COLLEGATI IN SERIE IN OPPOSIZIONE



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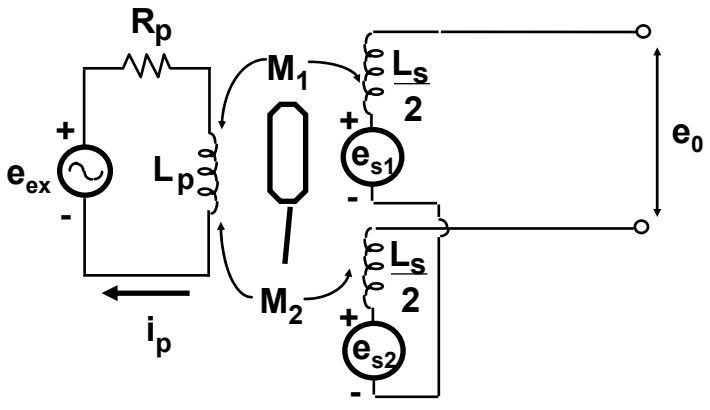
MUTUA INDUTTANZA



$$i_p R_p + L_p \frac{di_p}{dt} - e_{ex} = 0 \qquad e_o = e_{s1} - e_{s2} = (M_1 - M_2)\frac{di_p}{dt}$$

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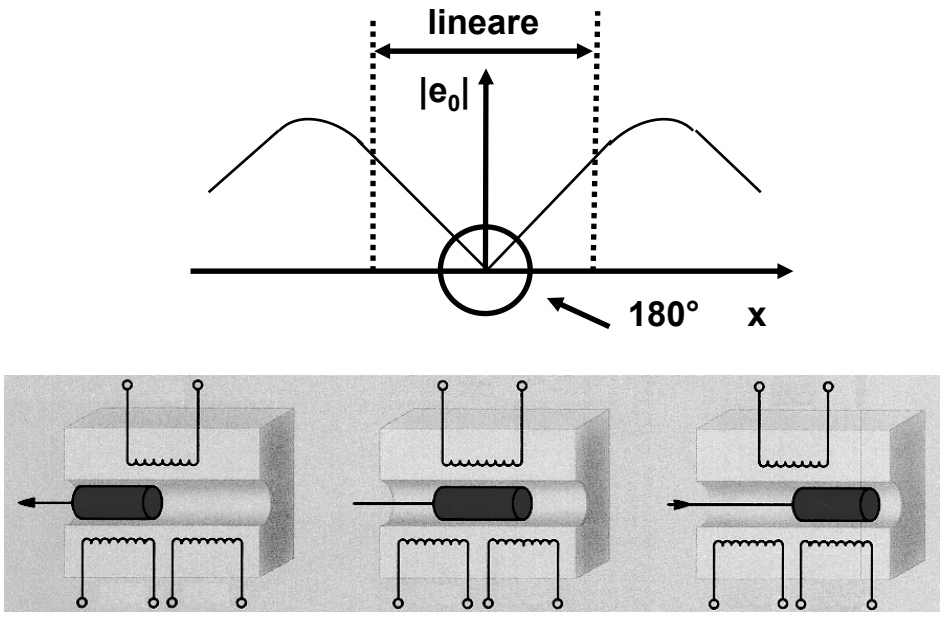
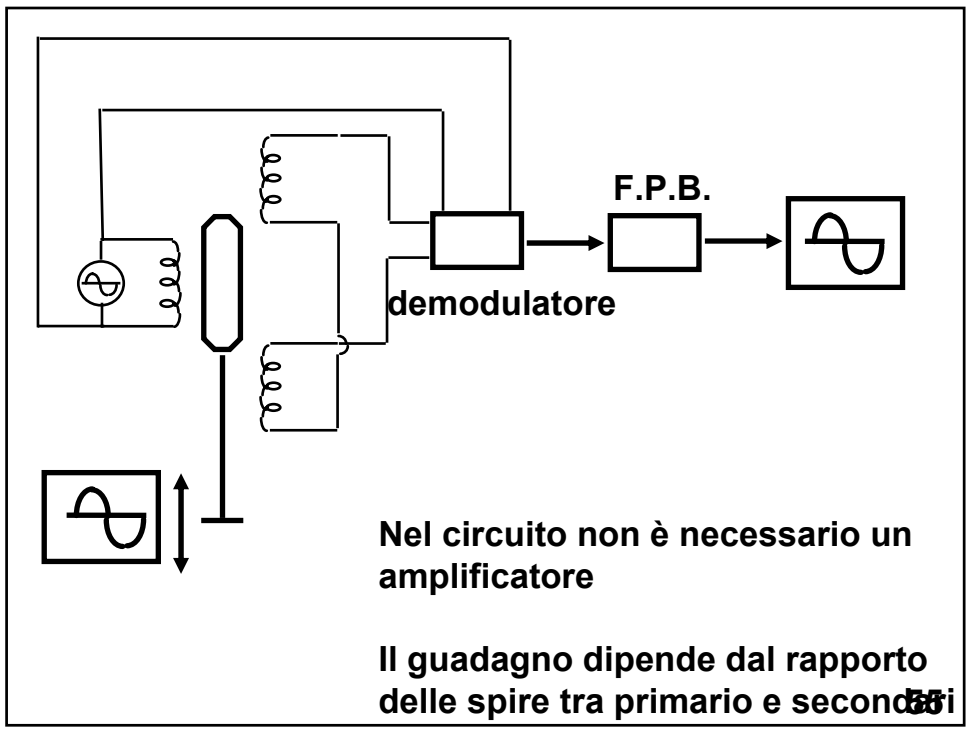


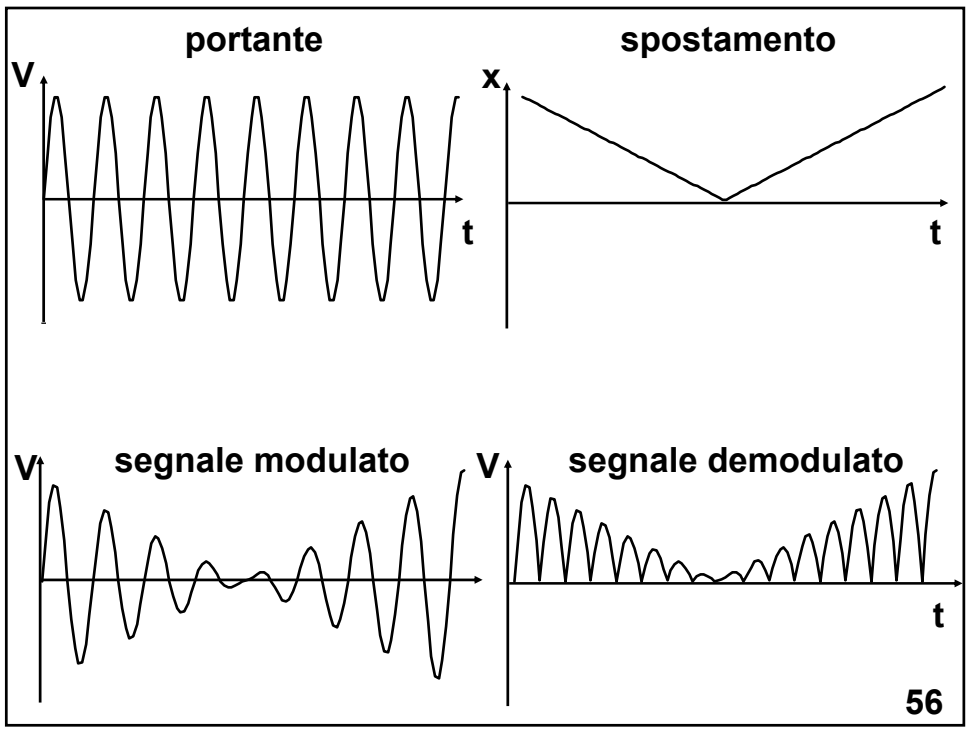
54



Nel circuito non è necessario un amplificatore

Il guadagno dipende dal rapporto delle spire tra primario e secondari

55



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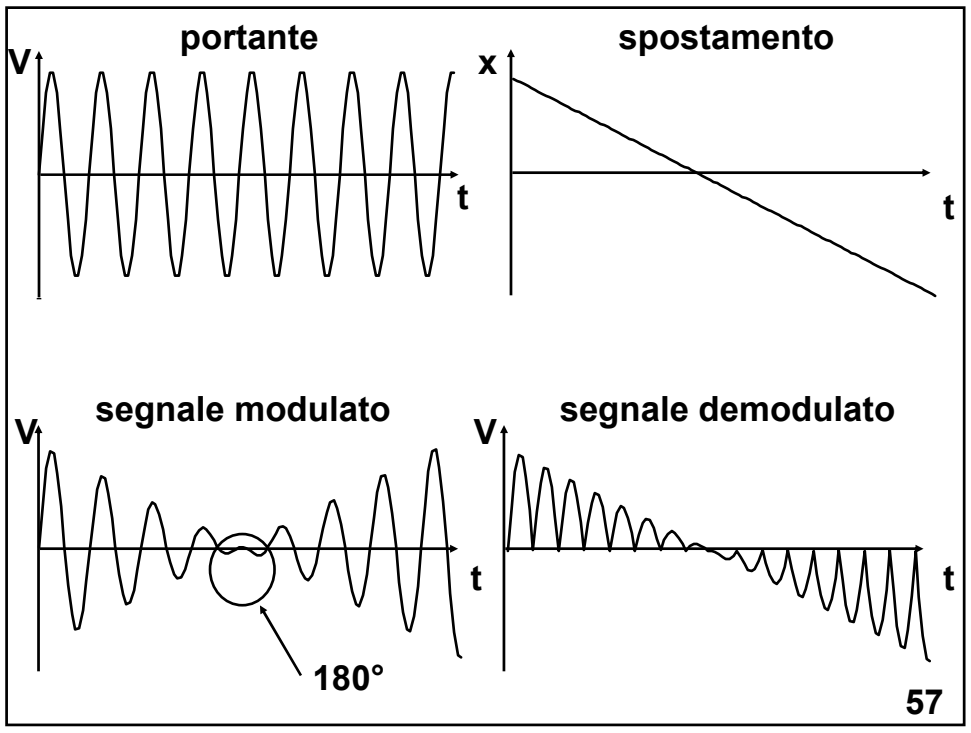
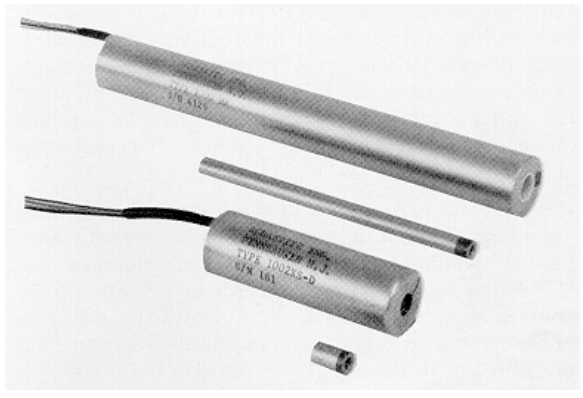
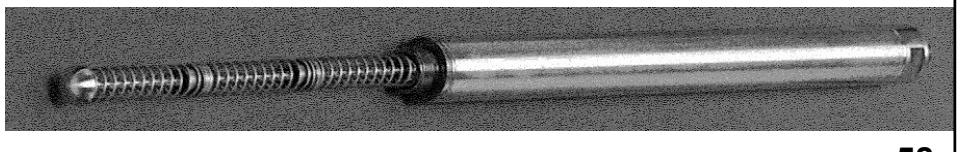


57





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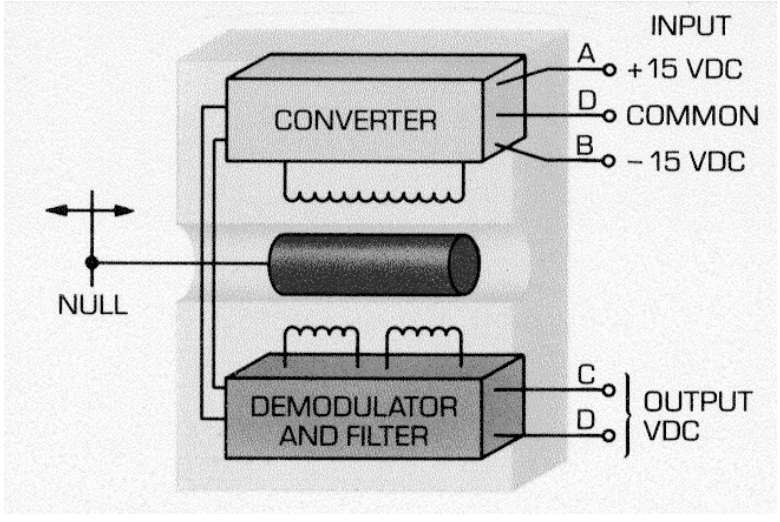
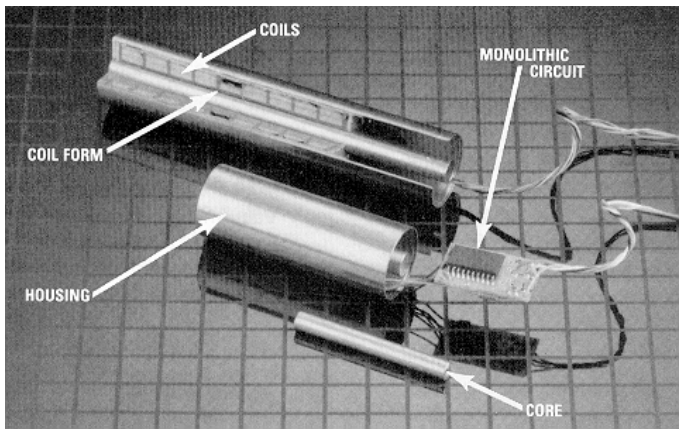
LVDT DC-DC



59



60

VALORI TIPICI:

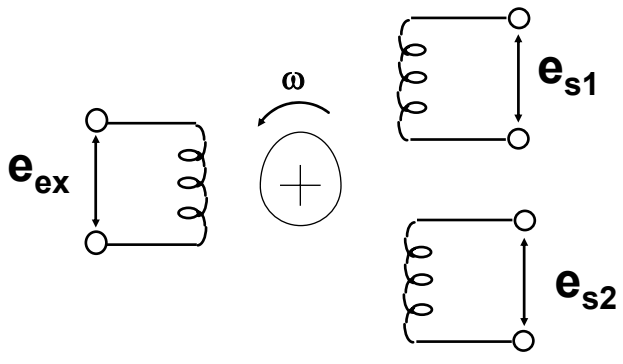
- **Portata (sonda a molla):** **± 2,5 ÷ 7,5 mm**
- **(sonda libera):** **± 1,25 ÷ 250 mm**
- **Sensibilità (tipo ac - ac):** **3 ÷ 250 mV/V/mm**
- **(tipo dc - dc):** **0,04 ÷ 8 V/mm**
- **Linearità (f.s.):** **< ± 0,25%**

Trasduttori angolari a trasformatore differenziale

RVDT

Rotary Variable Differential Transformer

PRINCIPIO DI FUNZIONAMENTO



VALORI TIPICI:

- **Portata:** **± 30° ÷ 40°**
- **Sensibilità (tipo ac - ac):** **2 ÷ 3 mV/V°**
- **(tipo dc - dc):** **125 mV/°**
- **Linearità (f.s.):** **< ± 0,3%**

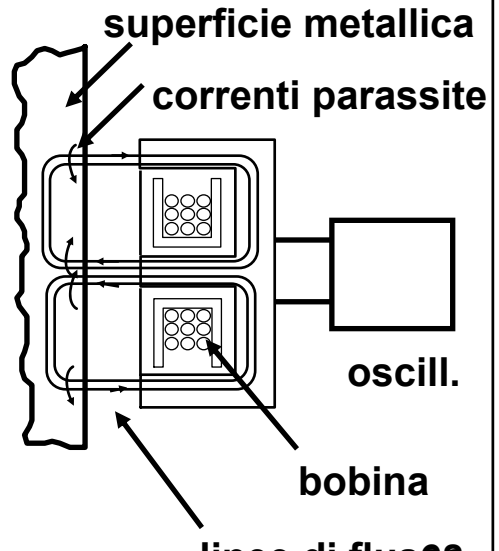
TRASDUTTORI DI SPOSTAMENTO SENZA CONTATTO

Misurano lo spostamento RELATIVO tra la sonda e l'oggetto (target)

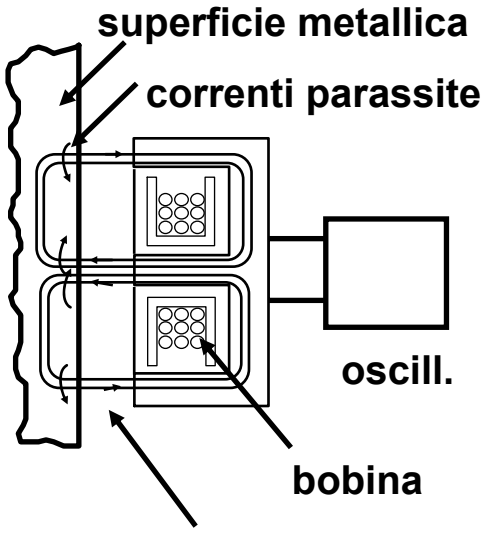
TRASDUTTORI INDUTTIVI A CORRENTI PARASSITE

PRINCIPIO DI FUNZIONAMENTO DEL TRASDUTTORE

- bobina alimentata con corrente alternata (≈1 MHz)
- la bobina genera un campo elettromagnetico

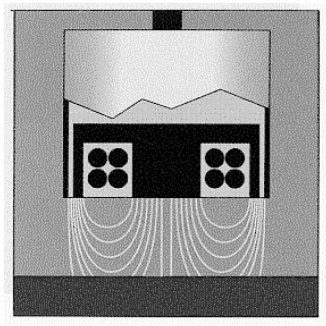


- sul conduttore nascono le correnti parassite
- l'intensità delle correnti parassite è funzione della distanza del trasduttore dal conduttore



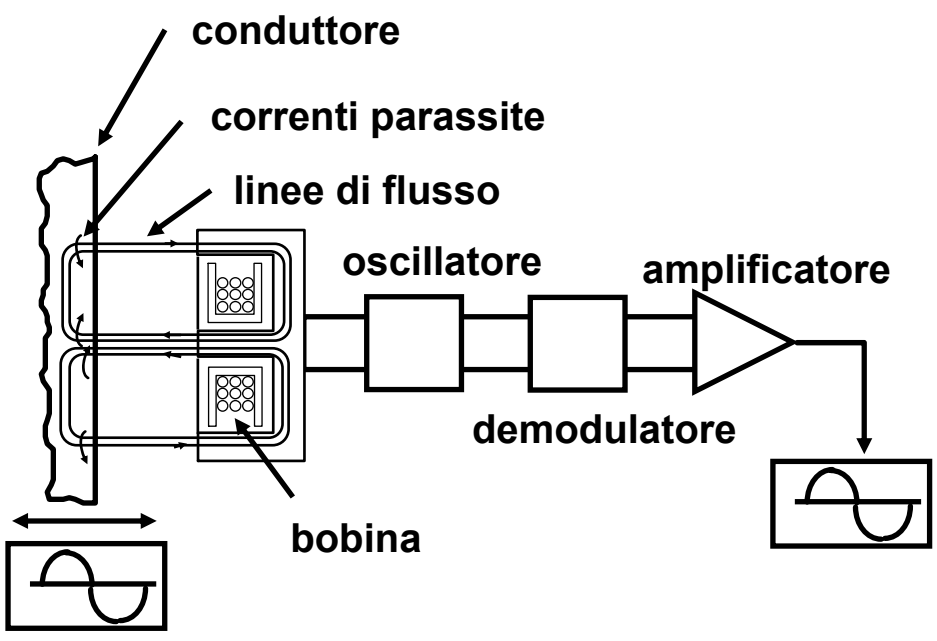
La misura della variazione di distanza del conduttore dal trasduttore può essere eseguita sfruttando due principi:

- I modo:

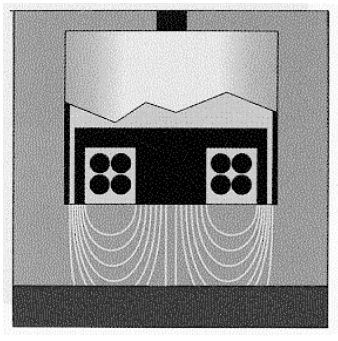


Le correnti parassite nel conduttore dissipano energia per effetto Joule

L'ampiezza del segnale dell'oscillatore viene attenuata in funzione dell'energia perduta, cioè della distanza relativa trasduttore-conduttore

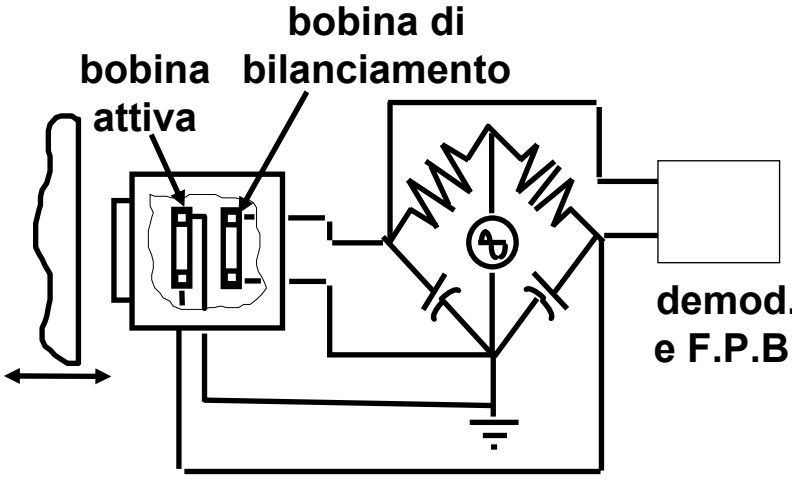


- II modo:



Le correnti parassite nel conduttore creano a loro volta un campo elettromagnetico che modifica l'induttanza della bobina

Si può dunque eseguire una misura di variazione di induttanza



si misura una variazione di induttanza

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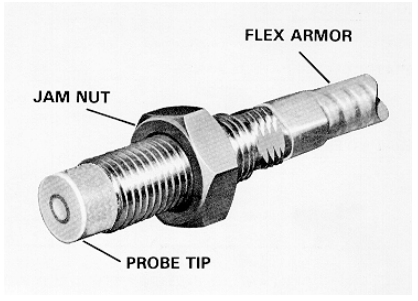

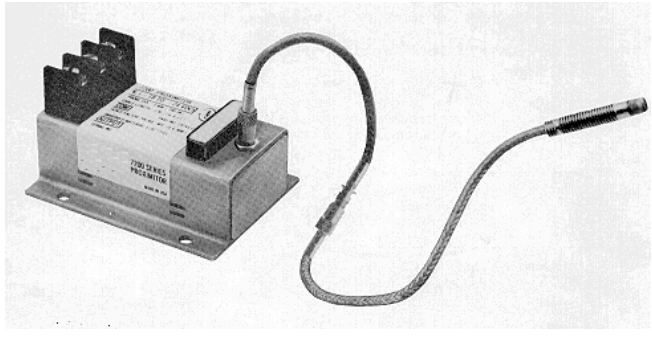

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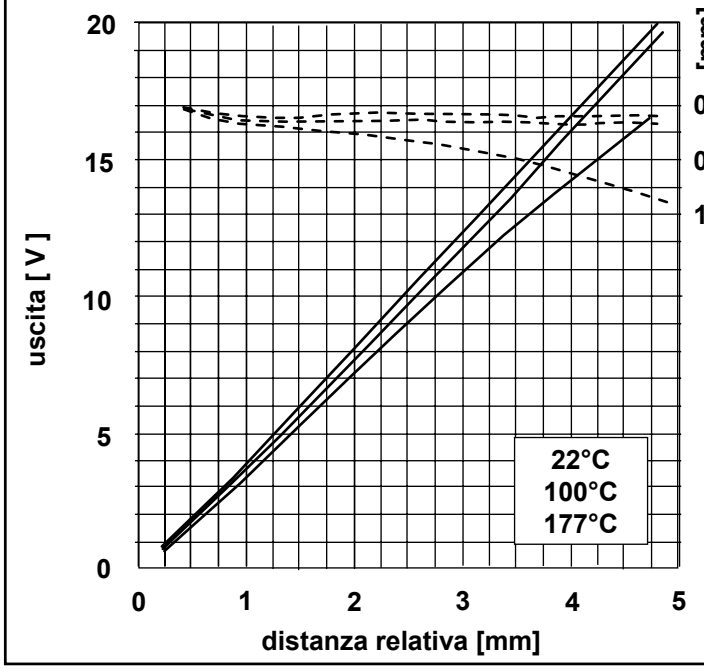
VALORI TIPICI:

Portata:	**2 mm (a partire da 0,25 mm)**
	4 mm (a partire da 1 mm)
Diametro sonda:	**5 ÷ 14 mm**
Sensibilità:	**8 ÷ 4 V/mm**
Linearità:	**< 0,05 ÷ 0.2 mm**

75

Sensibilità alla temperatura



Scostamento della distanza relativa rispetto alla sensibilità nominale

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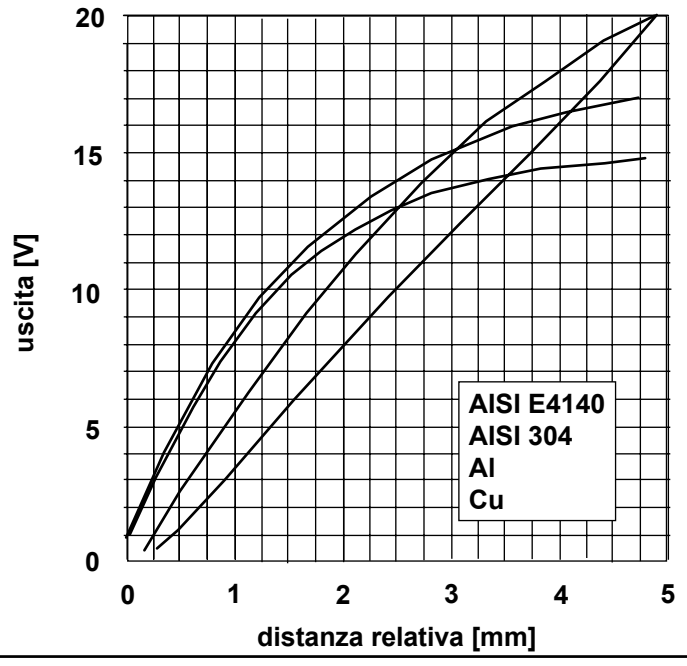
Sensibilità al materiale



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APPLICAZIONI

Trasduttori di prossimità on-off

Trasduttori di spostamento

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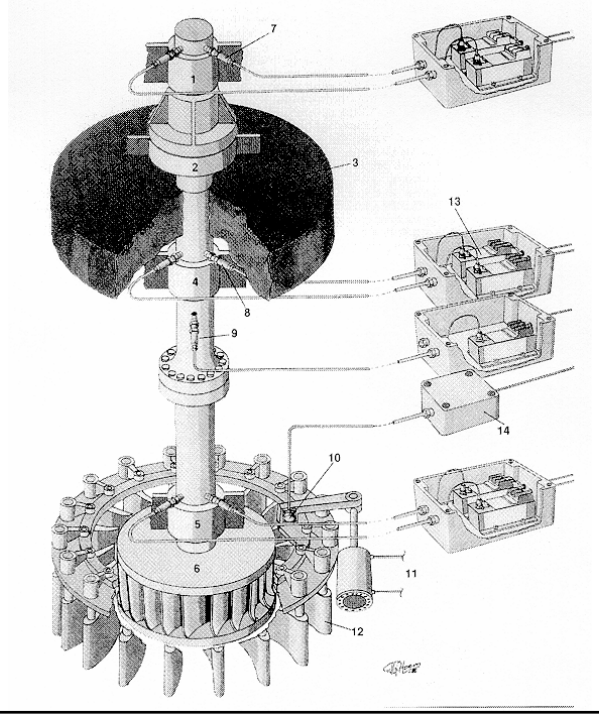
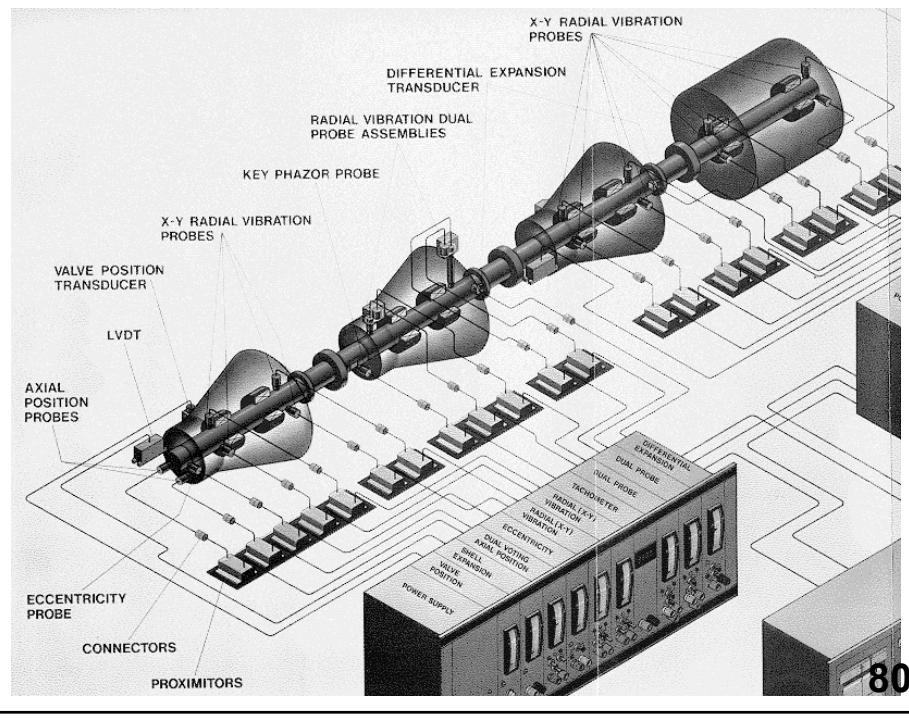


79



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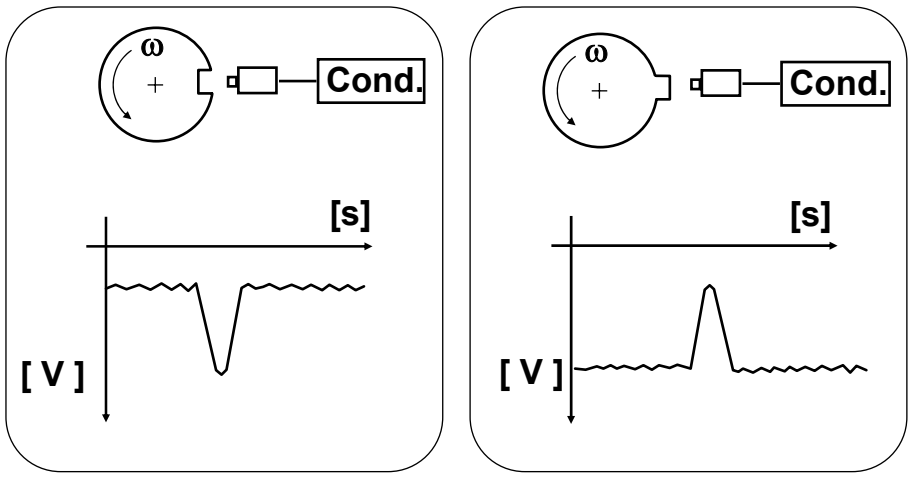
RIFERIMENTO DI FASE



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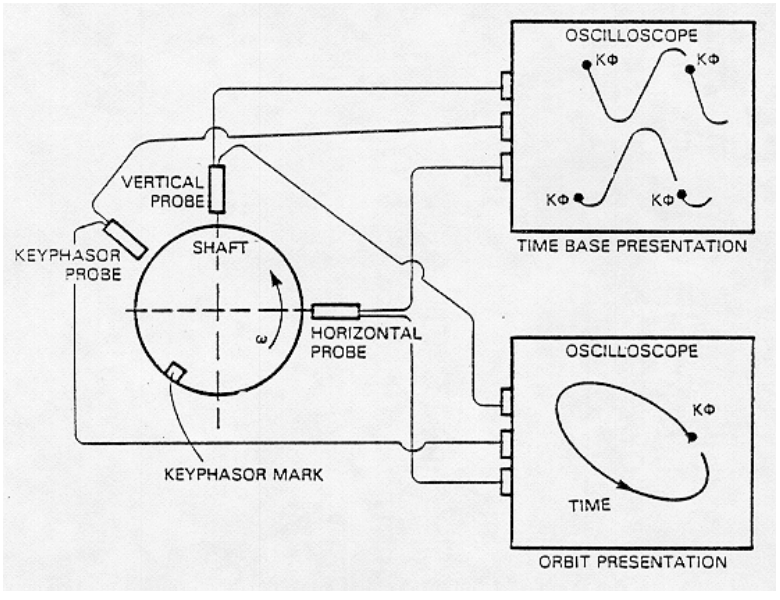
SPOSTAMENTO RELATIVO PERNO-CUSCINETTO



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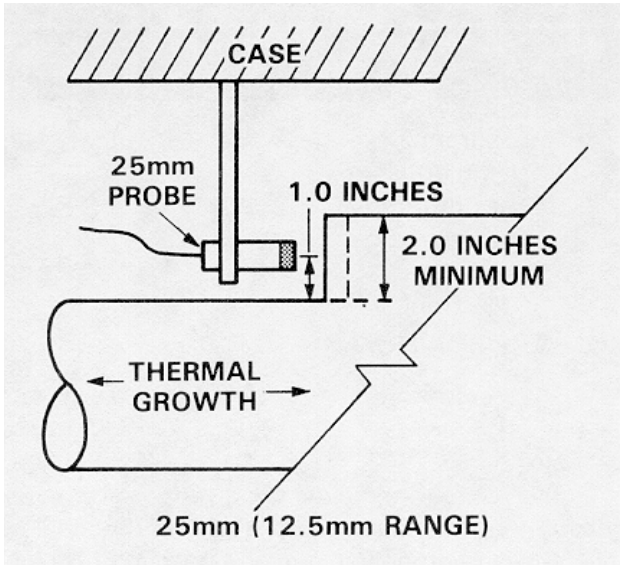
DILATAZIONI DIFFERENZIALI



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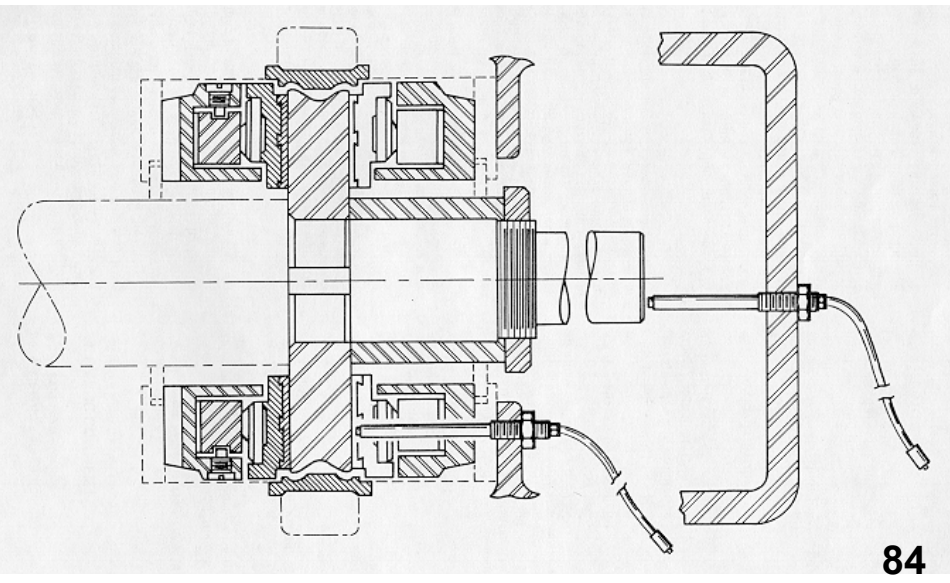
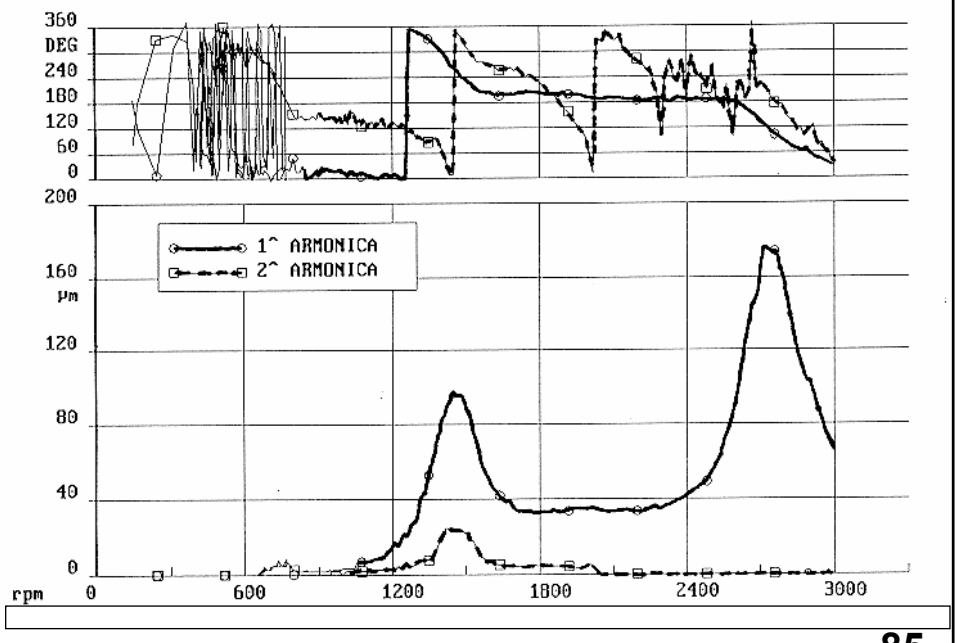
VIBRAZIONI ASSIALI



84



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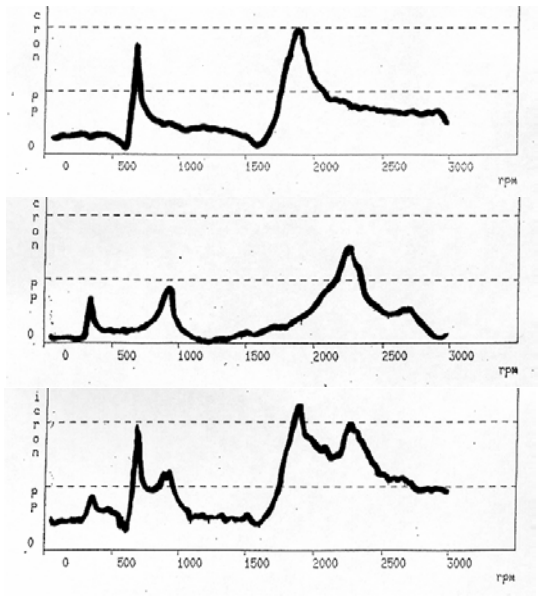
TRANSITORIO DI AVVIAMENTO GRUPPO DA 600 MW
ROTORE DI BASSA PRESSIONE



I armonica

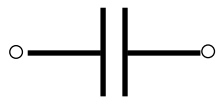
II armonica

totale

86

TRASDUTTORI CAPACITIVI

87



$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

- **C = capacità [pF]**
- **ε_0 = costante dielettrica dell'aria [pF/m]**
- **ε_r = costante dielettrica del materiale tra le armature [pF/m]**
- **A = area delle armature**
- **d = distanza tra le armature**

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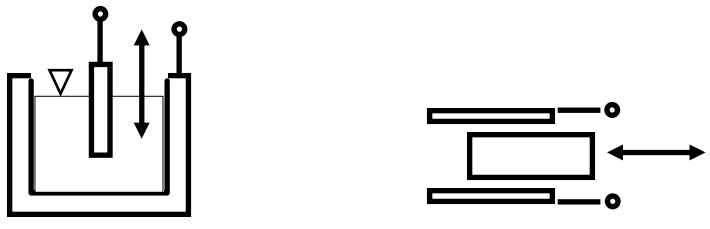
Si può variare C variando ε_r : legame lineare

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$



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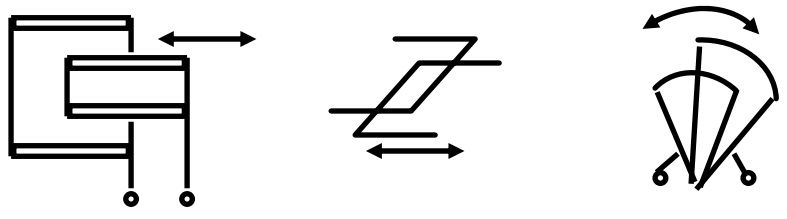
Si può variare C variando A: legame lineare

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$



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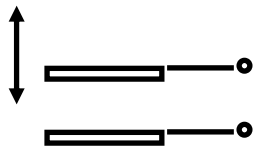
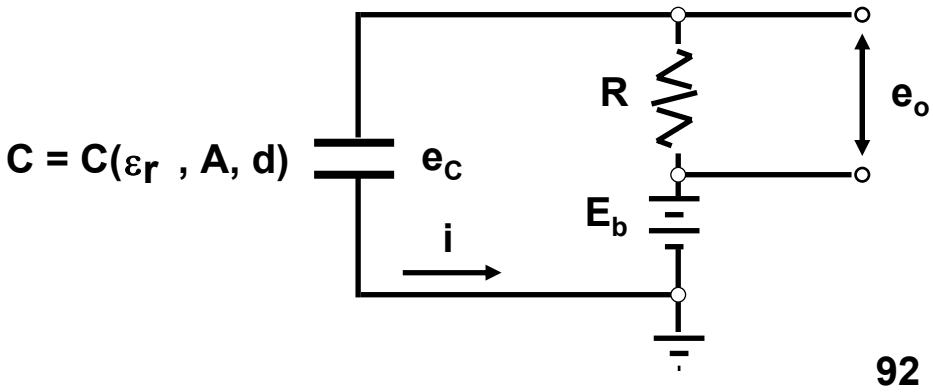
Si può variare C variando d: legame non lineare

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

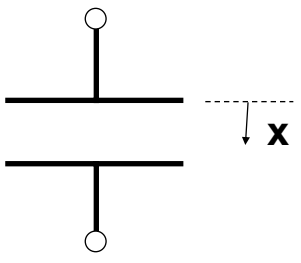


Circuiti di Misura: **si può misurare $e_0 = e_0(C)$**

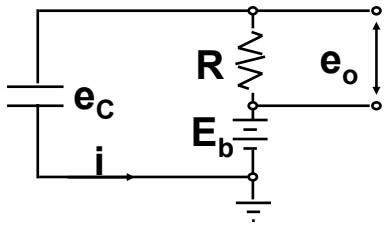
$$e_o = e_C - E_b = iR = -\frac{dq}{dt}R = -\frac{d}{dt}(Ce_C)$$



Esempio: **$C = C(\varepsilon_r, A, x)$**



$$q = Ce_C = \frac{\varepsilon A}{x} e_C$$



$$e_0 = -\frac{dq}{dt}R$$

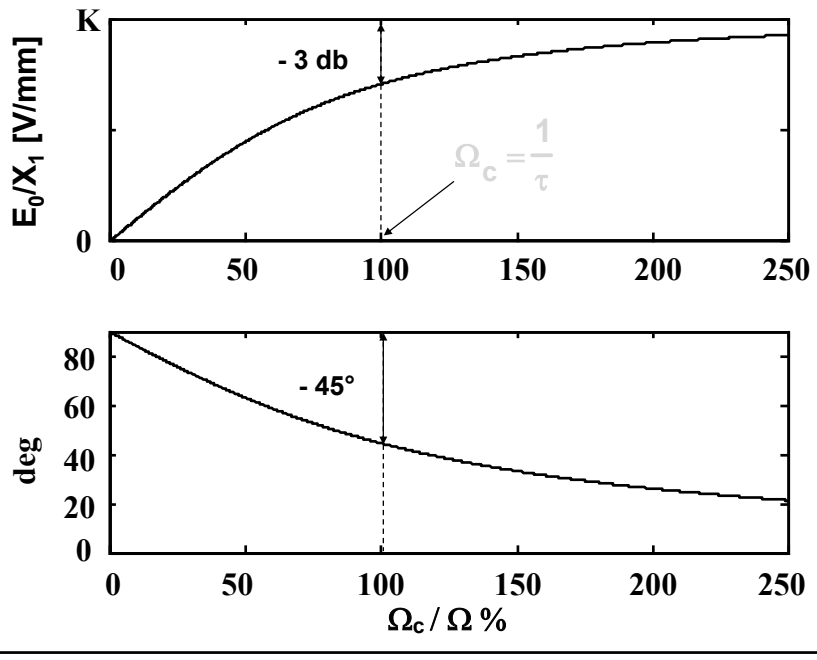
$$\frac{\varepsilon A R}{x_0} = \tau \quad [s] \qquad \frac{E_b}{x_0} = K \quad \left[\frac{V}{mm}\right]$$

Equazione differenziale del 1° ordine

$$\tau \frac{de_0}{dt} + e_0 = K\tau \frac{dx_1}{dt}$$

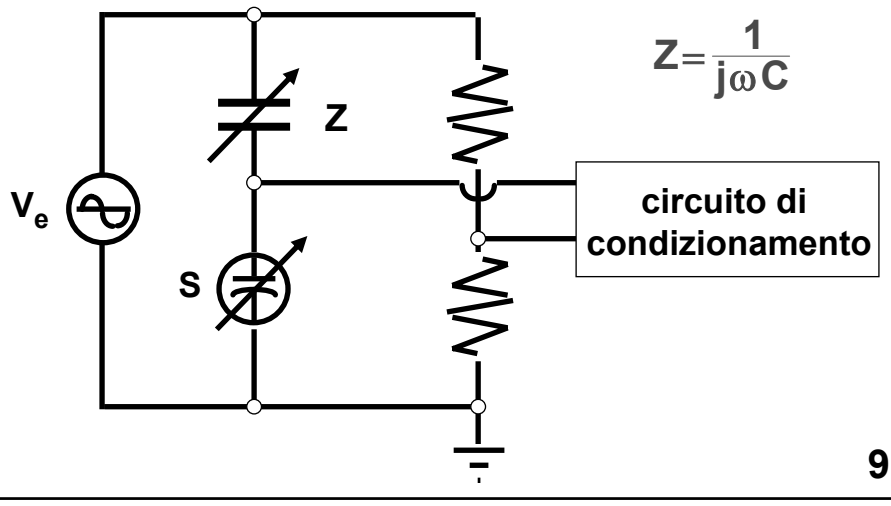
Funzione di trasferimento armonica

$$\frac{E_0}{X_1} = \frac{j\Omega K\tau}{j\Omega\tau + 1}$$



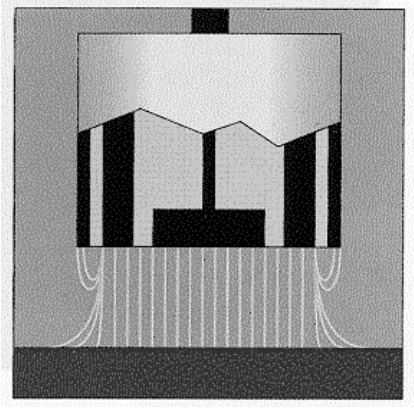
Circuiti di Misura: Ponte di Wheastone in c.a.

si misura la variazione di impedenza Z



$$Z = \frac{1}{j\omega C}$$

APPLICAZIONI: Misura di Spostamento Relativo



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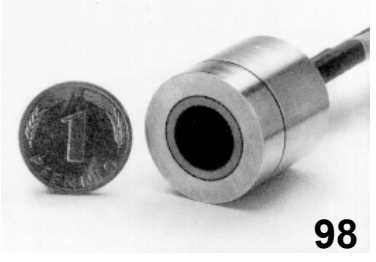
VALORI TIPICI:

- **Portata:** 0,05 ÷ 10 mm
- **Sensibilità:** 1 ÷ 200 V/mm
- **Risoluzione:** 0,02 % f.s.
- **Linearità:** > ± 0,2 % f.s.



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Vantaggi:

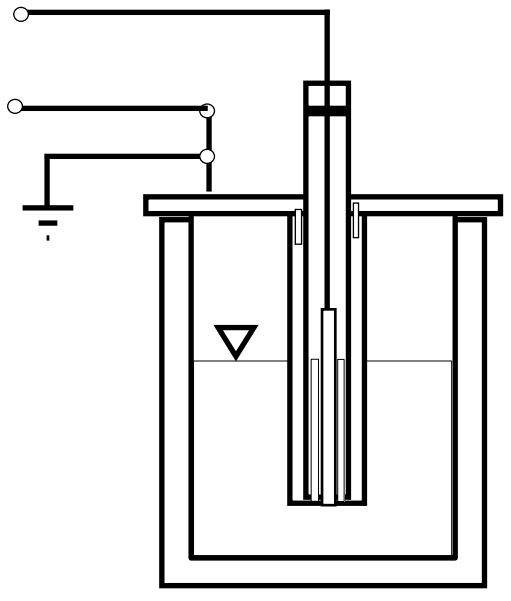
- elevata sensibilità e stabilità
- poco sensibili alle variazioni di temperatura
- target non conduttore

Svantaggi:

- sensibili alle variazioni di capacità del cavo
- sensibili alle variazioni delle caratteristiche del dielettrico (acqua, olio, umidità)
- elevata impedenza

99

APPLICAZIONI: Misura di Livello



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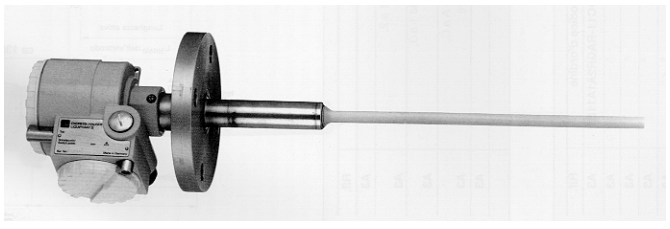
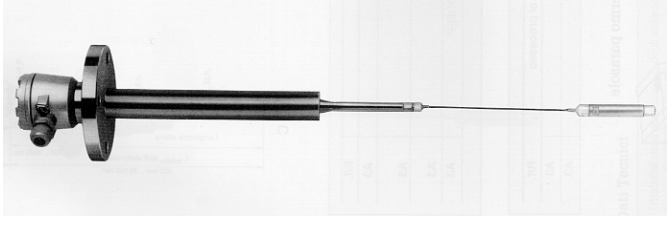
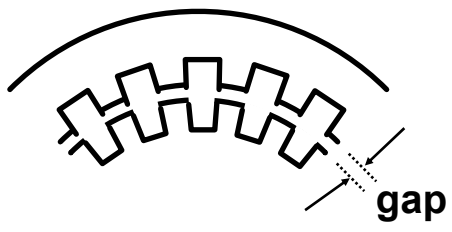


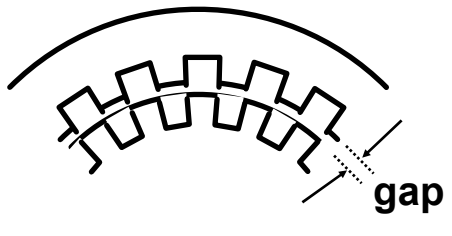


101

APPLICAZIONI: Misura di Coppia



massimo valore di capacità



minimo valore di capacità

102

LASER A TRIANGOLAZIONE

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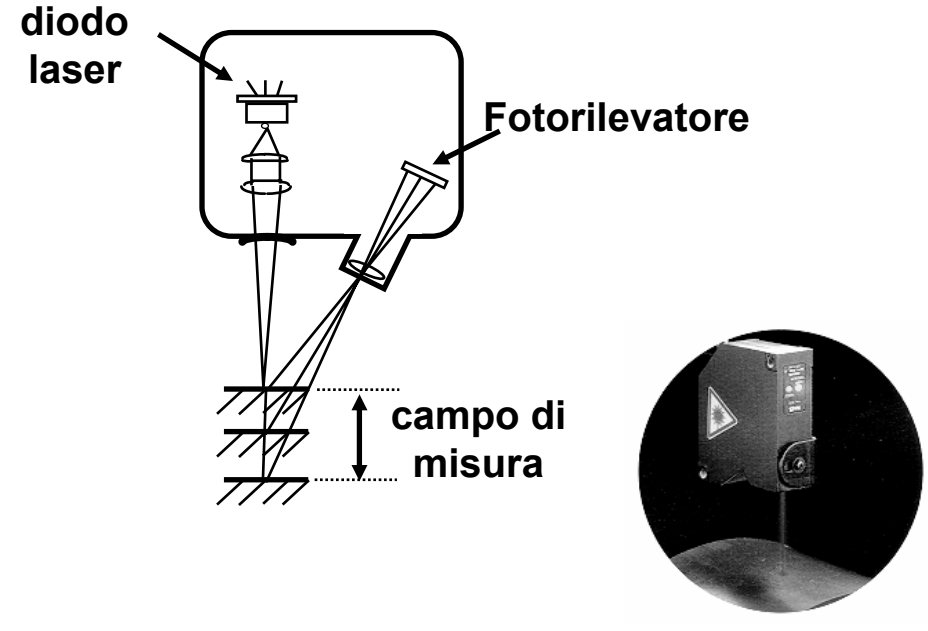

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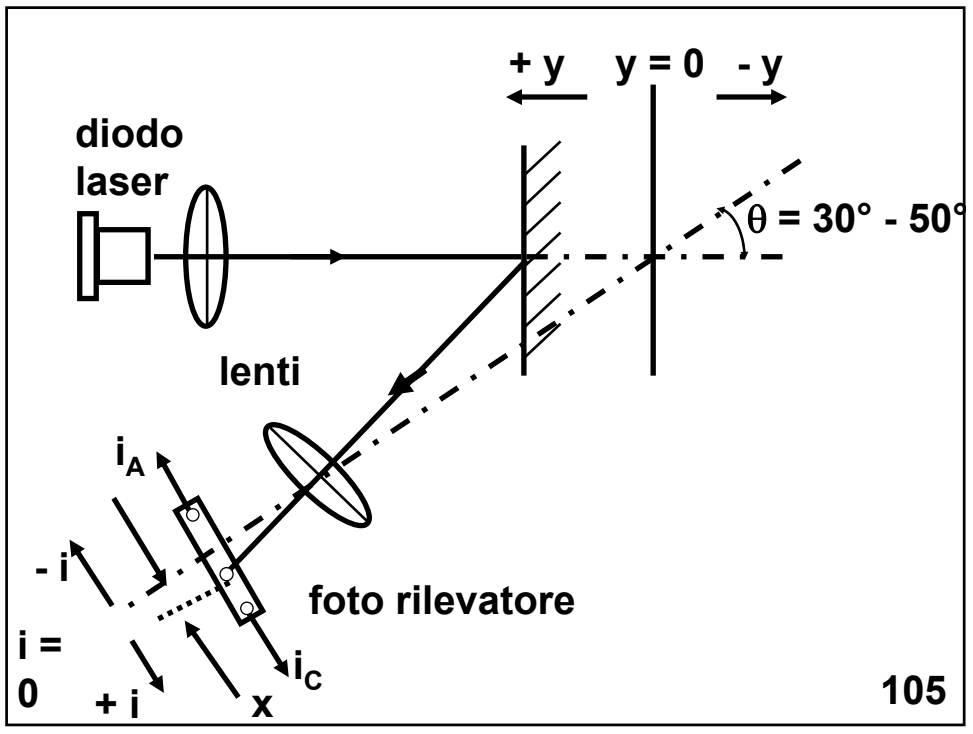

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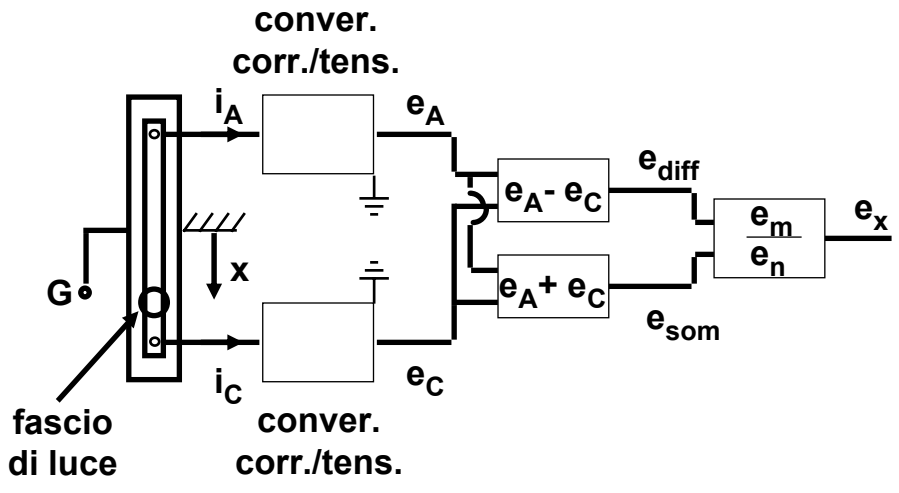

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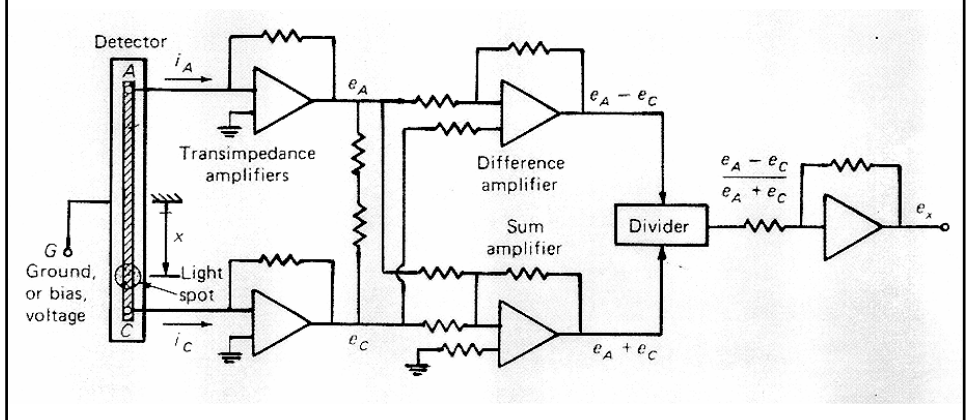

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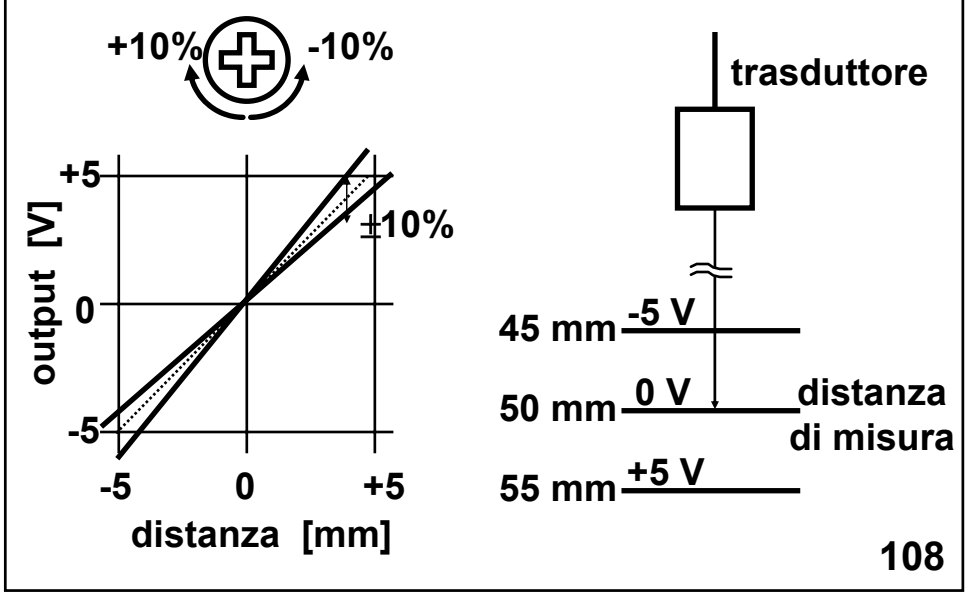

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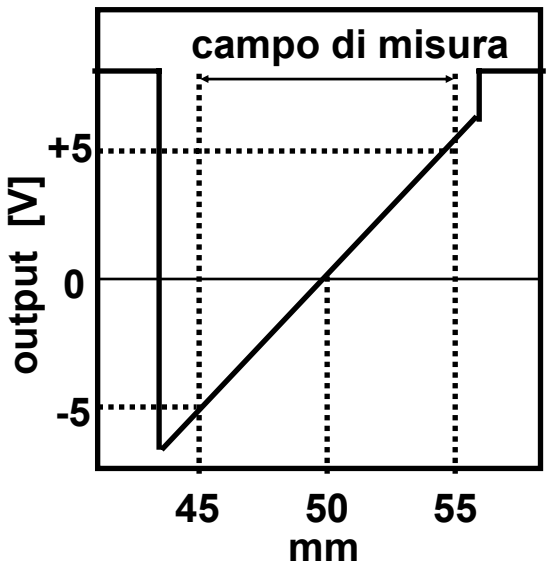
CURVA CARATTERISTICA



sensibilità
1 V/mm

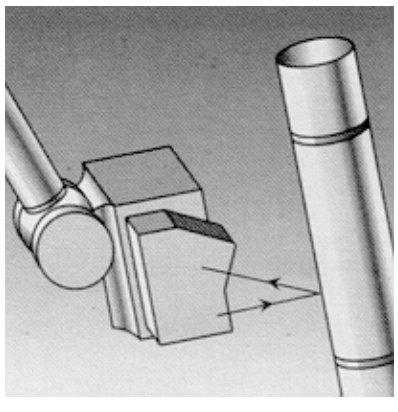
Caratteristiche:

- raggio laser visibile (λ = 675 nm)
- spot di piccole dimensioni (ϕ = 0,1 ÷ 1 mm)
- poco sensibili alla rugosità superficiale e alle variazioni di colore del target
- possibilità di misurare spessori di oggetti trasparenti

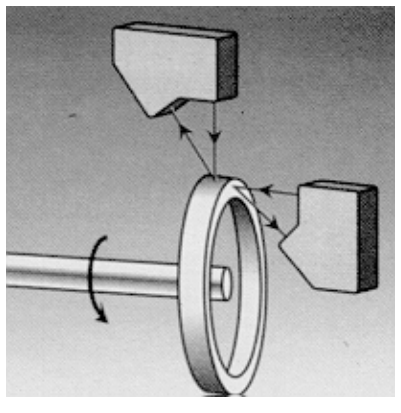
VALORI TIPICI:

◆ Portata:	± 0,25 ÷ 100 mm
◆ Distanza di misura:	5 ÷ 340 mm
◆ Linearità:	2 ÷ 600 μm
◆ Risoluzione:	0,1 ÷ 60 μm
◆ Tempo di integrazione:	0,1 ÷ 30 ms

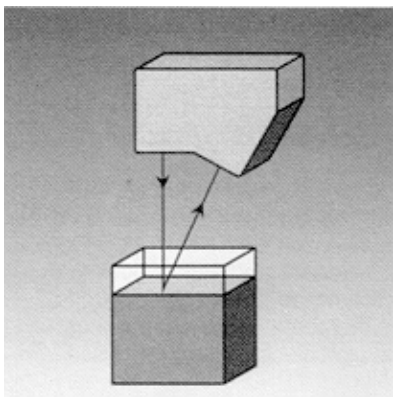
APPLICAZIONI



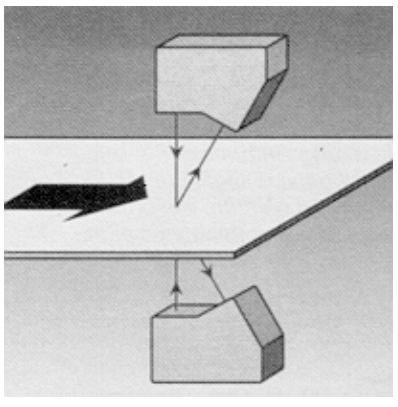
posizionamento
braccio robot



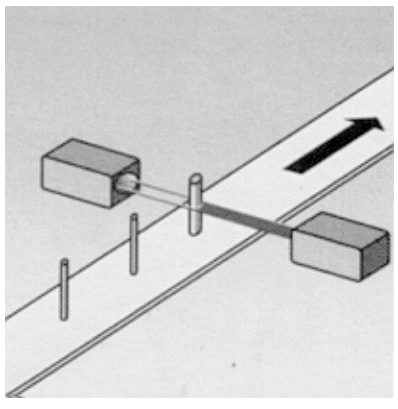
misura di
vibrazioni

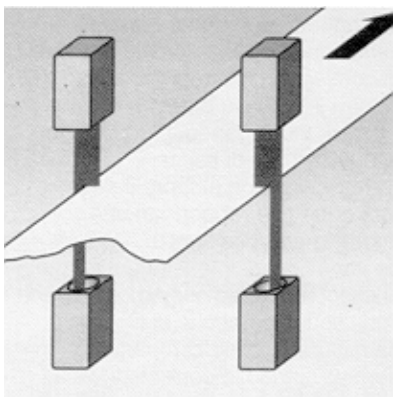


misura di
livello



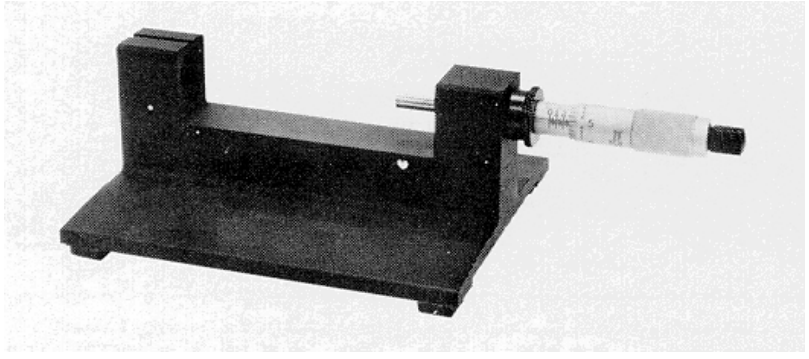
misura di
spessore





controllo di processi produttivi

TARATURA



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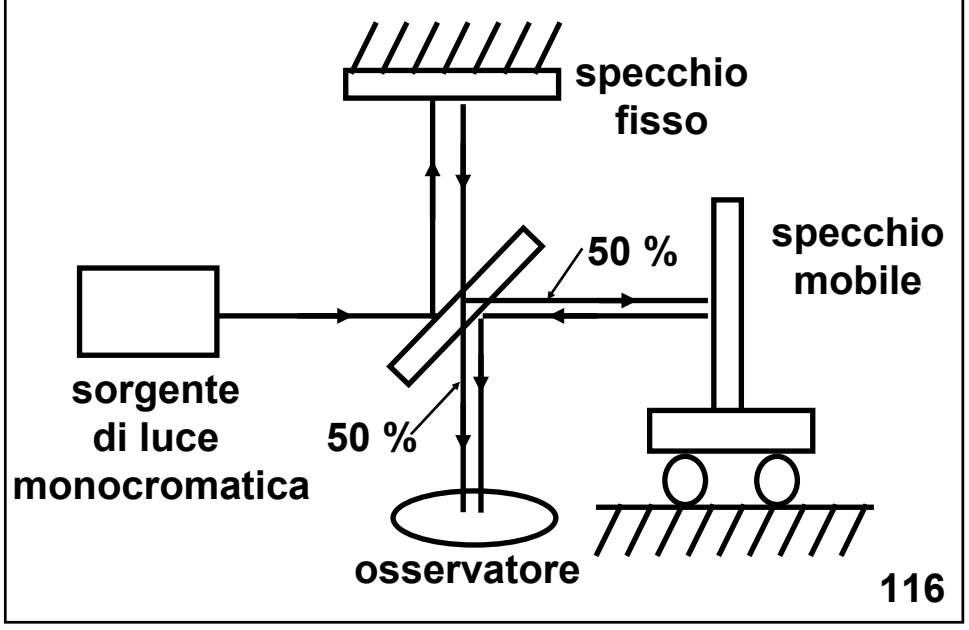
INTERFEROMETRO MICHELSON



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MISURE DI VELOCITA’

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Trasduttori di velocità lineare

LVT

Linear Velocity Transducers

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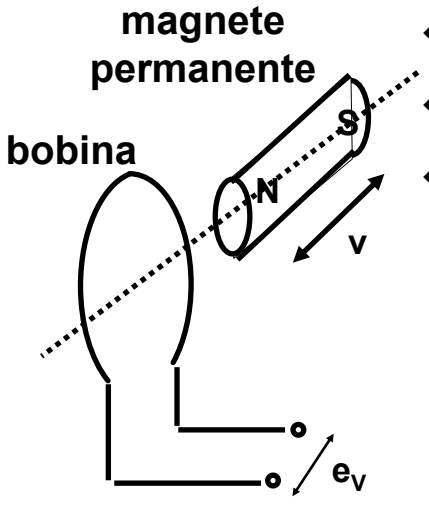
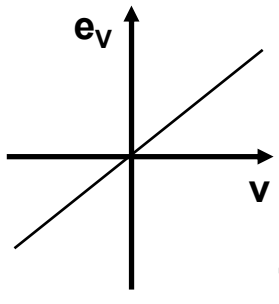
$e_v = B\ l\ v$



- B: densità di flusso
- l: lunghezza della bobina
- v: velocità relativa magnete - bobina



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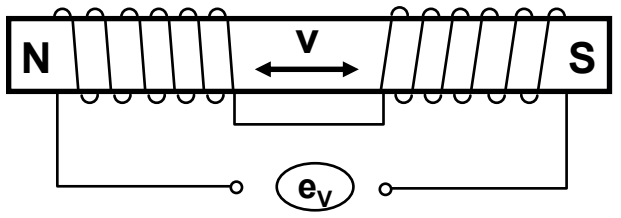
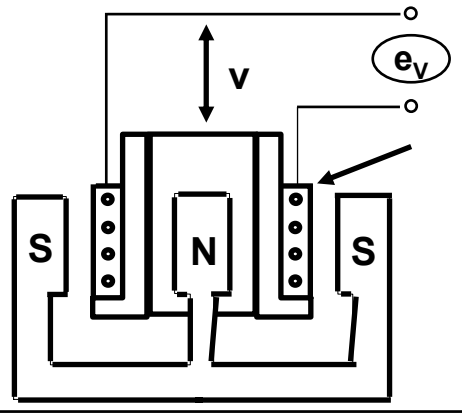


BOBINA FISSA

(avvolgimenti collegati in serie in opposizione)



BOBINA MOBILE

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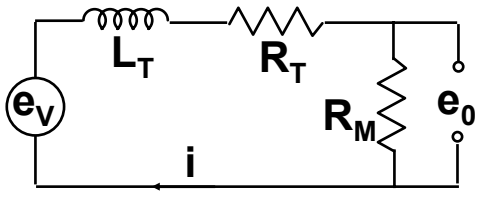
Circuito equivalente



Equazione differenziale del 1° ordine

$$L_T \frac{di}{dt} + (R_T + R_M)\, i = Blv$$

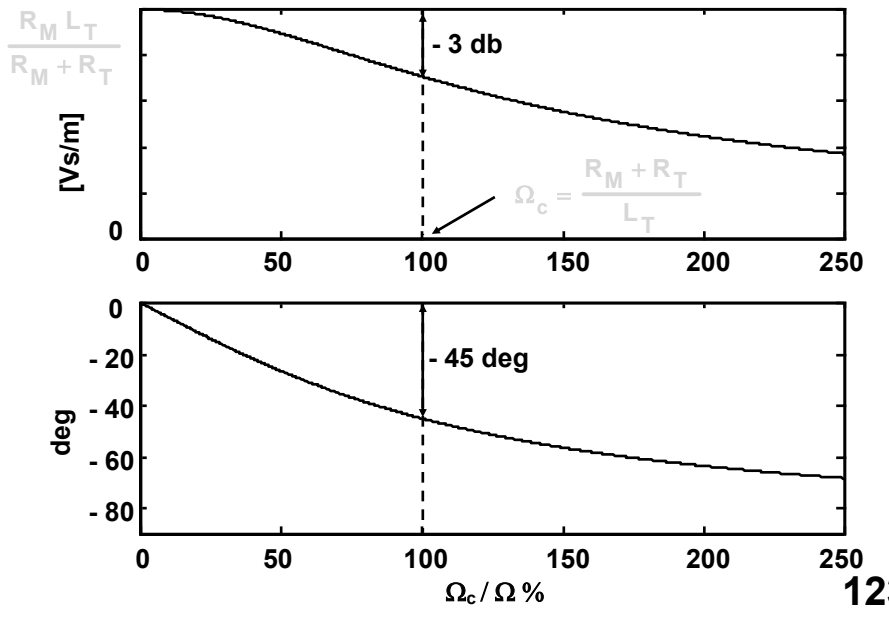
Funzione di trasferimento armonica

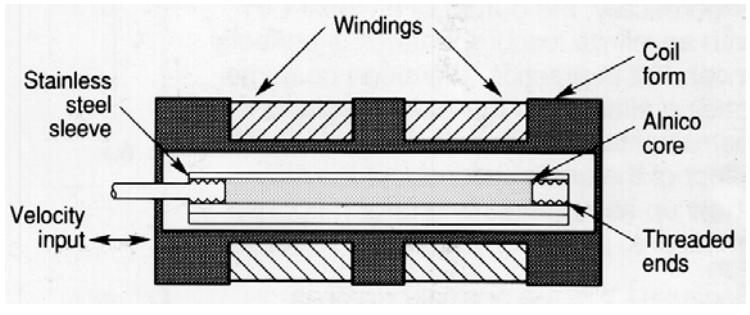
Se: $v = V e^{j\Omega t}$ ⇨ $\frac{dv}{dt} = j\Omega\, V e^{j\Omega t}$

$i = I e^{j\Omega t}$ ⇨ $\frac{di}{dt} = j\Omega\, I e^{j\Omega t}$

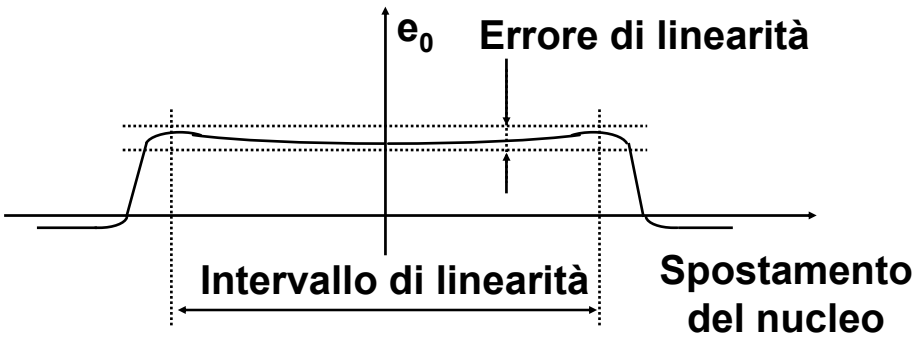
$$\frac{e_0}{V} = \frac{R_M}{V}\, i\, e^{j\Omega t} = \frac{R_M\, S_v}{(R_M + R_T) + j L_T \Omega}\, e^{j\Omega t}$$

LVT: Funzione di trasferimento del circuito





Uscita e_0 a velocità costante



VALORI TIPICI:

- **sensibilità:** 2 - 20 mV/mms^{-1}
- **intervallo di linearità:** 10 - 500 mm
- **linearità:** ± 1% f.s.

Caratteristiche:

- **autoalimentati**
- **elevato guadagno (anche senza amplificatori)**
- **nessun contatto tra bobine e nucleo (attrito molto basso e usura praticamente nulla)**

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Trasduttori di velocità angolare

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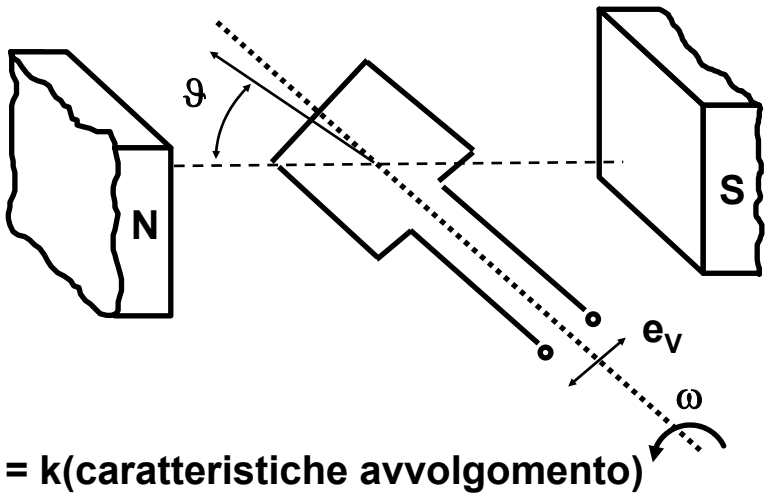
DINAMO TACHIMETRICA

$$e_v = k\,B\,\mathrm{sen}(\vartheta)\,\frac{d\vartheta}{dt} = k\,B\,\omega\,\mathrm{sen}(\vartheta)$$



k = k(caratteristiche avvolgomento)

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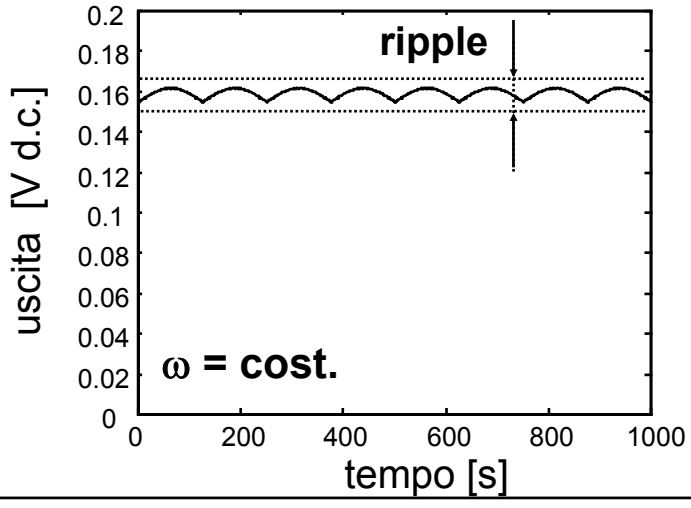
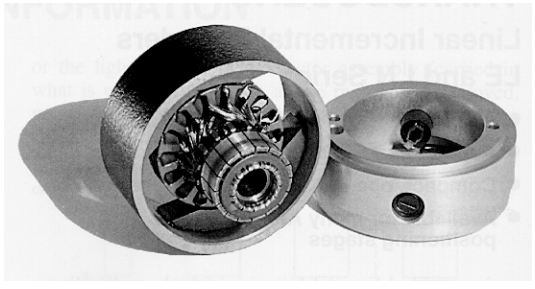
e_v viene raddrizzata con collettore e spazzole $\Rightarrow E_{dc}$

$E_{dc} = E_{dc}(\omega)$ presenta irregolarità (ripple) dovute a asimmetrie meccaniche, anisotropie magnetiche e discontinuità nel contatto tra collettore e spazzole



130



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VALORI TIPICI:

Sensibilità:	**2 .6 mV/rpm**
Linearità:	**< 9 mV**
Ripple (ω > 40 rpm):	**± 3% f.s.**
Velocità max.:	**12000 /rpm**
Durata delle spazzole:	
(@ 1 mA ÷ 3600 rpm)	**100000 h**

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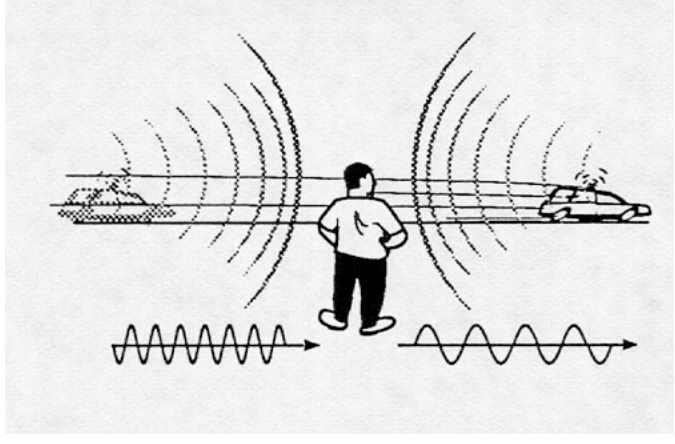
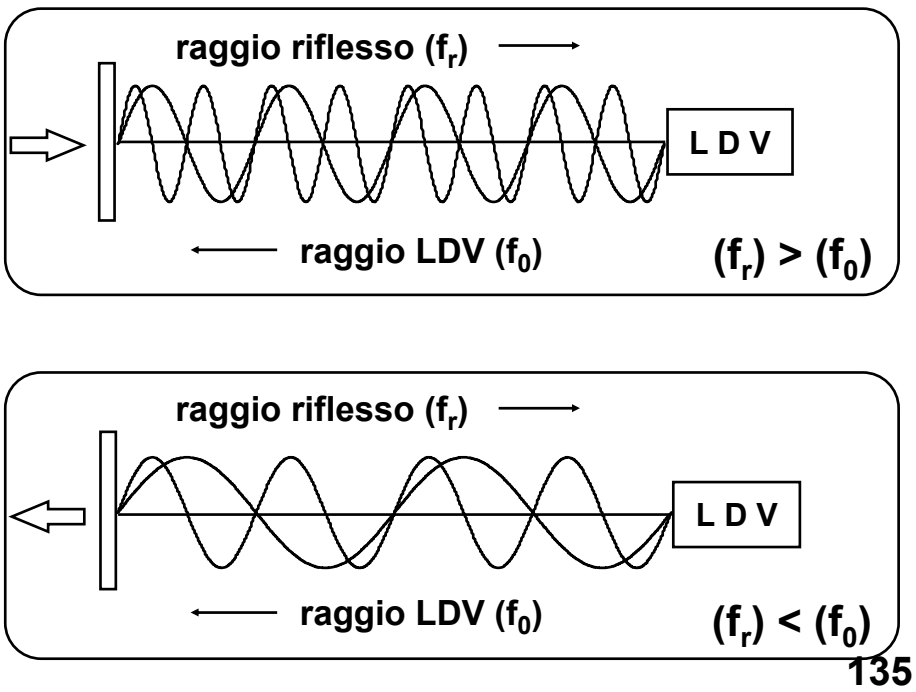
Velocimetri Laser Doppler

LDV

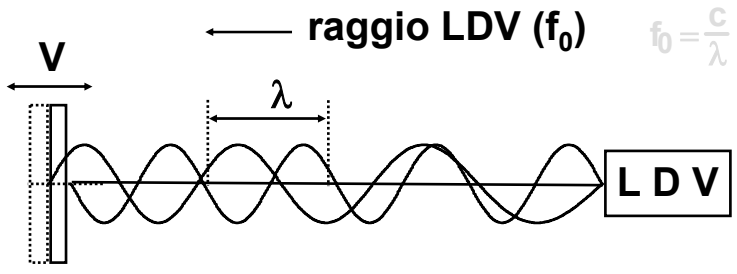
Laser Doppler Velocimeter

Che cosa sente il signor Rossi ???





EFFETTO DOPPLER



raggio riflesso (f_r) ⟶ $f_r = f_0 - f_{doppler}$

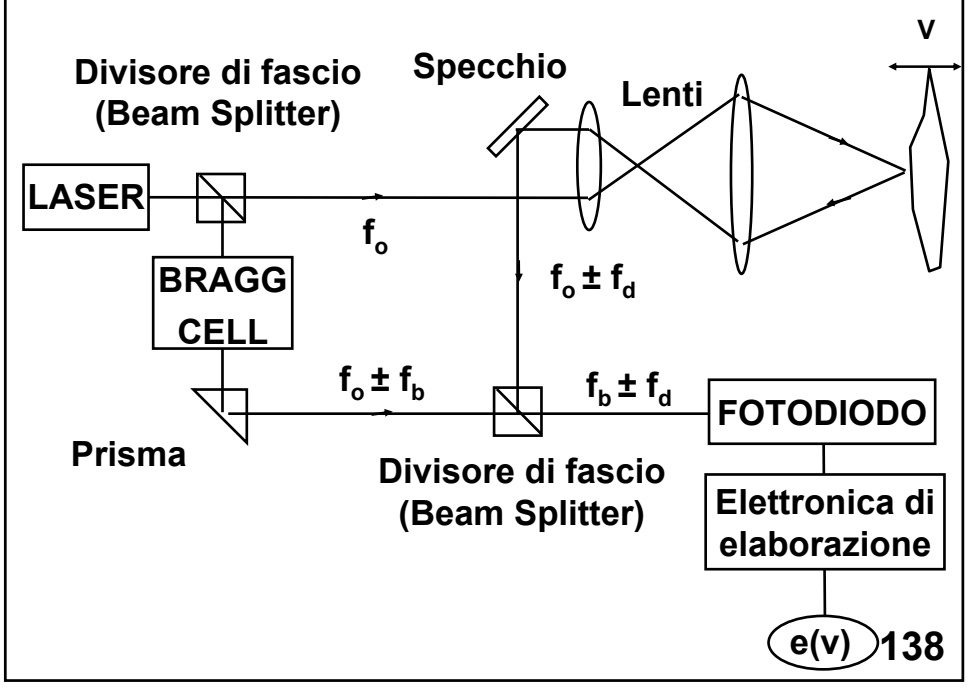
$$f_{doppler} = 2\frac{V}{\lambda}$$

ESEMPIO:

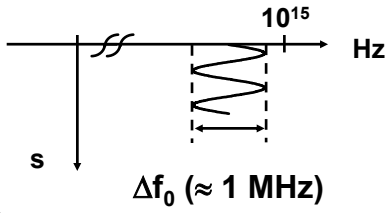
$c = 3 \times 10^8 \text{ m/s}$ $\lambda = 0{,}6328\ \mu\text{m}$

$$f_0 = \frac{3 \times 10^8}{0{,}6328 \times 10^{-6}} = 4{,}74 \times 10^{14} \text{ Hz}$$

Se: $v = 1 \text{ m/s}$ ⇨ $f_{doppler} = 2\frac{1}{0{,}6328} = 3{,}16 \text{ MHz}$

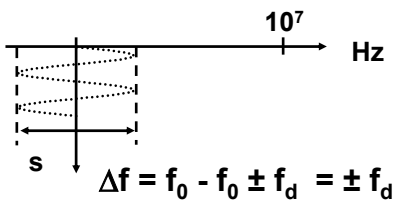


Fascio riflesso



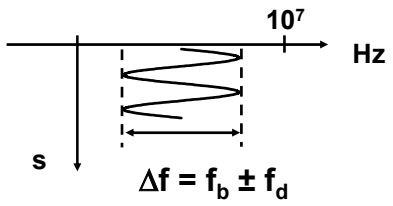
Δf_0 (≈ 1 MHz)

Facio sorgente + Fascio riflesso



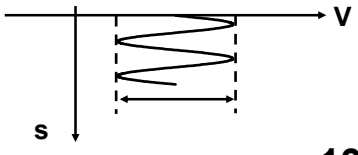
$\Delta f = f_0 - f_0 \pm f_d = \pm f_d$

Fascio sorgente *spostato* + Fascio riflesso



$\Delta f = f_b \pm f_d$

Uscita in tensione dopo demodulazione



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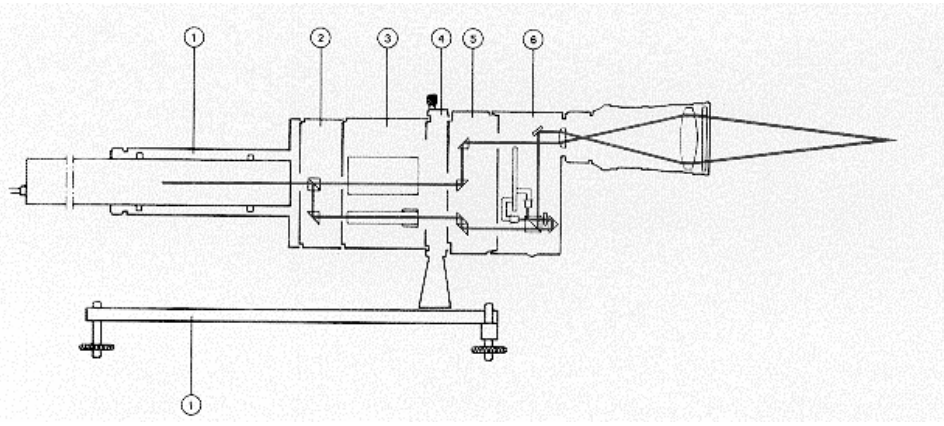

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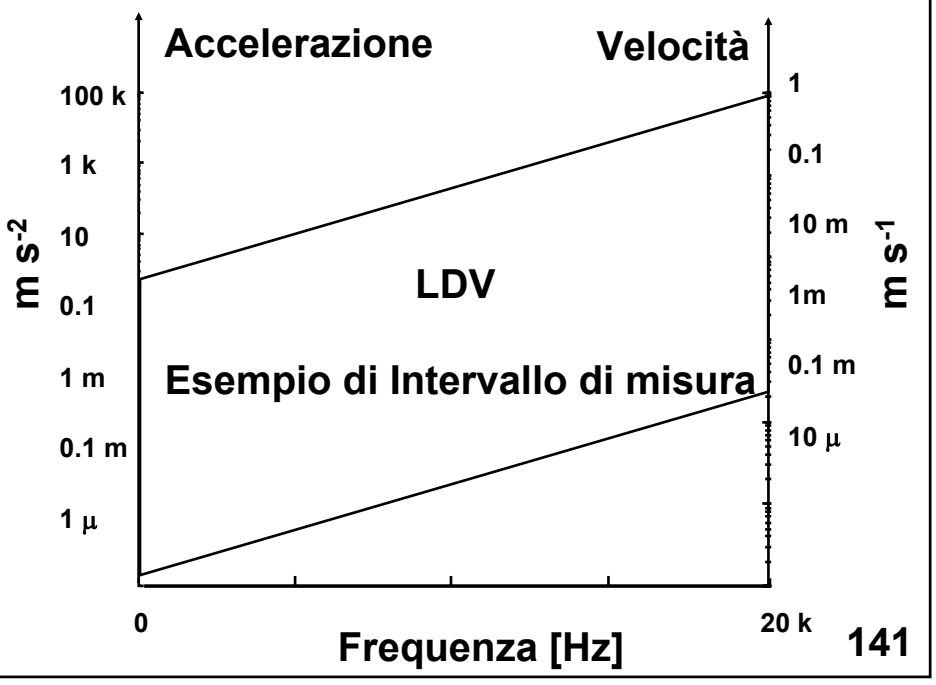

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VALORI TIPICI:

- **Sorgente:** Laser HeNe
- **Lunghezza d'onda (λ):** 632.8 nm
- **Frequenza:** 4.7×10^{14} Hz
- **Potenza:** 1 ÷ 50 mW
- **Sensibilità:** 1 V / ms^{-1}
- **Distanza del target (max):** 0,8 ÷ 200 m
- **Accuratezza:** < 3 % f.s.

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APPLICAZIONI TIPICHE:

Quando l'oggetto da misurare è:

- caldo
- sotto tensione
- radioattivo
- in rotazione
- molto piccolo
- in condizioni ambientali non compatibili con trasduttori tradizionali

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