Analogna i mješovita obrada signala

Predavanja – I. Ciklus

Hvala Darioli na bilježnici
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AMOS

MI	40	
ZI	40	$= P + U = 20+20$
DZ	20	$= 1DZ + 2DZ = 10+10$

1 → 0
2 → 5
3 → 10
4 → 15
5 → 20

PRAG

$MI + ZI_p$	50%	30
ZI	2	
DZ	50%	10

ROK

P	60
U	20
DZ	20

Literatura

S. Franco – ~~[illegible]~~ Designing with operational amplifiers and analog integ

Mijat – El. filtri – 2001. skripta

Lin. nelin izobličenja

definicije

SUSTAV → skup međusobno povezanih komp. koje zajedno obavljaju određenu funkciju

→ 

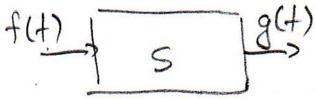
$f(t)$, $g(t)$ - mogu biti i vekt. funkcije - više ulaza i izlaza

ograničavamo se na $f(t)$ i $g(t)$ - skalari (1 ulaz, 1 izlaz)

→ Operator koji djeluje na $f(t)$ dajući $g(t)$

$$g(t) = S[f(t)]$$

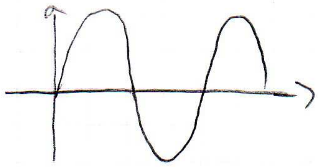
SIGNAL → promjenjiva vremenska veličina $x(t)$

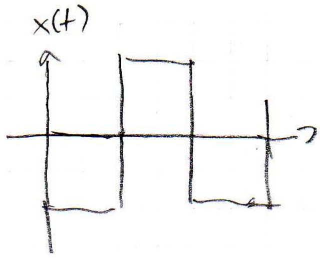


$f(t)$ i $g(t)$ signali

→ interesantni el. signali $u(t)$, $i(t)$, $(P(t), \ldots)$

- valni oblik signala





OBRADA SIGNALA

→ analogna obrada signala - bez pretvorbe

→ dig. obrada signala → nakon A/D pretvorbe

→ mješovita obrada signala - i A i D obrada signala

- Primjeri: audio/video sustavi, modemi, med. uređaji
- korištenje A i D obrade zahtjeva pretvorbu između različitih reprezentacija signala.

Dva moguća scenarija:

a)

2)

$\rightarrow$ D/A $\rightarrow$ ANAL. OBRADA $\rightarrow$ A/D $\rightarrow$

FUNKCIJE (OPERACIJE)

→ pojačavanje

→ filtriranje (smetnji, ...)

→ modulacije i demodulacije (za prijenos i obrade)

→ prilagodba razina

→ prilagodba impedancija

→ U/i i i/U pretvorba

→ linearizacija

→ zbrajanje i oduzimanje

→ derivacija i integracija

→ AC/DC pretvorba

→ detekcija razine

→ ograničavanje razine (limitiranje)

→ A/D ili D/A pretvorba

→ otipkavanje (uzimanje uzoraka)

→ kvantiziranje

⋮

SIGNALI I NJIHOVI SPEKTRI

→ valni oblik signala nam često ne daje dovoljno inf. o signalu
→ svaki signal je sastavljen od određenog broja frekv. komp.
→ skup svih frekv. komp. signala je **SPEKTAR**.

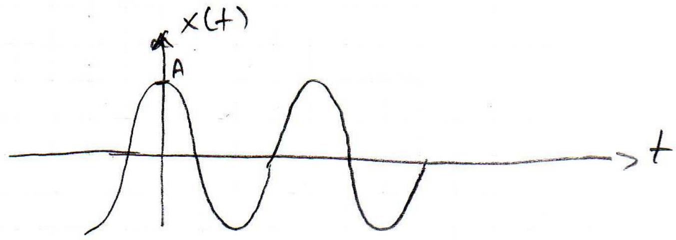
- periodički signali - mogu se prikazati Fourierovim redom - diskretan spektar
- neperiodički signali - prikazuju se Fourierovom transf. - kont. spektar

→ vremenska domena - valni oblik
→ frekv. domena - spektar signala

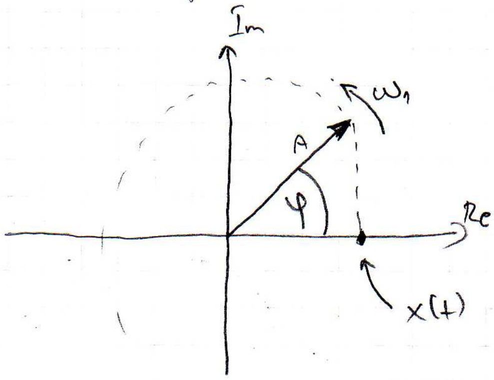
VALNI OBLIK, FAZORSKI PRIKAZ, SPEKTAR

$$x(t) = A\cos(\omega_1 t + \varphi)$$

$$x(t) = A \cdot Re\{e^{j(\omega_1 t + \varphi)}\}$$



Fazorski prikaz

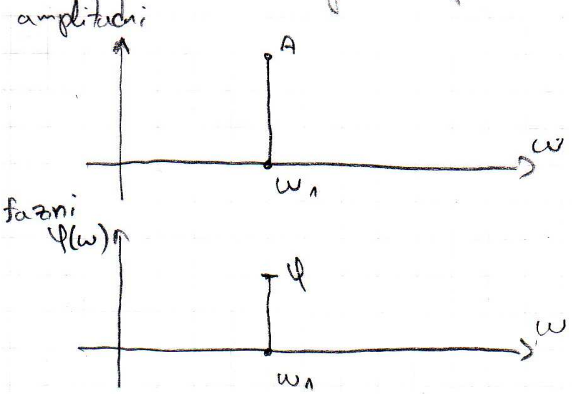


A ... modul

φ ... faza

ω ... kružna frekvencija (rotacije fazora)

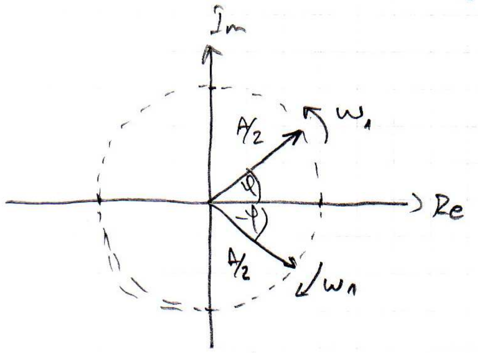
Jednostavni linijski spektar



Isti signal

$$x(t) = \frac{1}{2}Ae^{j(\omega_1 t+\varphi)} + \frac{1}{2}Ae^{-j(\omega_1 t+\varphi)} = A\cos(\omega_1 t + \varphi)$$

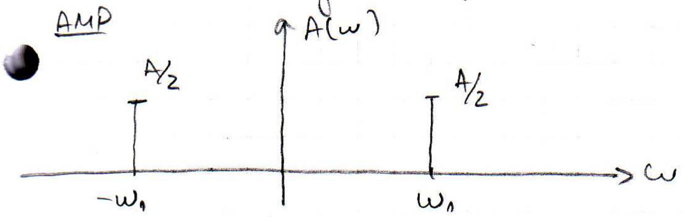
dva fazora istih amplituda koji rotiraju u suprotnim smjerovima



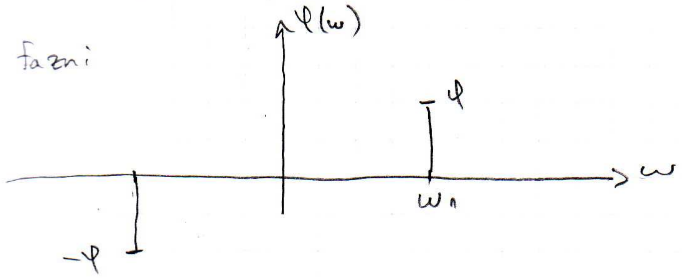
← rezultat vektorski zbroj

Dvostrani linijski spektar

AMP



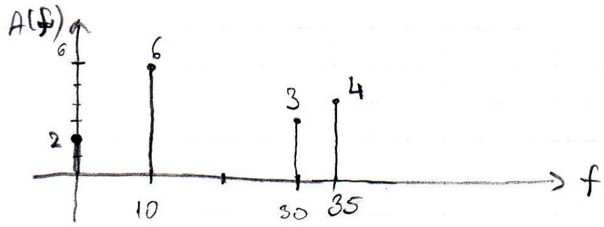
fazni



Primjer

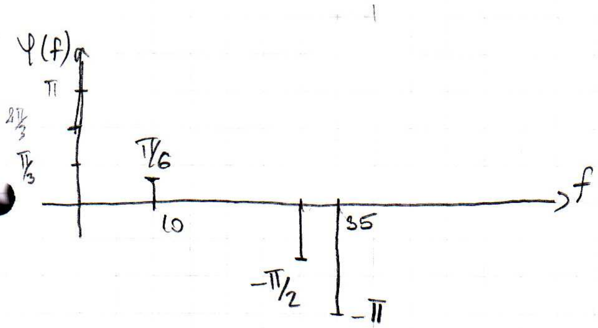
$$x(t) = 2 + 6\cos\left(2\pi 10 t + \frac{\pi}{6}\right) + 3\sin(2\pi 30 t) - 4\cos(2\pi 35 t)$$

Jednostrani linijski spektar



← amplitude su uvijek pozitivne veličine

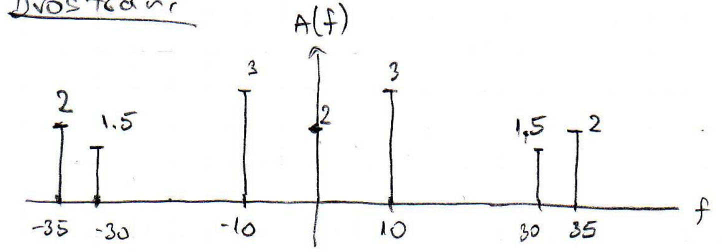
$$3\sin(2\pi 30 t) = 3\cos\left(2\pi 30 t - \frac{\pi}{2}\right)$$



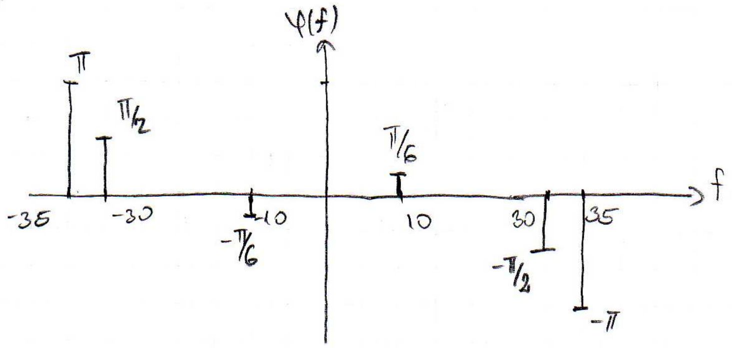
- uzimamo $-\pi$ zbog realnih sustava koji uvijek imaju kašnjenje.
- faza uvijek pada s rastom freku.

$$-4\cos(2\pi 35 t) = 4\cos(2\pi 35 t - \pi)$$

Dvostrani



parna funkcija



neparna funkcija

FOURIEROV RED

Za periodične signale → spektar diskretan

$$f(t) = \sum_{n=-\infty}^{+\infty} F_n \cdot e^{jn\omega_0 t} \quad , n = 0, \pm 1, \pm 2, \ldots$$

$$F_n = \frac{1}{T_0} \int_{-\frac{T_0}{2}}^{\frac{T_0}{2}} f(t) \cdot e^{-jn\omega_0 t} \, dt$$

$$F_n = |F_n| e^{j\phi_n}$$

amplit faze

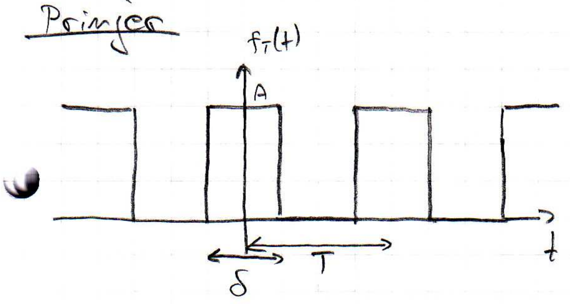
FOURIEROVA TRANSFORMACIJA

Za ne periodične signale → spektar kontinuiran.

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) \cdot e^{j\omega t} \, d\omega$$ ← inverzna F. transf. ← uvijek +j

$$F(\omega) = \int_{-\infty}^{+\infty} f(t) \, e^{-j\omega t} \, dt$$ ← uvijek ima −j

Primjer

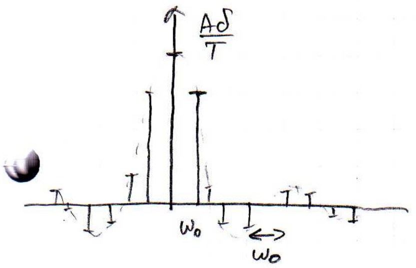


analitički zapis jednog perioda

$$f_T(t) = \begin{cases} A, & -\delta/2 < t < \delta/2 \\ 0, & \delta/2 < t < T-\delta/2 \end{cases}$$

$$f_T(t) = \sum_{n=-\infty}^{+\infty} F_n e^{j\omega_0 t}$$

$$F_n = \frac{1}{T}\int_{-T/2}^{T/2} f_T(t)\, e^{-j\omega_0 n t}\, dt = \frac{1}{T}\int_{-\delta/2}^{\delta/2} A\, e^{-j\omega_0 n t}\, dt = \frac{1}{T}\,\frac{A}{-j\omega_0 n}\, e^{-j\omega_0 n t}\Big|_{-\delta/2}^{\delta/2} = \frac{A\delta}{T}\,\frac{\sin\left(n\omega_0\frac{\delta}{2}\right)}{n\omega_0\frac{\delta}{2}}$$



$$\omega_0 = \frac{2\pi}{T}$$

kad $T \to \infty \Rightarrow \omega_0 \to 0$

↳ neperiodički signal → kont. spektar

odlici F. integrala

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)\, e^{-j\omega t}\, dt$$

model i faza

$F(\omega)$ kompleksna $\Rightarrow$ $F(\omega) = F_{Re}(\omega) + j F_{Im}(\omega) = |F(\omega)|\, e^{j\varphi(\omega)}$

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)\, e^{-j\omega t}\, dt = \int_{-\infty}^{+\infty} f(t)\left[\cos(\omega t) - j\sin(\omega t)\right] dt =$$

$$= \int_{-\infty}^{+\infty} f(t)\cos(\omega t)\, dt - j\int_{-\infty}^{+\infty} f(t)\sin(\omega t)\, dt = F_R(\omega) + j F_I(\omega)$$

$$F_{Re}(\omega) = |F(\omega)|\cos(\varphi(\omega))$$

$$F_{Im}(\omega) = |F(\omega)|\sin(\varphi(\omega))$$

1. $f(t)$ kompleksni

$$f(t) = f_{Re}(t) + j f_{Im}(t)$$

$$F(\omega) = \int_{-\infty}^{+\infty} \left[f_R(t) + j f_I(t)\right]\cdot\left[\cos(\omega t) - j\sin(\omega t)\right] dt =$$

$$= \underbrace{\int_{-\infty}^{+\infty} \left[f_R\cos(\omega t) + f_I\sin(\omega t)\right] dt}_{F_{Re}(\omega)} \underbrace{- j\int_{-\infty}^{+\infty} \left[f_R\sin(\omega t) - f_I\cos(\omega t)\right] dt}_{jF_{Im}(\omega)}$$

$$f_R = \frac{1}{2\pi}\int_{-\infty}^{+\infty}\left[F_R(\omega)\cos(\omega t) - F_i(\omega)\sin(\omega t)\right]d\omega$$

$$f_I(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty}\left[F_R(\omega)\sin(\omega t) + F_i(\omega)\cos(\omega t)\right]d\omega$$

Specijalni slučajevi

a) $f(t)$ realna

$$f(t) = f_R(t) \quad , \quad f_i(t) = 0$$

$$F_R(\omega) = \int_{-\infty}^{+\infty} f_r \cos(\omega t)\,dt \quad , \quad F_i(\omega) = -\int_{-\infty}^{+\infty} f(\omega)\sin(\omega t)\,dt$$

$$F_R(-\omega) = F_R(\omega) \quad , \quad F_i(-\omega) = -F_i(\omega)$$

$$F(-\omega) = {}^*F(\omega)$$

Inverzna transf.

$$f_i(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty}\Big[\underbrace{\overbrace{F_r(\omega)}^{\text{PARNA}}\overbrace{\sin(\omega t)}^{\text{NEP.}}}_{\text{NEPARNA}} + \underbrace{\overbrace{F_i}^{N}\overbrace{\cos(\omega t)}^{P}}_{\text{NEPARNA}}\Big]d\omega = 0$$

integral neparne funkcije po simetričnom intervalu jednak je 0 zbog jednakih površina na obe strane

$$f_r(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty}\Big[\underbrace{F_r(\omega)\cos(\omega t)}_{\text{PARNA}} - \underbrace{F_i(\omega)\sin(\omega t)}_{\text{PARNA}}\Big]d\omega = \frac{1}{\pi}\int_{0}^{+\infty}\left[F_r(\omega)\cos(\omega t) - F_i\sin(\omega t)\right]d\omega$$

b) $f(t)$ imaginarno

$$f(t) = j\,f_i(t) \quad , \quad f_R(t) = 0$$

$$F_R(\omega) = \int_{-\infty}^{+\infty} f_i(t)\sin\omega t\,dt \qquad F_i(\omega) = \int_{-\infty}^{+\infty} f(t)\cos(\omega t)\,dt$$

$$F_R(-\omega) = -F_R(\omega) \qquad F_i(-\omega) = F_i(\omega)$$

$$F(-\omega) = -{}^*F(\omega)$$

c) $f(t)$ parna

$$f_p(-t) = f_p(t)$$

$$F_R(\omega) = \int_{-\infty}^{+\infty} \overbrace{f_p(t)\cos\omega t}^{\text{PARNA}}\,dt = 2\int_{0}^{+\infty} f_p(t)\cos(\omega t)\,dt$$

$$F_i(\omega) = -\int_{-\infty}^{+\infty} \underbrace{f_p(t)\sin\omega t}_{\text{NEPARNA}}\,dt = 0$$

Inverzna

$$f_P(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} F_r(\omega)\cos(\omega t)\,d\omega = \frac{1}{\pi}\int_{0}^{+\infty} F_r(\omega)\cos(\omega t)\,d\omega$$

PARNA

d) $f(t)$ neparna

$$f_N(-t) = -f_N(t)$$

$$F_R(\omega) = \int_{-\infty}^{+\infty} f_N(t)\cos(\omega t)\,dt = 0$$

$$F_i(\omega) = -\int_{-\infty}^{+\infty} f_N(t)\sin(\omega t)\,dt = -2\int_{0}^{+\infty} f_N(t)\sin(\omega t)\,dt$$

e) $f(t)$ realna funkcija kao suma parne i neparne

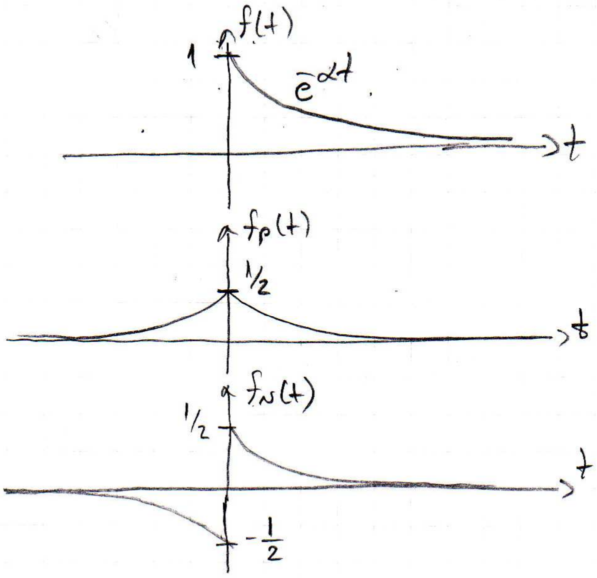
$$f(t) = f_P(t) + f_N(t)$$

$$f(-t) = f_P(-t) + f_N(-t) = f_P(t) - f_N(t)$$

$$\Rightarrow f_P(t) = \frac{f(t)+f(-t)}{2}, \quad f_N(t) = \frac{f(t)-f(-t)}{2}$$

Primjer

$$f(t) = e^{-\alpha t}s(t)$$



$f(t) = 2f_P(t)$, $t > 0$

$f(t) = 2f_N(t)$, $t > 0$

$$f(t) \circ\!\!-\!\!\bullet\; F_r(\omega) + jF_i(\omega)$$

$$f_P(t) \circ\!\!-\!\!\bullet\; F_r(\omega)$$

$$f_N(t) \circ\!\!-\!\!\bullet\; jF_i(\omega)$$

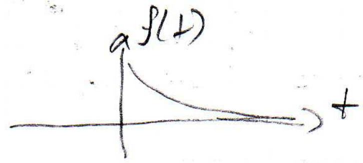
$$F_R(\omega) = 2\int_{0}^{+\infty} f_P(t)\cos(\omega t)\,dt \qquad f_P(t) = \frac{1}{\pi}\int_{0}^{+\infty} F_R(\omega)\cos(\omega t)\,d\omega$$

$$F_i(\omega) = -2\int_{0}^{\infty} f_N(t)\sin(\omega t)\,dt \qquad f_N(t) = \frac{-1}{\pi}\int_{0}^{+\infty} F_i(\omega)\sin(\omega t)\,d\omega$$

KAUZALNOST

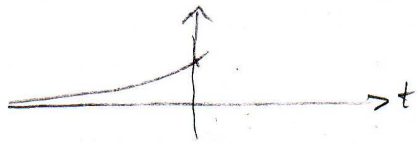
f) $f(t)$ kauzalan

$f(t) = 0 \quad , t < 0$



onda vrijedi

$f(-t) = 0 \quad , t > 0$



$f(t) = 2 f_p(t) \quad , t > 0$

$f(t) = 2 f_N(t) \quad , t > 0$

$$f(t) = \frac{2}{\pi} \int_0^{\infty} F_r(\omega) \cos(\omega t) d\omega = -\frac{2}{\pi} \int_0^{+\infty} F_i(\omega) \sin(\omega t) d\omega$$

$$F_i(\omega) = -\int_{-\infty}^{+\infty} f(t) \sin(\omega t) dt = -\int_{\underbrace{\scriptstyle 0}_{\text{zbog kauzalnosti}}}^{+\infty} f(t) \sin(\omega t) dt$$

$$\boxed{\begin{aligned} F_i(\omega) &= -\frac{2}{\pi} \iint_0^{+\infty} F_R(y) \cos yt \sin \omega t \, dy \, dt \\ F_R(\omega) &= -\frac{2}{\pi} \iint_0^{+\infty} F_i(y) \sin yt \cos \omega t \, dy \, dt \end{aligned}}$$

računanje Im spektra preko Re.

SVOJSTVA FOURIEROVIH TRANSFORMACIJA

$$\mathcal{F}[a_1 f_1(t) + a_2 f_2(t)] = a_1 F_1(\omega) + a_2 F_2(\omega)$$

simetrična

$$\mathcal{F}[f(t)] = F(t) \quad \Rightarrow \quad \mathcal{F}[F(t)] = 2\pi f(-\omega)$$

$$\mathcal{F}[f(at)] = \frac{1}{a} F\left(\frac{\omega}{a}\right)$$

Pomak

$$\mathcal{F}[f(t - t_0)] = F(\omega) e^{-j\omega t_0}$$

$$\mathcal{F}[f(t) e^{-j\omega_0 t}] = F(\omega - \omega_0)$$

$$\mathcal{F}\left[\frac{df(t)}{dt}\right] = j\omega F(\omega) - f(0)$$

$$\mathcal{F}\left[\frac{d^n f(t)}{dt^n}\right] = (j\omega)^n F(\omega) - (j\omega)^{n-1} f(0) - (j\omega)^{n-2} f'(0) \ \ldots$$

$$\mathcal{F}\left[\int_{-\infty}^{t} f(t) dt\right] = \frac{F(\omega)}{j\omega}$$

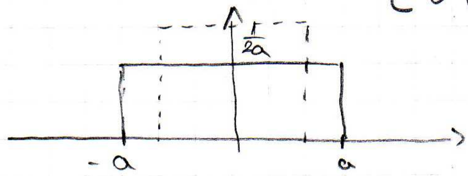
$$\mathcal{F}\left[\frac{d^n F(\omega)}{d\omega}\right] = (jt)^n f(t)$$

$$\mathcal{F}[f(t)*g(t)] = F(\omega)\cdot G(\omega)$$

$$f(t)*g(t) = \int_{-\infty}^{+\infty} f(\tau)\, g(t-\tau)\, d\tau$$

$$\mathcal{F}[f(t)\cdot g(t)] = \frac{1}{2\pi} F(\omega)*G(\omega)$$

$$p_a(t) = \begin{cases} \frac{1}{2a}, & -a<t<a \\ 0, & \text{inače} \end{cases}$$



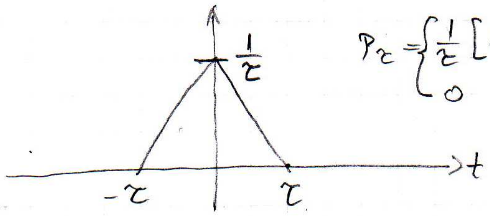
singularne funkcije

$$\int_{-\infty}^{+\infty} \delta(t)\,dt = 1$$

$$\int_{-\infty}^{+\infty} \delta(t)\,\phi(t)\,dt = \phi(0)$$

$$\int_{-\infty}^{+\infty} \delta(t-t_0)\,\phi(t)\,dt = \phi(t_0)$$

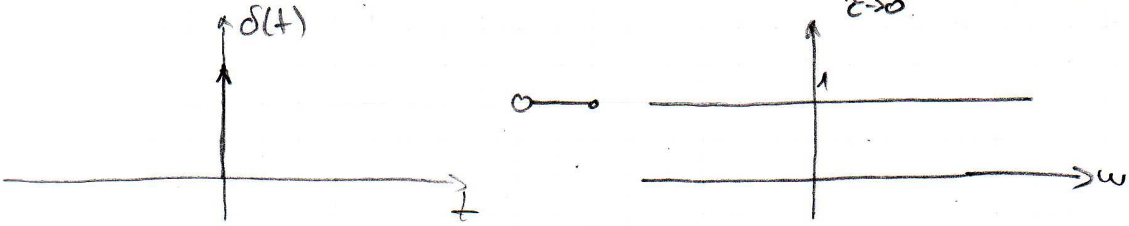
$$\delta(t) = \lim_{a\to 0} p_a(t) = \lim_{a\to 0} \frac{1}{2a}\left[S(t+a) - S(t-a)\right]$$



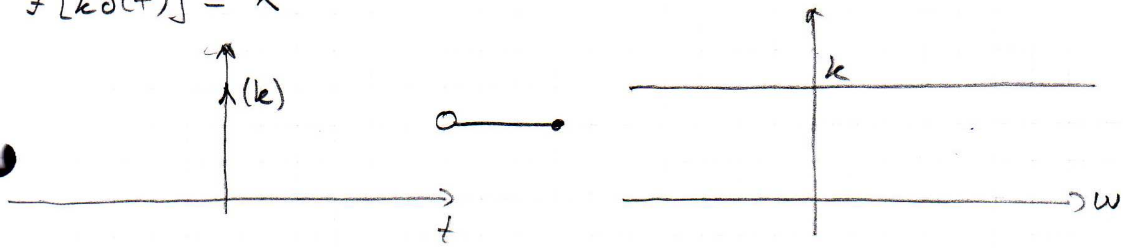
$$p_\tau = \begin{cases} \frac{1}{\tau}\left[1-\frac{|t|}{\tau}\right], & |t|<\tau \\ 0, & \text{inače} \end{cases}$$

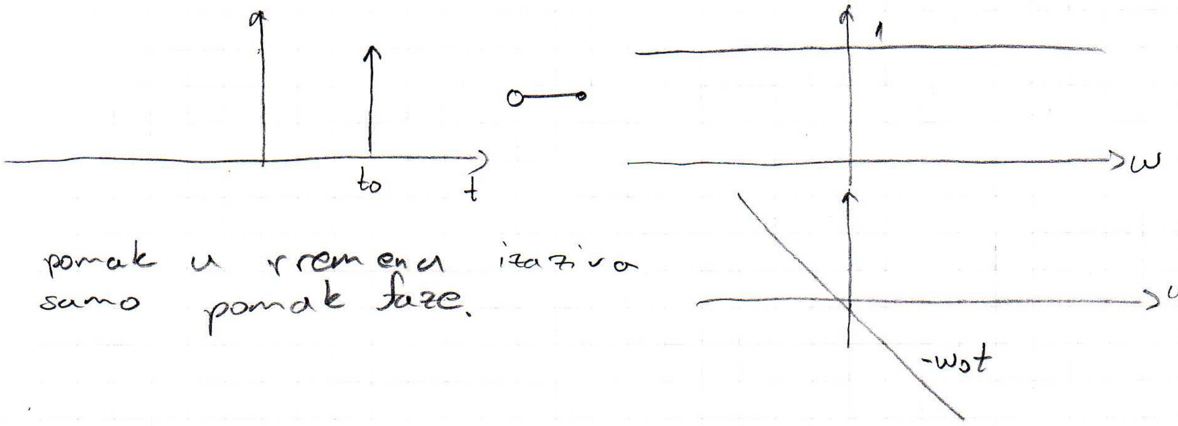
$$\delta(t) = \lim_{\tau\to 0} \frac{1}{\tau}\left(1-\frac{|t|}{\tau}\right)$$

$$\mathcal{F}[\delta(t)] = \int_{-\infty}^{+\infty} \delta(t)\, e^{-j\omega t}\, dt = 1$$



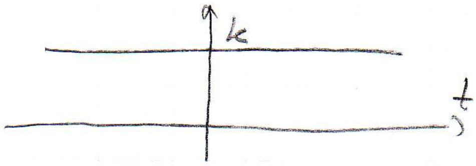
$$\mathcal{F}[k\delta(t)] = k$$

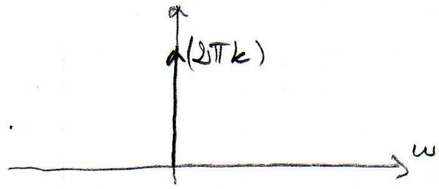




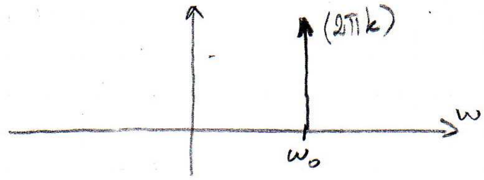
pomak u vremenu izaziva samo pomak faze.

$f(t)=k$ $\xrightarrow[]{\text{teorem dualnosti}}$ $F(\omega)=2\pi k\,\delta(\omega)$



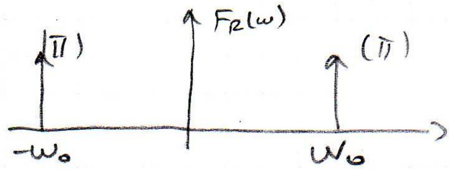


$f(t)=k\,e^{j\omega_0 t}$ $\circ\!\!-\!\!\bullet$ $F(\omega)=2\pi k\,\delta(\omega-\omega_0)$



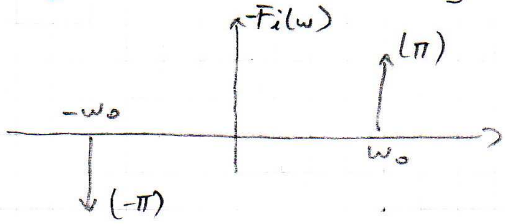
$f(t)=\cos(\omega_0 t)$ $\circ\!\!-\!\!\bullet$ $F(\omega)=\pi\,\delta(\omega+\omega_0)+\pi\,\delta(\omega-\omega_0)$

$\cos(\omega t)=\frac{1}{2}\left(e^{j\omega t}+e^{-j\omega_0 t}\right)$

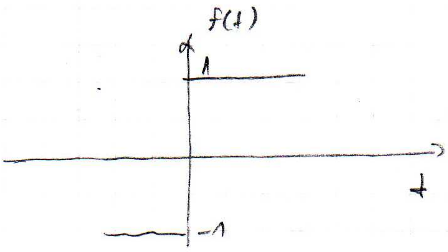


$f(t)=\sin(\omega_0 t)$ $\circ\!\!-\!\!\bullet$ $F_i(\omega)=j\left[\pi\,\delta(\omega-\omega_0)-\pi\,\delta(\omega+\omega_0)\right]$

$\sin(\omega_0 t)=\frac{1}{j2}\left(e^{j\omega_0 t}-e^{-j\omega_0 t}\right)$



$f(t)=\mathrm{sgn}(t)=\begin{cases}1, & t>0\\ -1, & t<0\end{cases}$ $\circ\!\!-\!\!\bullet$ $\mathcal{F}[s(t)]=\frac{2}{j\omega}=-j\frac{2}{\omega}$

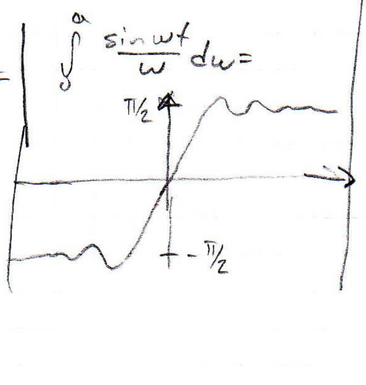


provjeravamo pomoću inverzne

$$f(t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}F(\omega)e^{j\omega t}d\omega=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\frac{2}{j\omega}e^{j\omega t}d\omega=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\underbrace{\frac{2}{j\omega}}_{\text{NEP.}}[\underbrace{\cos(\omega t)}_{\text{PARNA}}+j\sin(\omega t)]d\omega=$$

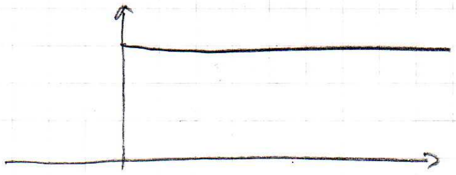
NEP $\Rightarrow 0$

$$=\frac{2}{\pi}\int_{0}^{+\infty}\frac{\sin\omega t}{\omega}d\omega=\left|\int_0^{\alpha}\frac{\sin\omega t}{\omega}d\omega=\right|=\begin{cases}1, & t>0\\ -1, & t<0\end{cases}$$



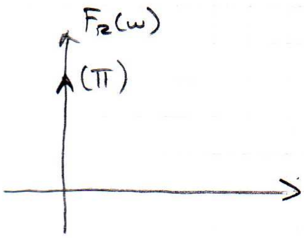
Heaviside step funkcija

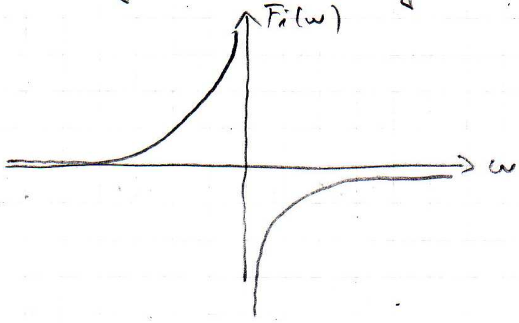
$$s(t) = \begin{cases} 1 & , t > 0 \\ 0 & , t < 0 \end{cases}$$



$$s(t) = \frac{1}{2} + \frac{1}{2}\,\mathrm{sgn}(t)$$

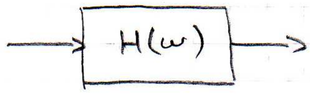
$$\mathcal{F}[s(t)] = \frac{1}{2} \cdot 2\pi\delta(\omega) + \frac{1}{2} \cdot \frac{2}{j\omega} = \pi\delta(\omega) + \frac{1}{j\omega} = \pi\delta(\omega) - j\frac{1}{\omega} = F_R(\omega) + jF_i(\omega)$$





frekv. karak. i odziv sustava

$$H(\omega) = H_R(\omega) + jH_I(\omega) = |H(\omega)|\, e^{j\varphi(\omega)} = A(\omega) e^{j\varphi(\omega)}$$



atenuacija $\alpha(\omega) = -\ln A(\omega)$

fazno kašnjenje $\theta(\omega) = -\varphi(\omega)$

$$H(\omega) = e^{-\alpha(\omega)} e^{-j\theta(\omega)}$$

Impulsni odziv

$$f(t) = \delta(t)$$

$$g(t) = f(t) * h(t) = \int_{-\infty}^{\infty} f(\tau) h(t-\tau)\, d\tau \quad \circ\!-\; G(\omega) = H(\omega) \cdot F(\omega) = 1 \cdot H(\omega)$$

$$\mathcal{F}^{-1}[G(\omega)] = g(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} H(\omega) e^{j\omega t}\, d\omega = h(t) \leftarrow \text{impulsni odziv}$$

$$h(t) = h_r(t) + j\,h_i(t)$$

~~Skokoviti odziv~~.

$$f(t) = S(t)$$

$$G(\omega) = \left(\pi \cdot \delta(\omega) - \frac{j}{\omega}\right) H(\omega)$$

$$g(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \left(\pi\delta(\omega) - j\frac{1}{\omega}\right) H(\omega)\, e^{j\omega t}\, d\omega$$

približno određivanje odziva

$$g(t) = \int_{-\infty}^{+\infty} f(t-\tau)\, h(\tau)\, d\tau$$

$$f(t-\tau) \approx f(t)$$

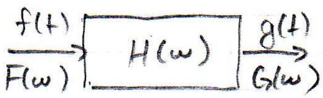
za uski vremenski interval

$$g(t) \approx \int_{-\infty}^{+\infty} f(t)\, h(\tau) d\tau = f(t) \int_{-\infty}^{+\infty} h(\tau) d\tau = f(t) \int_{-\infty}^{+\infty} h(\tau) e^{j0t} d\tau = f(t) \cdot H(0)$$

$h(t-\tau) = h(t)$ na kratkom intervalu

$$g(t) = \int_{-\infty}^{+\infty} f(\tau) h(t-\tau) d\tau = \int_{-\infty}^{+\infty} f(\tau) h(t) d\tau = h(t) \int_{-\infty}^{+\infty} f(\tau) d\tau = h(0) \cdot \int_{-\infty}^{+\infty} f(\tau) d\tau$$

Idealizirani sustavi



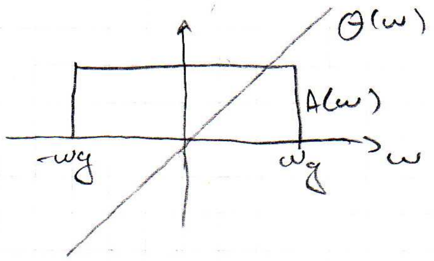
$f(t) = g(t) \Rightarrow F(\omega) = G(\omega)$

$H(\omega) = 1$, $A(\omega) = 1$, $\Theta(\omega) = 0$

↳ ne unosi kašnjenje signala

$G(j\omega) = F(j\omega) \cdot H(j\omega) = A \cdot F(j\omega)$

idealni NP filtar



Sustav bez izobličenja

- ima linearnu faznu karakt.

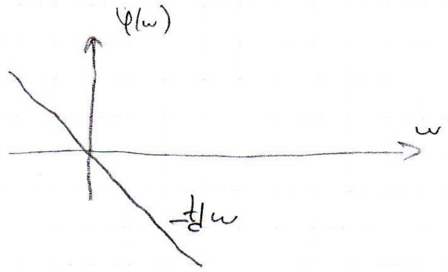
$H(j\omega) = A(\omega)\, e^{j\varphi(\omega)}$

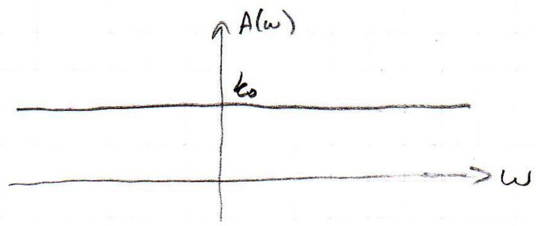
$A(\omega) = k_0$ - konstanta

$\varphi(\omega) = -t_d \cdot \omega$

$$g(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \underbrace{A(\omega) e^{j\overset{-t_d\omega}{\varphi(\omega)}} \cdot F(\omega)}_{G(\omega)} e^{j\omega t} d\omega = k_0 \overbrace{\frac{1}{2\pi} \int_{-\infty}^{+\infty} F(\omega) e^{j\omega(t-t_d)} d\omega}^{f(t-t_d)} = k_0 \cdot f(t-t_d)$$

Amplitudno skaliran i ponaknut u vremenu

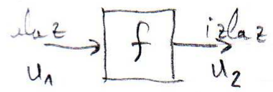




- Linearna izobličenja nastaju kad karakt. odstupaju od prethodne.

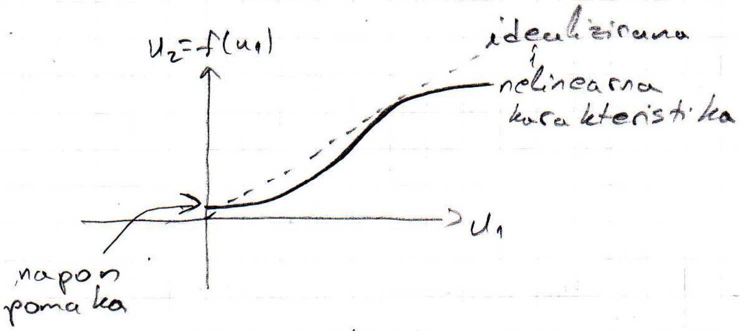
- ne nastaju novi harmonici, nastaju samo amplitudna i fazna izobličenja.

- Nelinearna izobličenja



statička kar. sustava (amplitudno-amplitudna) nelinearna

$u_2 = f(u_1)$



prinjer

$$u_2 = a_0 + a_1 u_1 + a_2 u_2^2 + a_3 u_3^3$$

Ako je $u_1 = U_1 \sin(\omega t)$

$$u_2 = a_0 + a_1 U_1 \sin(\omega t) + a_2 U_1^2 \sin^2(\omega t) + a_3 U_1^3 \sin^3(\omega t) =$$

$$= a_0 + a_1 U_1 \sin(\omega t) + \frac{a_2}{2} U_1^2 - \frac{1}{2} a_2 U_1^2 \cos(2\omega t) + \frac{3}{4} a_3 U_1^3 \sin(\omega t) - \frac{a_3}{4} U_1^3 \sin(3\omega t) =$$

$$= a_0 + \frac{1}{2} u_2 U_1^2 + (a_1 U_1 + \frac{3}{4} a_2 U_1^3) \sin(\omega t) - \frac{a_2}{2} U_1^2 \cos(2\omega t) - \frac{a_3}{4} U_1^3 \sin(3\omega t)$$

novi harmonici

Ako je $u_1 = U_{11} \sin(\omega_1 t) + U_{12} \sin \omega_2 t$

$$u_2 = a_0 + a_1 u_1 + a_2 u_1^2$$

$$\Downarrow$$

$$u_2 = a_0 + a_1 U_{11} \sin \omega_1 t + a_1 U_{12} \sin \omega_2 t + \frac{a_2}{2} U_{11}^2 + \frac{a_2}{2} U_{12}^2 - \frac{a_2}{2} U_{11}^2 \cos 2\omega_1 t - \frac{a_2}{2} U_{12}^2 \cos \omega_2 t 2 +$$

$$+ \frac{a_2}{2} U_{11} U_{12} \cos(\omega_1 - \omega_2) t + \frac{a_2}{2} U_{11} U_{12} \cos(\omega_1 + \omega_2) t$$

uz ω_1 i ω_2 imamo još: DC, $2\omega_1$, $2\omega_2$, $\omega_1 - \omega_2$, $\omega_1 + \omega_2$

Faktor nelinearnog izobličenja - Total harmonic distortion - THD

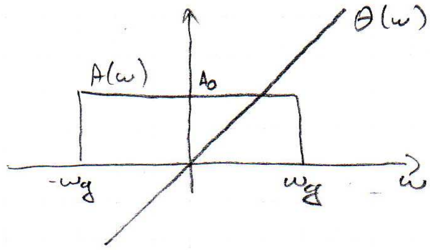
THD (D)

$$THD = \frac{\sqrt{A_2^2 + A_3^2 + \dots + A_n^2}}{A_1}$$

← amplitude ostalih harmonika

amplitude osnovnog harmonika

IDEALNI NP FILTAR



$\varphi(\omega) = -\Theta(\omega)$

faza — fazno kašnjenje

$$A(\omega) = \begin{cases} A_0, & -\omega_g < \omega < \omega_g \\ 0, & \text{inače} \end{cases}$$

$$\Theta(\omega) = \omega \cdot t_0$$

$$H(\omega) = A_0 \cdot e^{j\omega t_0} \cdot p_{\omega_g}(\omega)$$

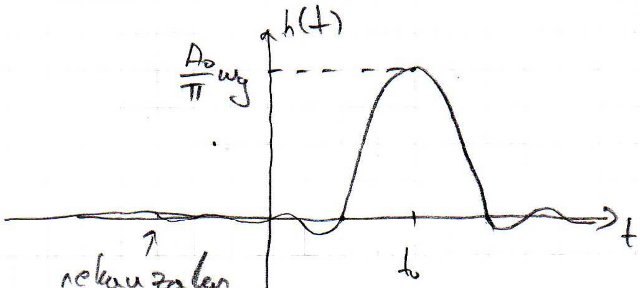
prozor na intervalu $|\omega_g|$

impulsni odziv

$$h(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} H(\omega)\, e^{j\omega t}\, d\omega = \frac{1}{2\pi}\int_{-\omega_g}^{\omega_g} A_0\, e^{j\omega t_0} e^{j\omega t}\, d\omega = \frac{1}{2\pi}\int_{-\omega_g}^{\omega_g} A_0\, e^{j\omega(t-t_0)}\, d\omega = \frac{A_0}{\pi}\int_{0}^{\omega_g} e^{j\omega(t-t_0)}\, d\omega =$$

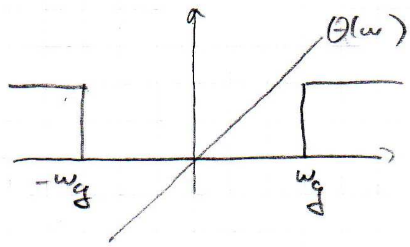
$$= \frac{A_0}{\pi}\int_0^{\omega_g}\Big(\cos(\omega(t-t_0)) + \underbrace{j\sin\omega(t-t_0)}_{\text{neparna komponenta se poništava na simet. intervalu}}\Big)\, d\omega = \frac{A_0}{\pi}\int_0^{\omega_g}\cos(\omega(t-t_0))\, d\omega = \boxed{\frac{A_0}{\pi}\omega_g\, \frac{\sin \omega_g (t-t_0)}{\omega_g (t-t_0)}}$$

IMPULSNI ODZIV IDEALNOG NP FILTRA



nekauzalan (odziv prije pobude) nemoguće realizirati

VP filtar



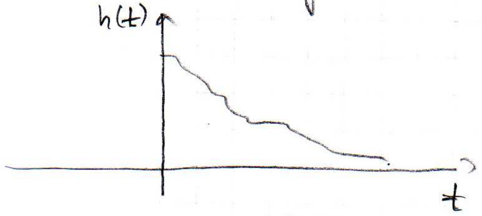
$\Rightarrow$

HILBERTOVA TRANSFORMACIJA

$$H(\omega) = H_r(\omega) + j\,H_i(\omega)$$

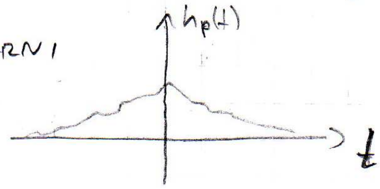
$$H_i(\omega) = -\frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{H_r(y)}{\omega - y}\,dy \quad , \quad H_r = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{H_i(y)}{\omega - y}\,dy$$

kauzalna funkcija

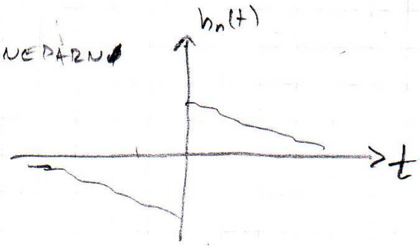


impulsni odziv nekog kauzalnog sustava

PARNI



NEPARNI



$$\left.\begin{aligned} h_p(t) &= h_n(t) \quad , t > 0 \\ h_p(t) &= -h_n(t) \quad , t < 0 \end{aligned}\right\} \Rightarrow \begin{aligned} h_p(t) &= h_n(t) \cdot sig(t) \\ h_n(t) &= h_p(t) \cdot sig(t) \end{aligned}$$

$$\boxed{\begin{aligned} h_p(t) &\circ\!\!-\!\!\bullet\; H_r(\omega) \\ h_n(t) &\circ\!\!-\!\!\bullet\; jH_i(\omega) \end{aligned}}$$

$$f(t)\cdot g(t) \circ\!\!-\!\!\bullet\; \frac{1}{2\pi} F(\omega) * G(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} F(y)\,G(\omega - y)\,dy$$

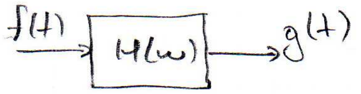
$$sgn(t) \circ\!\!-\!\!\bullet\; \frac{2}{j\omega}$$

$$jH_i(\omega) = \frac{1}{2\pi}\cdot H_r(\omega) * \frac{2}{j\omega} = \frac{1}{j\pi}\int_{-\infty}^{+\infty} H_r(y)\,\frac{1}{\omega - y}\,dy = -j\,\frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{H_r(y)}{\omega - y}\,dy$$

$$\Rightarrow H_i(\omega) = -\frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{H_r(y)}{\omega - y}\,dy$$

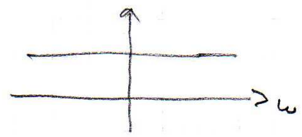
VEZA IZMEĐU A i φ karakteristike

- općenito <u>nije</u> jednoznačna

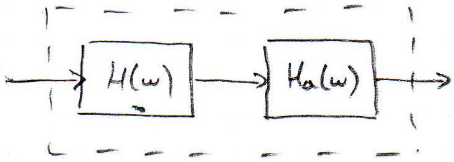


neki kauzalni sustav

svepropusna funkcija



- formiramo kaskadu



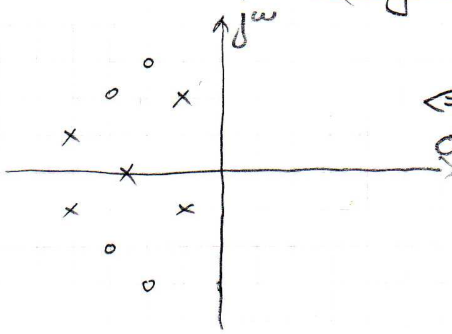
$H_u(\omega) = H(\omega) \cdot H_a(\omega)$

$\hookrightarrow |H(\omega)| e^{j\varphi(\omega)}$ $\quad \hookrightarrow |H_a(\omega)| e^{j\varphi_a(\omega)}$

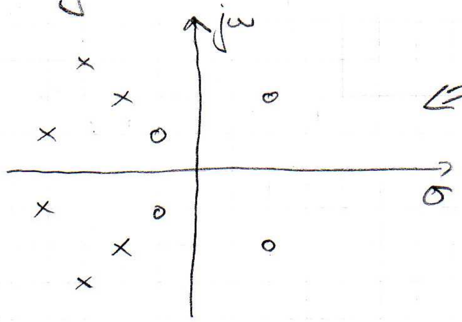
$$\Rightarrow H_u(\omega) = |H(\omega)| e^{j(\varphi(\omega)+\varphi_a(\omega))} = |H(\omega)| e^{j\varphi_u(\omega)}$$

sustavi s minimumom faze

- za njih se može odrediti jednoznačna veza A i f karakteristike.
- oni koji se nemogu rastaviti na produkt $H(j\omega)$ i propusne funkcije
- kako utvrditi da se radi o sustavu s minimumom faze?
  - ti sustavi <u>nemaju nula</u> u desnoj ravnini



⇐ sustav s minimumom faze



⇐ nije sustav s minimumom faze

$$H(\omega) = \underbrace{e^{-\alpha(\omega)}}_{|H(\omega)|} e^{-j\Theta(\omega)}$$

$\alpha(\omega)$ - log. mjera amp. karakt.

veza između $\alpha(\omega)$ i $\Theta(\omega)$:

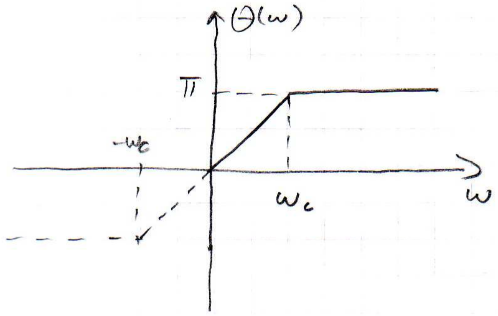
$$\boxed{\begin{aligned} \Theta(\omega) &= \frac{\omega}{\pi} \int_{-\infty}^{+\infty} \frac{\alpha(y)}{y^2-\omega^2}\, dy \\ \alpha(\omega) &= \alpha(0) - \frac{\omega^2}{\pi} \int_{-\infty}^{+\infty} \frac{\Theta(y)}{y(y^2-\omega^2)}\, dy \end{aligned}}$$

DEFINICIJA

- za danu amp. karak. može se fizički realizirati fazna karak. s mini. faze, tj. ne može se očekivati manje fazno kašnjenje od ovog koje ima sustav s minimumom faze.
- Moguće su i druge faz. karakt. uz zadanu amp. karakt. no sve one će imati veće fazno kašnjenje od sustava s min. faze.

Izračunati gušenje $\alpha(\omega)$ filtra s prijen. funk. minim. faze, i AF karakt.

$$\Theta(\omega) = \begin{cases} t_0\omega ; & |\omega| < \omega_c \\ t_0\omega_c ; & \omega > \omega_c \end{cases}$$



$t_0\omega_c = \pi$

vrijedi Hilbertova transf.

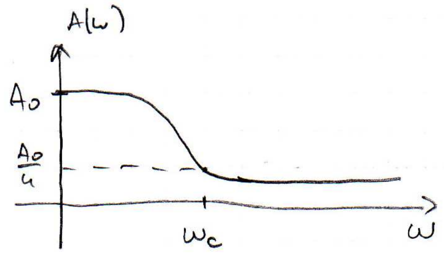
$$\alpha(\omega) = \alpha(0) - \frac{\omega^2}{\pi}\int_{-\infty}^{+\infty} \frac{\Theta(y)}{y(y^2-\omega^2)}\,dy =$$

$$= \alpha(0) - \frac{\omega^2}{\pi}\int_{-\infty}^{\omega_c} \frac{-t_0\omega_c}{y(y^2-\omega^2)}\,dy - \frac{\omega^2}{\pi}\int_{-\omega_c}^{\omega_c} \frac{t_0 y}{y(\omega^2-y^2)}\,dy - \frac{\omega^2}{\pi}\int_{\omega_c}^{+\infty} \frac{t_0\omega_c}{y(y^2-\omega^2)}\,dy =$$

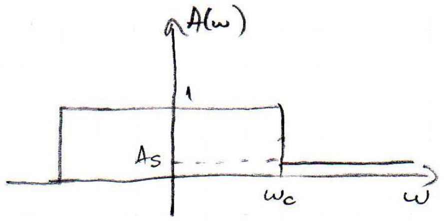
$$\left\{ \begin{aligned} \int \frac{dy}{y(y^2-\omega^2)} &= \frac{1}{2\omega^2}\ln\left|1-\frac{\omega^2}{y^2}\right| \\ \int \frac{dy}{y^2-\omega^2} &= \frac{1}{2\omega}\ln\left|\frac{y-\omega}{y+\omega}\right| \end{aligned} \right\}$$

$$= \alpha(0) + \frac{t_0\omega_c}{\pi}\left[\left(1+\frac{\omega}{\omega_c}\right)\ln\left|1+\frac{\omega}{\omega_c}\right| + \left(1-\frac{\omega}{\omega_c}\right)\ln\left|1-\frac{\omega}{\omega_c}\right|\right]$$

$$A(\omega) = e^{-\alpha(\omega)}$$



Primjer 2



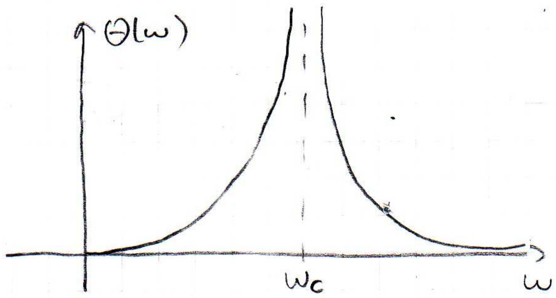
$$A(\omega) = \begin{cases} 1, & |\omega| < \omega_c \\ A, & |\omega| > \omega_c \end{cases}$$

$$\Theta(\omega) = ?$$

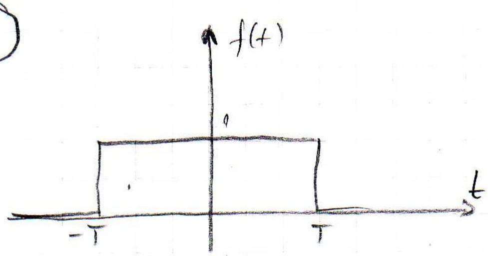
$$H(\omega) = e^{-\alpha(\omega) - j\theta(\omega)} = A(\omega)\, e^{-j\theta(\omega)} \qquad A(\omega) = e^{-\alpha(\omega)} \Rightarrow \alpha(\omega) = \ln \frac{1}{A(\omega)}$$

$$\theta(\omega) = \frac{\omega}{\pi} \int_{-\infty}^{+\infty} \frac{\alpha(y)}{y^2 - \omega^2}\, dy = \frac{\omega}{\pi} \int_{-\infty}^{+\infty} \frac{-\ln A(y)}{y^2 - \omega^2}\, dy = -\frac{\omega}{\pi} \int_{-\infty}^{-\omega_c} \frac{\ln A_s}{y^2 - \omega^2}\, dy - \frac{\omega}{\pi} \int_{-\omega_c}^{\omega_c} \frac{\ln 1}{y^2 - \omega^2}\, dy -$$

$$- \frac{\omega}{\pi} \int_{\omega_c}^{+\infty} \frac{\ln A_s}{y^2 - \omega^2}\, dy = \dots = -\frac{\ln A_s}{\pi} \ln \left| \frac{\omega - \omega_c}{\omega + \omega_c} \right|$$



1.

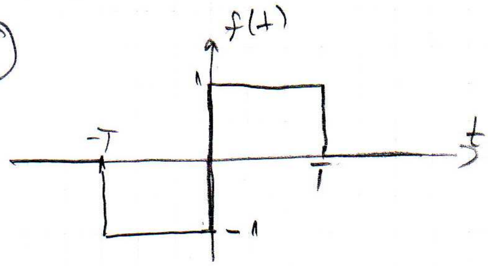


$$F(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} f(t)\, e^{-j\omega t}\, dt$$

$f(t)$ parna $\Rightarrow$ $F(\omega) = F_r(\omega) = \int_{-\infty}^{+\infty} f_p(t) \cdot \cos(\omega t)\, dt$

$$= 2 \int_0^{\infty} f_p(t) \cos(\omega t)\, dt = 2\, \frac{\sin(\omega t)}{\omega} \Big|_0^T = 2\, \frac{\sin(\omega T)}{T}$$

2.

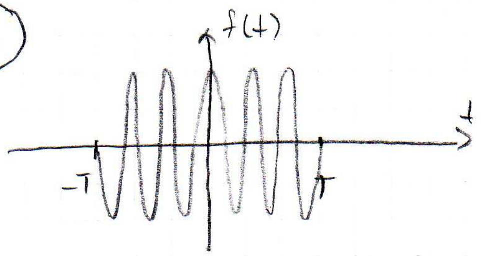


$$F(\omega) = -j F_i(\omega)$$

$$F_i(\omega) = -\int_{-\infty}^{+\infty} f_N(t) \sin \omega t\, dt = -2 \int_0^T \sin \omega t\, dt =$$

$$= \frac{2}{\omega} (\cos \omega - 1)$$

3.



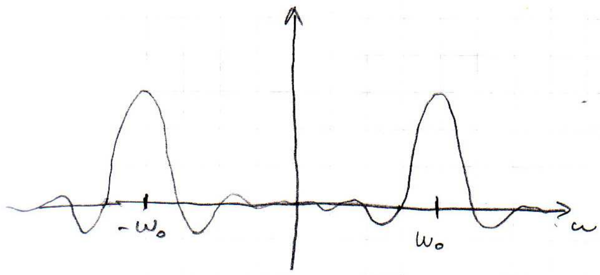
$$f(t) = f_T(t) \cos(\omega_0 t)$$

$$F(\omega) = \int_{-\infty}^{+\infty} f_T(t) \cos \omega_0 t \cdot e^{-j\omega t}\, dt = \int_{-T}^{T} \cos(\omega_0 t)\, e^{-j\omega t}\, dt = \int_{-T}^{T} \frac{1}{2} \left(e^{j\omega_0 t} + e^{-j\omega_0 t}\right) e^{-j\omega t}\, dt$$

$$= \frac{1}{}$$

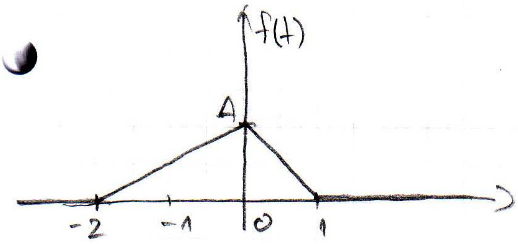
$$= \frac{1}{2}\int_{-T}^{T} e^{-j(\omega-\omega_0)t} + e^{-j(\omega+\omega_0)t}\, dt =$$

$$F(\omega) = \frac{e^{-j(\omega-\omega_0)t}}{2j(\omega-\omega_0)} - \frac{e^{-j(\omega+\omega_0)t}}{2j(\omega+\omega_0)} = \frac{\sin(\omega-\omega_0)T}{\omega-\omega_0} + \frac{\sin(\omega+\omega_0)T}{\omega+\omega_0}$$



ZADATAK

odrediti $\mathcal{F}\{f(t)\}$



$F(\omega) = ?$

$F_r(\omega) = ?$

$F_i(\omega) = ?$

$$f(t) = \begin{cases} \frac{A}{2}t + A, & -2 \le t \le 0 \\ -At + A, & 0 < t < 1 \end{cases}$$

$$F(\omega) = \int_{-\infty}^{+\infty} f(t) e^{-j\omega t} dt = \int_{-2}^{0} \left(\frac{A}{2}t + A\right) e^{-j\omega t} dt + \int_{0}^{1} (A - At) e^{-j\omega t} dt =$$

$$= \frac{A}{2}\int_{-2}^{0} t e^{-j\omega t} dt - \frac{A}{j\omega} e^{-j\omega t}\Big|_{-2}^{0} - \frac{A}{j\omega} e^{-j\omega t}\Big|_{0}^{1} - A\int_{0}^{1} t e^{-j\omega t} dt =$$

$$= \frac{A}{2}\left[\frac{e^{-j\omega t}}{(-j\omega)^2}(-j\omega t - 1)\right]\Big|_{-2}^{0} + j\frac{A}{\omega}(1 - e^{j2\omega}) - A\left[\frac{e^{-j\omega t}}{(-j\omega)^2}(-j\omega t - 1)\right]\Big|_{0}^{1} +$$

$$+ j\frac{A}{\omega}\left[e^{-j\omega} - 1\right] =$$

$$= \frac{A}{2}\left[\frac{1}{-\omega^2}(-1) - \frac{e^{j2\omega}}{-\omega^2}(2j\omega - 1)\right] + j\frac{A}{\omega}(e^{-j\omega} - e^{2j\omega}) - A\left[\frac{e^{-j\omega}}{-\omega^2}(-j\omega - 1) + \frac{1}{-\omega^2}\right] =$$

$$= \frac{A}{2\omega^2} + \cancel{\frac{A}{2\omega^2} e^{2j\omega} 2j\omega} - \frac{A}{2}\frac{e^{2j\omega}}{\omega^2} + \cancel{j\frac{A}{\omega} e^{-j\omega}} - \cancel{j\frac{A}{\omega} e^{2j\omega}} - \cancel{A\frac{e^{-j\omega}}{\omega^2} j\omega} - A\frac{e^{-j\omega}}{\omega^2} + \frac{A}{\omega^2} =$$

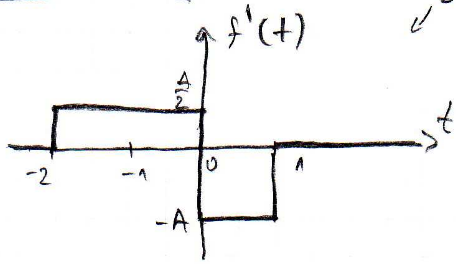
$$= \frac{3A}{2\omega^2} - \frac{A}{2\omega^2}[\cos 2\omega + j\sin 2\omega] - \frac{A}{\omega^2}(\cos\omega - j\sin\omega) =$$

$$= \frac{3A}{2\omega^2} - \frac{A}{2\omega^2}\cos 2\omega - \frac{A}{\omega^2}\cos\omega - j\frac{A}{2\omega^2}\sin 2\omega + j\frac{A}{\omega^2}\sin\omega =$$

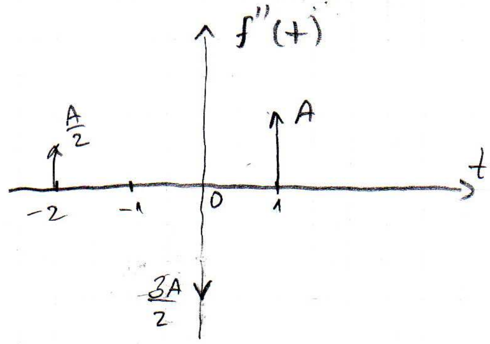
$$= \underbrace{\frac{A}{2\omega^2}(3 - \cos 2\omega - 2\cos\omega)}_{F_r(\omega)} + j\underbrace{\frac{A}{2\omega^2}(-\sin 2\omega + 2\sin\omega)}_{F_i(\omega)}$$

2. NAČIN

Derivacija



$\Rightarrow$



$$\frac{d^{(n)} f(t)}{dt^n} \circ\!\!-\!\!\bullet \ (j\omega)^n \cdot F(\omega)$$

$$\delta(t-t_0) \circ\!\!-\!\!\bullet \ e^{-j\omega t_0} \cdot 1$$

$$f''(t) \circ\!\!-\!\!\bullet \ (j\omega)^2 \cdot F(\omega) = -\omega^2 F(\omega)$$

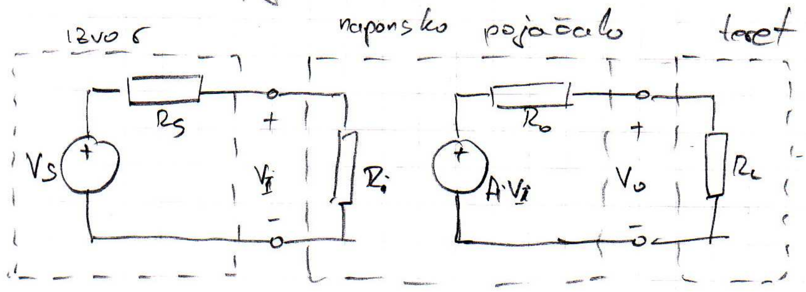
$$f''(t) = \frac{A}{2}\delta(t+2) - \frac{3A}{2}\delta(t) + A\delta(t-1)$$

$$-\omega^2 F(\omega) = \frac{A}{2} e^{j2\omega} - \frac{3A}{2} + A e^{-j\omega}$$

$$\Rightarrow F(\omega) = \frac{3A}{2\omega^2} - \frac{A}{2\omega^2} e^{j2\omega} - \frac{A}{\omega^2} e^{-j\omega} = \underbrace{\frac{A}{2\omega^2}\left(3 - \cos 2\omega - 2\cos\omega\right)}_{F_r(\omega)} + j\underbrace{\frac{A}{2\omega^2}\left(-\sin 2\omega + 2\sin\omega\right)}_{F_i(\omega)}$$

POJAČALA

Naponsko pojačalo



$$V_I = \frac{R_i}{R_S + R_i} V_S$$

$$V_o = A_o \cdot V_I \frac{R_L}{R_o + R_L}$$

$$\frac{V_o}{V_S} = \frac{R_i}{R_S + R_i} A_{oc} \frac{R_L}{R_o + R_L}$$

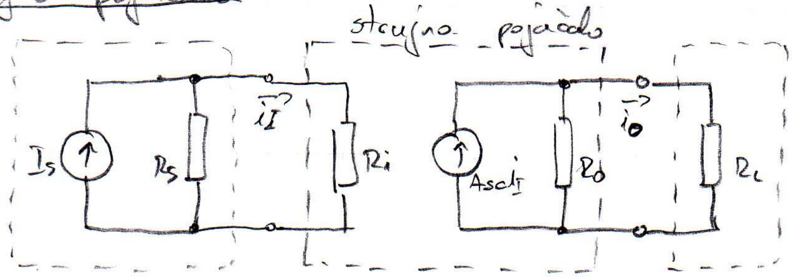
FAKTORI OPTEREĆENJA
ULAZNOG I IZLAZNOG STUPNJA

A_{oc} - amplificatio in open circuit
(pojačanje pri otvorenom krugu)

$R_I >> R_S \Rightarrow V_I \approx V_S$

$R_o \to 0 \Rightarrow V_o \approx A_{oc} V_I$

Strujno pojačalo



$$\frac{i_o}{i_s} = \frac{R_S}{R_S + R_i} A_{sc} \frac{R_o}{R_o + R_L}$$

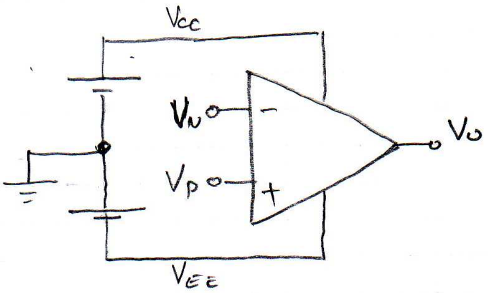
A_{sc} - short-circuit, current gain

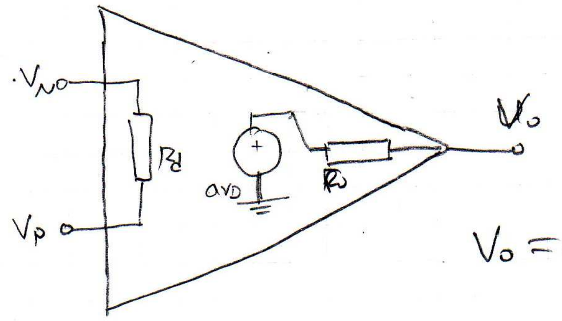
$R_i \to 0 \Rightarrow i_S \approx i_I$

$R_o \to \infty \Rightarrow i_o \approx A_{sc} i_I$

input	output	
V_I	V_o	naponsko
i_I	i_o	strujno
V_I	i_o	
i_I	V_o	

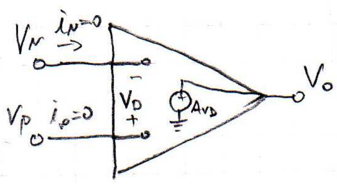
Operacijsko pojačalo





$$V_o = a(V_P - V_N)$$

idealno



$a \to \infty$

$r_d = \infty$

$r_o = 0$

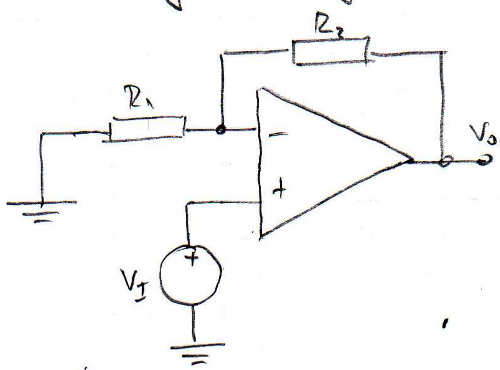
$i_P = i_N = 0$

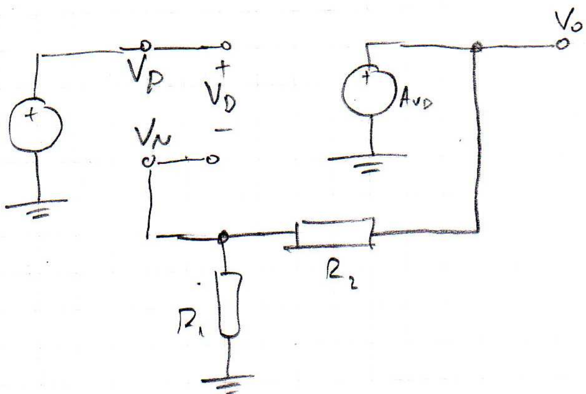
$$\frac{V_o}{a} = V_P - V_N \Rightarrow V_P = V_N$$

$\frac{V_o}{a} \to 0$

OSNOVNE KONFIGURACIJE

Neinvertirajuće pojačalo





$V_P = V_I$

$$V_N = \frac{R_1}{R_1 + R_2} \cdot V_o$$

$$V_o = a(V_P - V_N) = a\left(V_I - V_o \frac{R_1}{R_1 + R_2}\right) \Rightarrow \frac{V_o}{V_I} = \left(1 + \frac{R_2}{R_1}\right) \cdot \frac{1}{1 + \frac{1 + R_2/R_1}{a}}$$

a je konačan

$$A_{IDEALNO} \Rightarrow \lim_{a \to \infty} \frac{V_o}{V_I} = 1 + \frac{R_2}{R_1}$$

$R_i = \infty$, $R_o = 0$

Primjer

$V_I = 1V$
$R_1 = 2k\Omega$
$R_2 = 18k\Omega$

a) $a = 10^2 [V/V]$

b) $a = 10^4$

c) $a = 10^6$

$V_o = ?$

IDEALNO $\Rightarrow \boxed{V_o = 10\,V}$

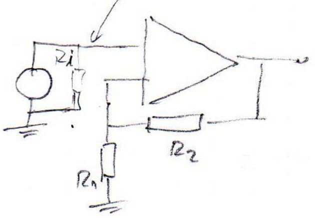
a) $V_o = 9{,}091\,V$

b) $V_o = 9{,}990\,V$

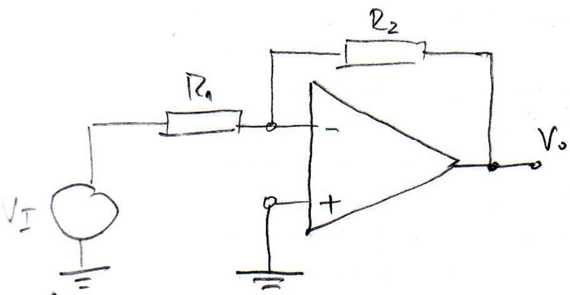
c) $V_o = 9{,}9999\,V$

$R_i = \frac{V_i}{i_p} = \infty$, $R_o = R_{ovo} = 0$

Definiramo ulazni otpor



Invertirajuće pojačalo



$R_i = R_1$
$R_o = 0$

$V_p = 0$

$$V_N = \frac{R_2}{R_1+R_2} V_i + \frac{R_1}{R_1+R_2} V_o$$

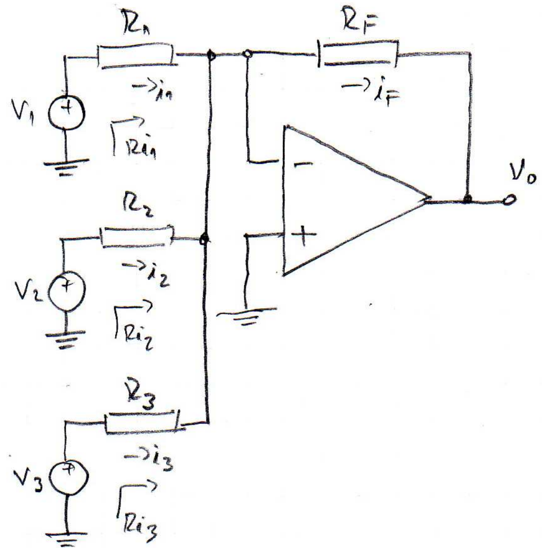
$$V_o = a(V_p - V_N) = a\left(-\frac{R_2}{R_1+R_2} V_i - \frac{R_1}{R_1+R_2} V_o\right)$$

$$A = \frac{V_o}{V_i} = -\frac{R_2}{R_1} \cdot \frac{1}{1 + \frac{1+R_2/R_1}{a}}$$

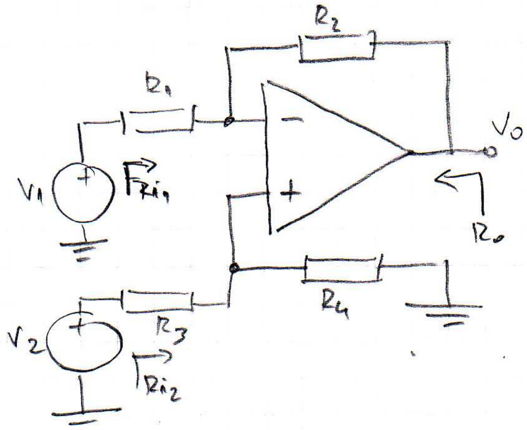
$$A_{IDEAL} = \lim_{a \to \infty} A = -\frac{R_2}{R_1}$$

Sumirajuće pojačalo

$i_F = i_1 + i_2 + i_3$



Diferencijsko pojačalo



$$V_o = V_{o1} + V_{o2}$$

$$V_o = \frac{R_2}{R_1}\left(\frac{1+\frac{R_1}{R_2}}{1+\frac{R_3}{R_4}} V_2 - V_1\right)$$

$$\frac{R_3}{R_4} = \frac{R_1}{R_2} \Rightarrow V_o = \frac{R_2}{R_1}(V_2 - V_1)$$

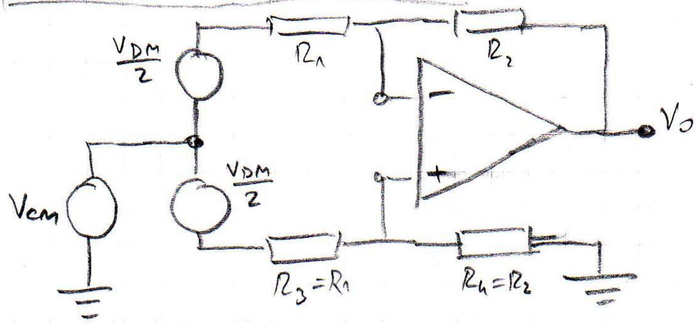
$\frac{R_2}{R_1} \leftarrow$ Diferencijsko pojačanje

$R_{i1} = R_1$

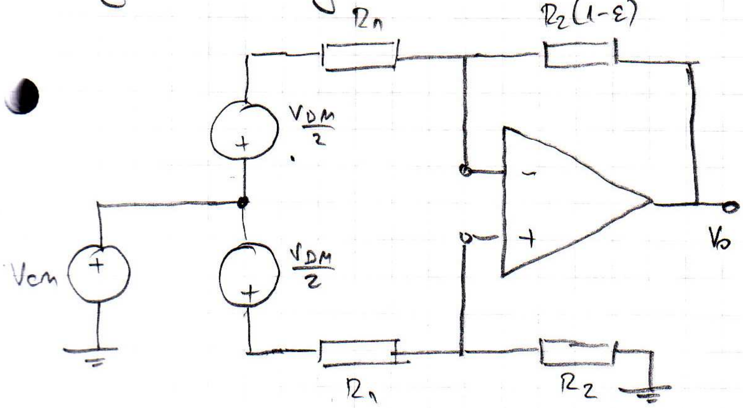
$R_{i2} = R_3 + R_4$

$$\boxed{\left.\begin{aligned} V_{DM} &= V_2 - V_1 \\ V_{CM} &= \frac{V_1+V_2}{2} \end{aligned}\right\} \Rightarrow \begin{aligned} V_1 &= V_{CM} - \frac{V_{DM}}{2} \\ V_2 &= V_{CM} + \frac{V_{DM}}{2} \end{aligned}}$$

$$\boxed{V_o = A_{dm} \cdot V_{DM} + A_{cm} \cdot V_{CM}}$$



razgođeni krug



$$A_{dm} = \frac{R_2}{R_1}\left(1 - \frac{R_1 + 2R_2}{R_1 + R_2} \cdot \frac{\varepsilon}{2}\right)$$

$$A_{cm} = \frac{R_2}{R_1 + R_2} \cdot \varepsilon$$

unosi nam istofaznu komponentu (neželjena)

$$CMRR_{dB} = 20 \log \left| \frac{A_{dm}}{A_{cm}} \right|$$

za $\varepsilon \to 0 \Rightarrow A_{dm} = \frac{R_2}{R_1}$

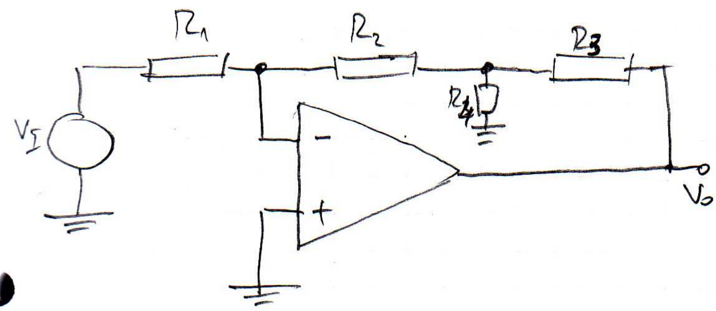
$$A_{cm} = 0$$

$$\boxed{R_{id} = 2R_1}$$

$$\boxed{R_{ic} = \frac{R_1 + R_2}{2}}$$

ULAZNI OTPORI

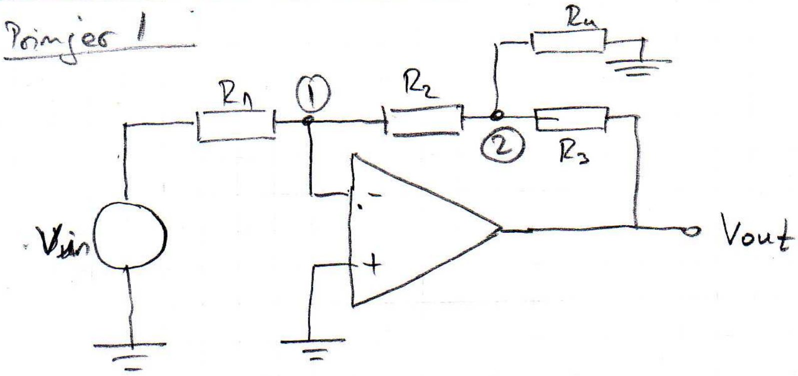
T mreža u povratnoj vezi



$$A = \frac{V_o}{V_I} = -\frac{R_2 + R_3 + R_2 \frac{R_3}{R_4}}{R_1}$$

zbog neprihvatljivih iznosa otpora koristi se T mreža

Primjer 1



$$V_1\left(\frac{1}{R_1}+\frac{1}{R_2}\right)-V_2\frac{1}{R_2}=\frac{V_{in}}{R_1}$$

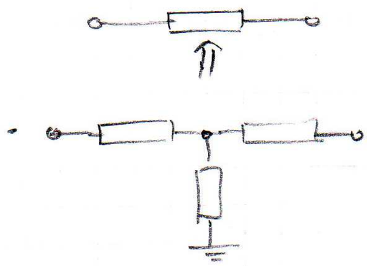
$$-V_1\frac{1}{R_2}+V_2\left(\frac{1}{R_2}+\frac{1}{R_3}+\frac{1}{R_4}\right)=\frac{V_{out}}{R_3}$$

$V_1=0$ (virtualni KS)

$$V_2=-\frac{R_2}{R_1}V_{in}$$

$$-V_{in}\frac{R_2}{R_1}\left(\frac{1}{R_2}+\frac{1}{R_3}+\frac{1}{R_4}\right)=\frac{V_{out}}{R_3}$$

$$\Rightarrow V_{out}=-V_{in}\frac{R_2+R_3+\frac{R_2R_3}{R_4}}{R_1}$$



$R_{ul}=R_1$

$$A=-\frac{R_2+R_3+\frac{R_2R_3}{R_4}}{R_1}$$

ZAHTJEV

$$\boxed{\begin{array}{l}R_{ul}=100k\Omega\\ A=-100\end{array}}$$

$\Rightarrow$ za klasičnu povratnu vezu (samo R_2) otpor bi morao iznositi $10M\Omega$ što je previše

Za T mrežu

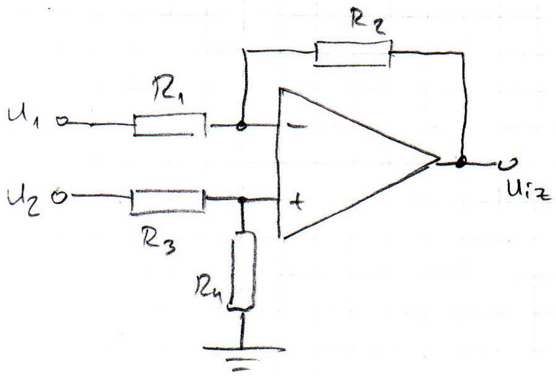
$R_1=100k\Omega$

$R_2=R_3=100k\Omega$

$R_4=1k\Omega \Rightarrow A=-\frac{100+100+\frac{100\cdot100}{1}}{100}=-102\approx-100$

Primjer 2

- Nacrtaj shemu dif. poj. s operac. pojač. i odredite iznos otpora, nominalno pojačanje 10. Na raspolaganju su otpornici toler. ±1% najvećeg iznosa otpora 100kΩ. Kolika je pojačanje istosmjernog i diferenc. u najnepogodnijem slučaju.



$$U_{iz} = -\frac{R_2}{R_1}U_1 + \frac{R_4}{R_3+R_4}\left(1+\frac{R_2}{R_1}\right)U_2$$

$$U_d = U_2 - U_1, \quad U_i = \frac{U_1+U_2}{2}$$

$$U_1 = U_i - \frac{U_d}{2}, \quad U_2 = U_i + \frac{U_d}{2}$$

IDEALNO

$$\frac{R_2}{R_1} = \frac{R_4}{R_3} \Rightarrow U_{iz} = \frac{R_2}{R_1}(U_2 - U_1)$$

$$A_D = 10 = \frac{R_2}{R_1} \qquad R_2 = 100k\Omega \Rightarrow R_1 = 10k\Omega$$

$$\left.\begin{array}{l} R_1 = R_3 = 10k\Omega \\ R_2 = R_4 = 100k\Omega \end{array}\right\} A_N = 10$$

$p = \pm 1\%$

Najnepovoljniji slučaj

$$\left(\frac{R_2}{R_1}\right)_{min} \Downarrow \frac{R_2(1-p)}{R_1(1+p)} \qquad \left(\frac{R_4}{R_3}\right)_{max} \Downarrow \frac{R_4(1+p)}{R_3(1-p)}$$

$$U_{iz} = -\frac{R_2}{R_1}\left(U_i - \frac{U_d}{2}\right) + \frac{R_4}{R_3+R_4}\left(1+\frac{R_2}{R_1}\right)\left(U_i + \frac{U_d}{2}\right)$$

$$U_{iz} = U_d \underbrace{\frac{1}{2}\left[\frac{R_2}{R_1} + \frac{R_4}{R_3+R_4}\left(1+\frac{R_2}{R_1}\right)\right]}_{A_d} + U_i \underbrace{\left[-\frac{R_2}{R_4} + \frac{R_4}{R_3+R_4}\left(1+\frac{R_2}{R_1}\right)\right]}_{A_i}$$

Najgori slučaj: $R_1' = 10{,}1k\Omega$
$R_2' = 99k\Omega$
$R_3' = 9{,}9k\Omega$
$R_4' = 101k\Omega$

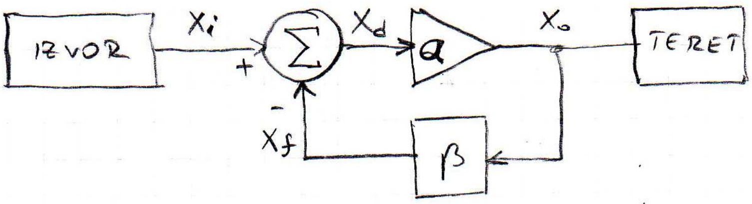
za $p = 1\%$

$$\boxed{\frac{R_2'}{R_1'} = 9,80198} \qquad \frac{R_4'}{R_3'+R_4'}\left(1+\frac{R_2'}{R_1'}\right) = 0,91073 \cdot 10,80198 = \boxed{9,83769}$$

$$\boxed{A_d = 9,82} \approx 10 \quad , \quad \boxed{A_i = 0,0357} \approx 0$$

$$F = 20 \log \frac{A_d}{A_i} = \underline{\underline{48,8 dB}}$$

Sustav s negativnom povratnom vezom



$$\left.\begin{aligned} X_o &= a X_d \\ X_d &= X_i - X_f \\ X_f &= X_o \beta \end{aligned}\right\} \quad X_o = a(X_i - X_f) = a(X_i - \beta X_o)$$

$$\Rightarrow X_o = \frac{a}{1+a\beta} X_i \quad \Rightarrow A = \frac{X_o}{X_i} = \frac{a}{1+a\beta}$$

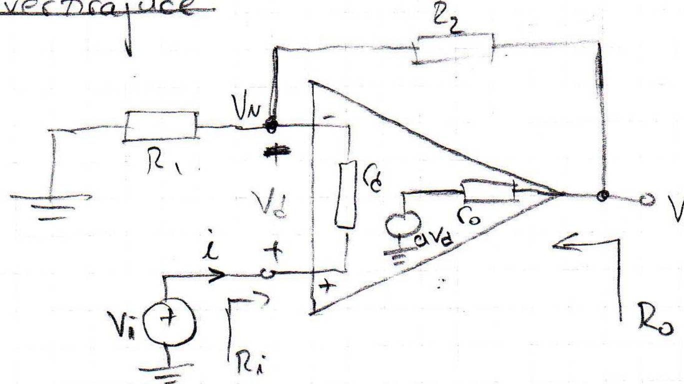
$\boxed{a\beta = T}$ ← pojačanje petlje

$$\lim_{a\to\infty} A = \lim_{a\to\infty} \frac{a}{1+a\beta} = \lim_{a\to\infty} \frac{1}{\frac{1}{a}+\beta} = \boxed{\frac{1}{\beta} = A_{ideal}}$$

↑ za beskonačno pojačanje

$$A = \underbrace{A_{IDEAL}}_{\frac{1}{\beta}} \cdot \frac{1}{1+\frac{1}{\underbrace{a\beta}_{T}}}$$

- Utjecaj ulaznog i izlaznog otpora OP
- Neinvertirajuće



$$\frac{V_i - V_N}{r_d} - \frac{V_N}{R_1} + \frac{V_o - V_N}{R_2} = 0$$

$$\frac{V_N - V_o}{R_2} + \frac{a(V_i - V_N) - V_o}{r_o} = 0$$

$A = \frac{v_o}{v_i} = ?$ $\quad R_i = ?$, $R_o = ?$

$$\boxed{A = \frac{v_o}{v_i} = \frac{\left(1+\frac{R_2}{R_1}\right)a + \frac{r_o}{r_d}}{1 + a + \frac{R_2}{R_1} + \frac{R_2 + r_o}{r_d} + \frac{r_o}{R_1}}} \quad (1)$$

$r_o \approx 80\Omega$

$r_d \approx 500k - 1M\Omega$

$\frac{r_o}{r_d} \ll$ ← za dobro dizajnirano pojačalo

$\frac{R_2 + r_o}{r_d} \ll$

$\frac{r_o}{R_1} \ll$

$$\Rightarrow \boxed{A = \left(1 + \frac{R_2}{R_1}\right)\frac{1}{1 + \frac{1}{T}}} \quad (2) \quad , \; T = a\beta \quad , \; \beta = \frac{R_1}{R_1 + R_2}$$

$R_i = \frac{v_i}{i}$

$$\frac{v_i - v_N}{r_d} - \frac{v_N}{R_1} + \frac{a(v_i - v_N) - v_N}{R_2 + r_o} = 0$$

$v_N = v_i - v_d = v_i - i \cdot r_d$

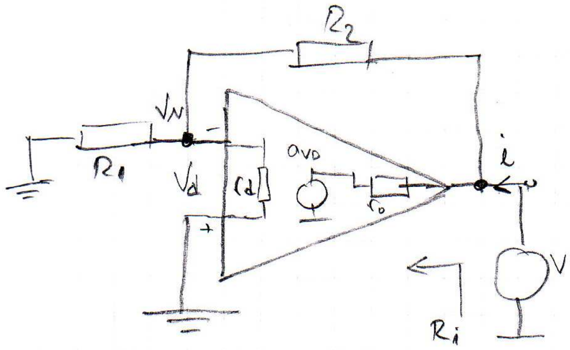
$$\boxed{R_i = \underbrace{\left(1 + \frac{a}{1 + \frac{R_2 + r_o}{R_1}}\right) r_d}_{I} + \underbrace{R_1 \| (R_2 + r_o)}_{II}}$$

$r_o \ll R_2$

$I \gg II$ za dobar dizajn

$$\Rightarrow \boxed{R_i = r_d(1 + a\beta) = r_d(1 + T)}$$

~~Izlazni otpor~~



$$v_N = \frac{R_1 \| r_d}{(R_1 \| r_d) + R_2} \cdot v$$

$$i + \frac{v_N - v}{R_2} + \frac{-a v_N - v}{r_o} = 0$$

$$\boxed{R_o = \frac{v}{i} = \frac{r_o}{1 + \frac{\left(a + \frac{r_o}{R_1} + \frac{r_o}{r_d}\right)}{1 + \frac{R_2}{R_1} + \frac{R_2}{r_d}}}}$$

$\frac{r_o}{R_1}, \frac{r_o}{r_d}, \frac{R_2}{r_d} \ll$

$$\Rightarrow \boxed{R_o = r_o \cdot \frac{1}{1 + T}}$$

← povratna veza smanjuje izlazni otpor

Primjer   Neinvertirajuća konfiguracija

741 pojačalo
$A = 200 V/mV = 2 \cdot 10^5$
$r_d = 2 M\Omega$
$r_o = 75 \Omega$

a) $R_1 = 1 k\Omega$
$R_2 = 999 k\Omega$

b) sljedilo ($R_1 = \infty$, $R_2 = 0$)

a) $A_{IDEALNO} = \frac{1}{\beta} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1} = \underline{\underline{1000}}$; $A = 995,022$

↑ egzaktni izraz (velika formula) (1)

$T = 200$
$A = 995,024$ ← nakon prirodnog zanemarenja (formula s T) (2)

$R_{i\,egzaktno} = 401,97 M\Omega$, $R_i = 402 M\Omega$

$R_{o_{IDEAL}} = 0$, $R_o = 373,32\, m\Omega$, $R_o = 373,13\, m\Omega$

↑ egzaktni   ↑ aproks.

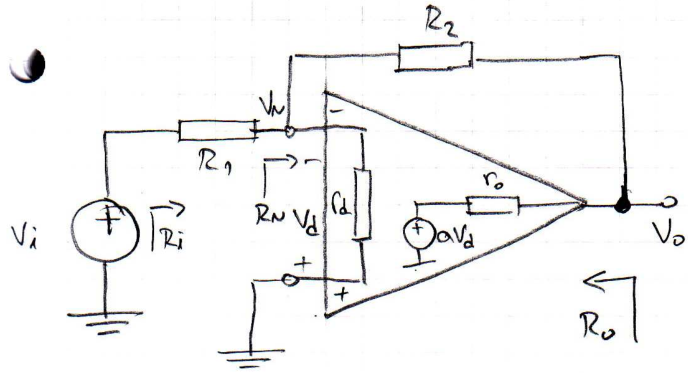
b) $T = 200\,000$

$A_{IDE} = 1$, $A_T = 0,999995$

$R_{i_{IDE}} = \infty$, $R_{i_T} = 400 G\Omega$

$R_{o_{IDE}} = 0$, $R_{o_T} = 375\, \mu\Omega$

INVERTIRAJUĆE POJAČALO

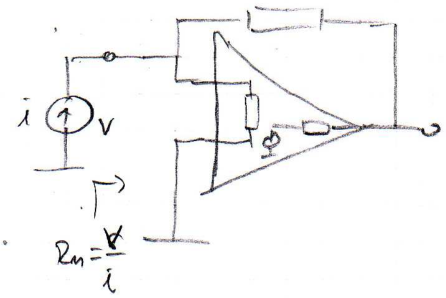


$$\boxed{A = -\frac{aR_2 - r_o}{(1+a)R_1 + (R_2 + r_o)\left(1 + \frac{R_1}{r_d}\right)}}$$

$r_o \ll R_2$, $\frac{R_1}{r_d} \ll 1$, $aR_2 \gg r_o$ ← mora biti ispunjeno

$$\Rightarrow \boxed{A = -\frac{R_2}{R_1} \cdot \frac{1}{1 + \frac{1}{T}}}$$

$$T = a \cdot \beta = a \cdot \frac{R_1}{R_1 + R_2}$$



$$\boxed{R_n = \frac{R_2 + r_o}{1 + a + \frac{R_2 + r_o}{r_d}}} \approx \frac{R_2}{1+a}$$ ← smanjenje otpora

$$\boxed{R_i = R_1 + R_n = R_1 + \frac{R_2 + r_o}{1 + a + \frac{R_2 + r_o}{r_d}}}$$

$$\boxed{R_o \approx \frac{r_o}{1+T}}$$ ← smanjenje otpora

Primjer

741 (iste vrijednosti)

a) $R_1 = R_2 = 100\,k\Omega$

$T = a \cdot \beta = 10^5$

$A = -0{,}99999$

$R_n = 0{,}5\,\Omega$

$R_i = R_1 + R_n \approx 100\,k\Omega$

$R_o = \frac{75}{1+10^5} = 0{,}75\,m\Omega$

b) $R_1 = 1\,k\Omega$, $R_2 = 1\,M\Omega$

$T = 199{,}8$

$A = -995$

$R_n = 5\,\Omega$

$R_i = R_1 + R_n = 1{,}005\,k\Omega$

$R_o = \frac{75}{1+199{,}8} = 0{,}374\,\Omega$

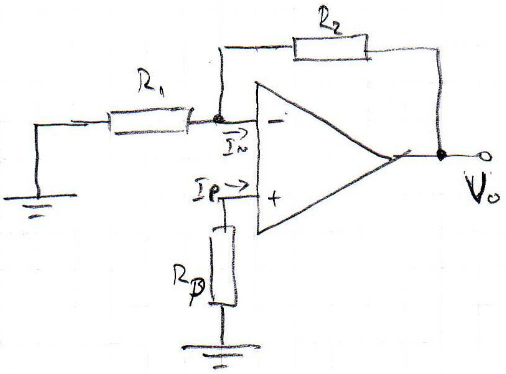
Statičke nesavršenosti OP-a
(neovisne o f)

- Ulazna struja pomaka I_{pom} (I_{off} - input offset curent)

$$I_{pom} = \left| |I_+| - |I_-| \right|$$

- Ulazna struja I_{ue} (I_b input bias current)

$$I_{ue} = \frac{|I_+| + |I_-|}{2}$$



$$I_B = \frac{I_N + I_P}{2} \gg , \quad I_{OS} = I_P - I_N$$

$$E_o = V_o = \left(1 + \frac{R_2}{R_1}\right)\left[(R_1 \| R_2) I_N - R_P I_P\right]$$

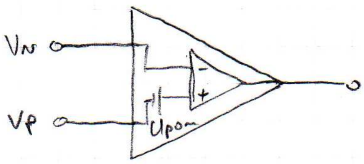
$$\Downarrow$$

$$E_o = \left(1 + \frac{R_2}{R_1}\right)(-R_1 \| R_2) I_{OS}$$

$$R_P = R_1 \| R_2$$

$$E_o = \left(1 + \frac{R_2}{R_1}\right)\left\{\left[(R_1 \| R_2) - R_P\right] I_B - \left[(R_1 \| R_2) + R_P\right] \frac{I_{OS}}{2}\right\}$$

- Greška ulaznog napona pomaka:



$$V_o = a\left[V_P + V_{OS} - V_N\right]$$

Ukupna greška

$$\boxed{E_o = \left(1 + \frac{R_2}{R_1}\right)\left\{V_{OS} + \left[(R_1 \| R_2) - R_P\right] I_B + \left[(R_1 \| R_2) + R_P\right] \frac{I_{OS}}{2}\right\}}$$

vrijedi za INV i NEINV.

za OP s FET na ulazu V_{OS} dominira

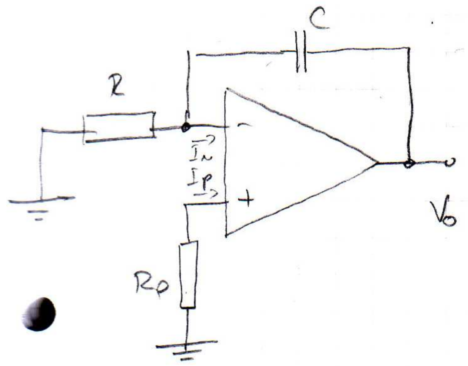
s BIPOLARNIM dominira I_B

Eliminacija smetnji

$R_p = R_1 \| R_2$

- Manji iznosi otpora reda 1k-10kΩ

INTEGRATOR



$V_N = V_P = -R_P I_P$

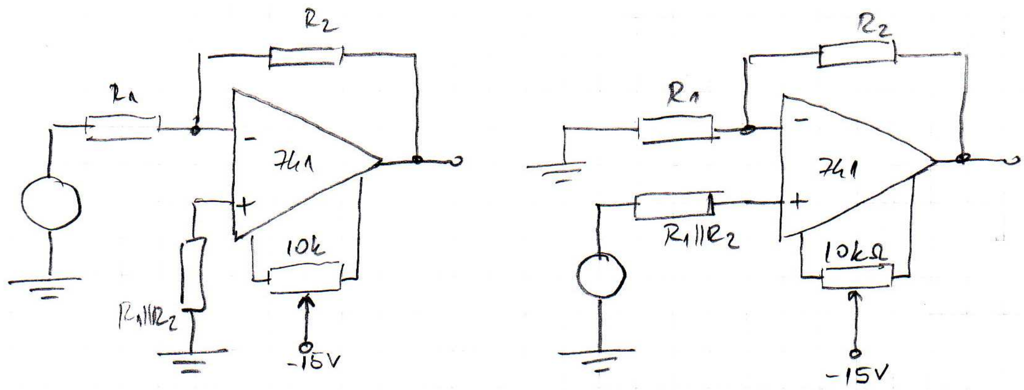
$I_C = \frac{1}{R}(R I_N - R_P I_P) = \frac{1}{R}\left[(R-R_P)I_B - (R+R_P)\frac{I_{OS}}{2}\right]$

$E_o(t) = \frac{1}{RC}\int_0^t -R I_{os}\, d\xi$

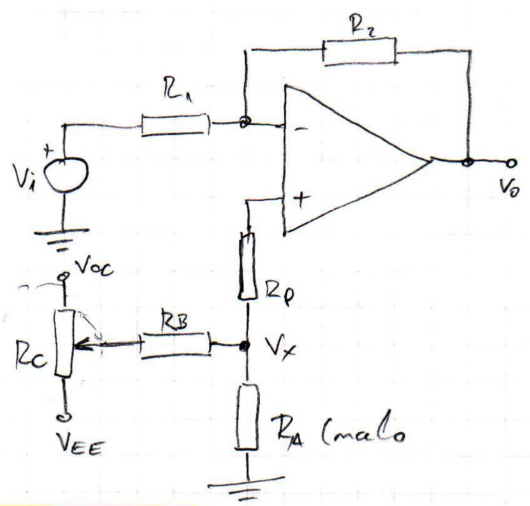
$\uparrow R_P = R$

$E_o(t) : \left[(R-R_P)I_B - (R+R_P)\frac{I_{OS}}{2}\right]\frac{t}{RC}$

INTERNA KOMP. NAPONA POMAKA



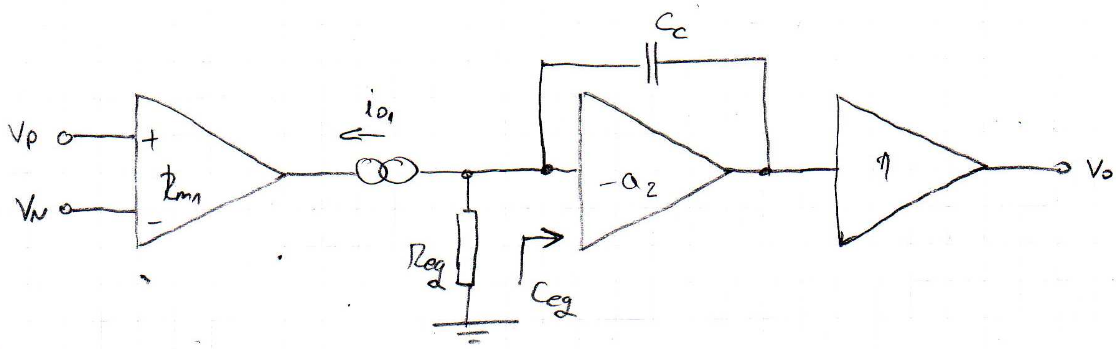
VANJSKA KOMP. NAPONA POMAKA

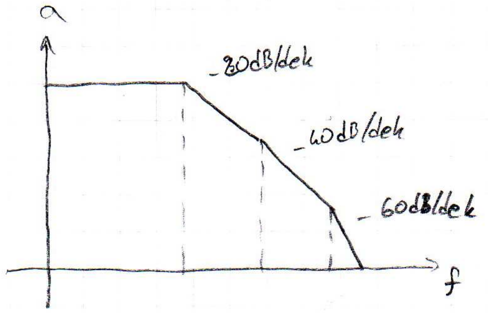


$I_B = 20\,\mu A$
$I_{OS} = 0{,}2\,\mu A$
$V_{OS} = 10\,\mu V$
$R_2 = 10\,k\Omega$
$R_1 = 1\,k\Omega$

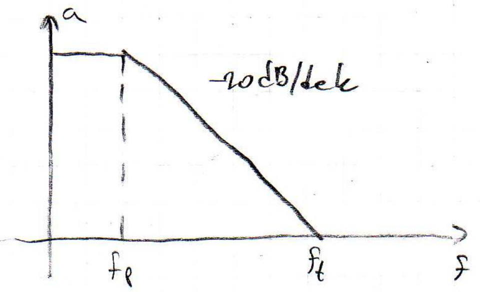
$R_p = R_1 \| R_2$

DINAMIČKE NESAVRŠENOSTI OP-a





A-f karakt. nekompenziranog OP-a



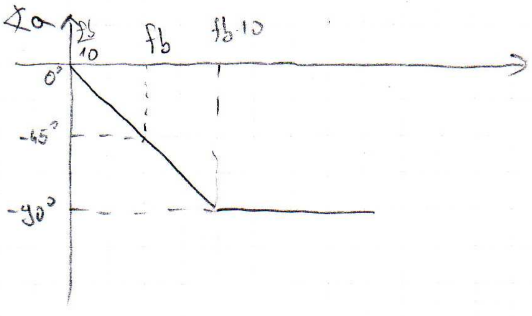
kompenzirani OP

$$f_t = a \cdot f_b$$

$$a(jf) = \frac{a_0}{1 + j\frac{f}{f_b}}$$

Din. nesavršenosti:

- frekv. ovisnost pojačanja u otvorenoj petlji
- Ulazna i izlazna impedancija
- Vrijeme porasta izlaznog napona
- Konačna brzina porasta izlaznog napona (slew rate) $\left(\frac{dU}{dt}\right)_{max}$
- Šum



$$\measuredangle a = -tg^{-1}\left(\frac{f}{f_b}\right)$$

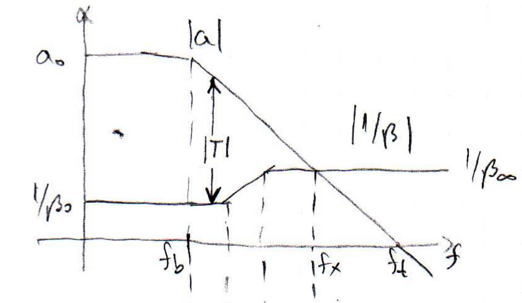
$$a(jf)\big|_{f \ll f_b} \rightarrow a_0 \angle 0^\circ$$

$$a(jf)\big|_{f = f_b} \rightarrow \frac{a_0}{\sqrt{2}} \angle 45^\circ$$

$$a(jf)\big|_{f \gg f_b} \rightarrow \frac{f_t}{f} \angle 90^\circ$$

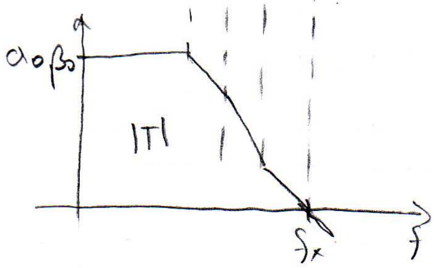
$$A = \frac{a}{1+a\beta} = \frac{1}{\beta} \cdot \frac{1}{1+\frac{1}{a\beta}} = \underbrace{A_{IDEALNO}}_{1/\beta} \frac{1}{1+\frac{1}{T}}$$

$$T = a \cdot \beta$$

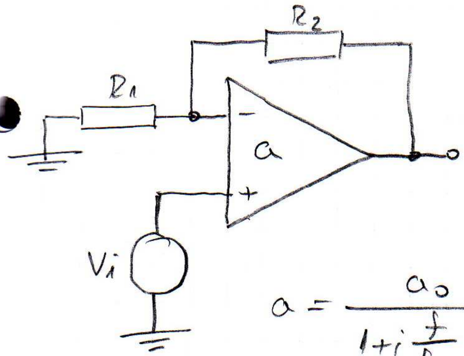


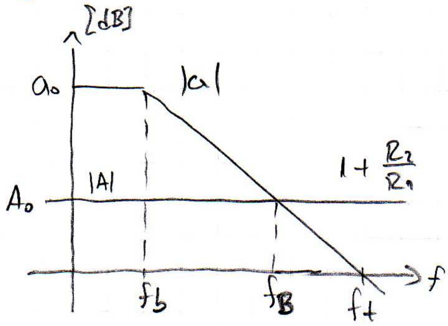
$$|T|_{dB} = |a|_{dB} - \left|\frac{1}{\beta}\right|_{dB}$$

$$\measuredangle T = \measuredangle a - \measuredangle(1/\beta)$$



Neinvertirajuće pojačalo





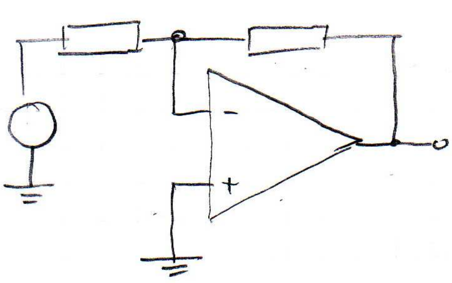
RAZUMJETI!

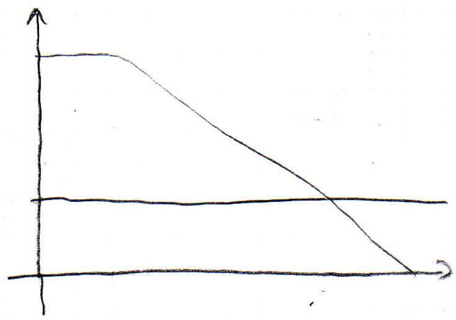
$$a = \frac{a_0}{1+j\frac{f}{f_b}}$$

$$A(jf) = \left(1+\frac{R_2}{R_1}\right)\frac{1}{1+\left(1+\frac{R_2}{R_1}\right)\left(1+j\frac{f}{f_b}\right)\frac{1}{a_0}} = A_{IDE} \cdot \frac{1}{1+\frac{1}{T(jf)}}$$

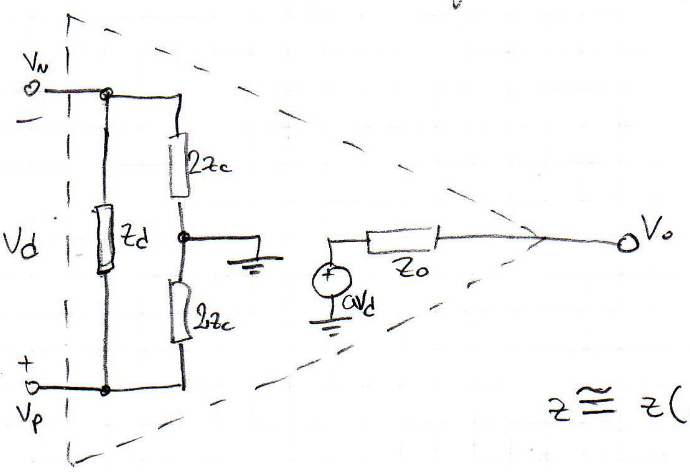
$$f_B = f_b\left(1+a_0\frac{R_1}{R_1+R_2}\right)$$

Invertirajuće pojačalo



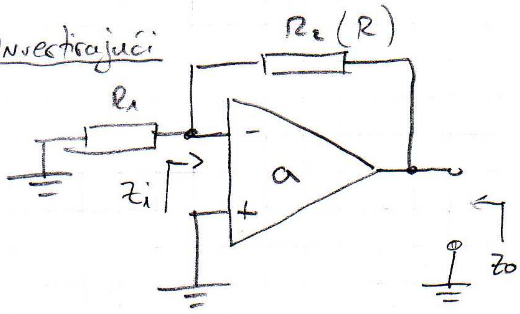


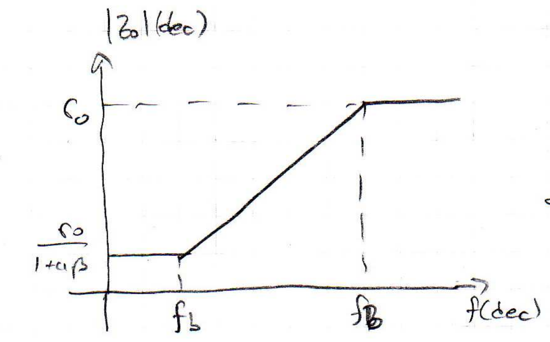
Ulazne i izlazne impedancije



$$z \cong z(1+T)^{\pm 1}$$

Invertirajući





← kvarimo izlazni otpor višom frekv.

$$z_o \cong \frac{r_o}{1+a\beta}$$

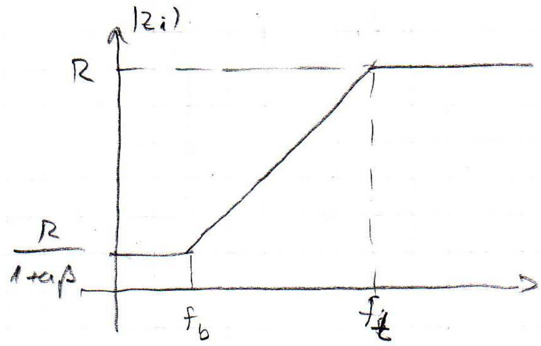
$$\beta \cong \frac{R_1}{R_1+R_2}$$

$$z_o \cong R_o \frac{1+j\frac{f}{f_b}}{1+j\frac{f}{f_B}}$$

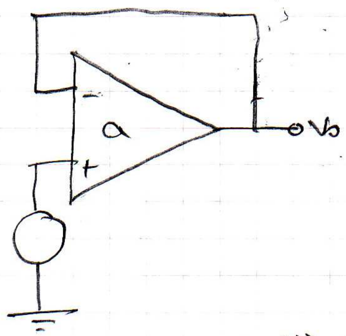
$$z_i \cong \frac{R}{1+a}$$

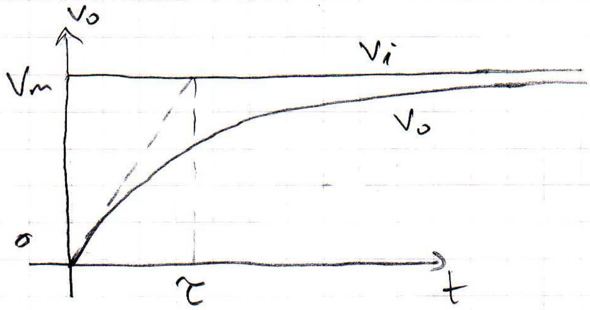
$$z_i \cong R_i \frac{1+j\frac{f}{f_b}}{1+j\frac{f}{f_t}}$$

$$R_i \cong \frac{R}{1+a_o}$$



VRIJEME PORASTA IZLAZNOG NAPONA





$$V_o(t) = V_m\left(1 - e^{-t/\tau}\right)$$

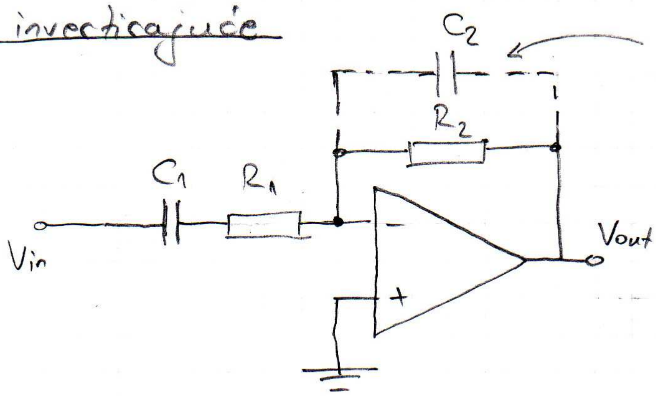
$$t_r = \frac{0{,}35}{f_t}$$

$$t_r = \tau(\ln 0.9 - \ln 0.1)$$

$$\tau = \frac{1}{2\pi f_t}$$

IZMJENIČNA (AC) POJAČALA

AC invertirajuće



ograničava gornju frekvencijsku karakteristiku pojačala

$$\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \cdot \underbrace{\frac{jf}{f_1 + jf}}_{\text{ZBOG KAPACITETA}} \cdot \frac{1}{1 + \frac{1}{a\beta}}$$

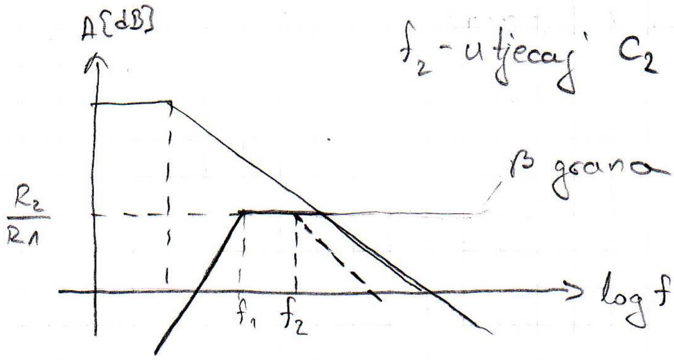
$$f_1 = \frac{1}{2\pi R_1 C_1}$$ ← DONJA GRANIČNA FREKV.

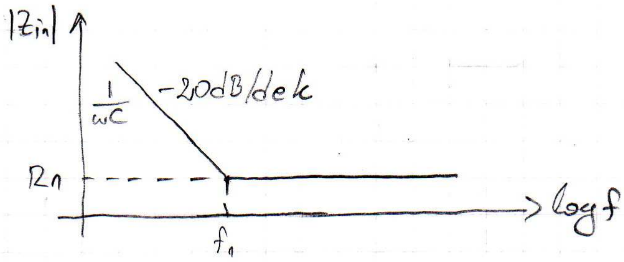
$$\beta = \frac{Z_1}{Z_1 + Z_2}$$

$$Z_1 = X_{C_1} + R_1 = \frac{1}{sC_1} + R_1$$

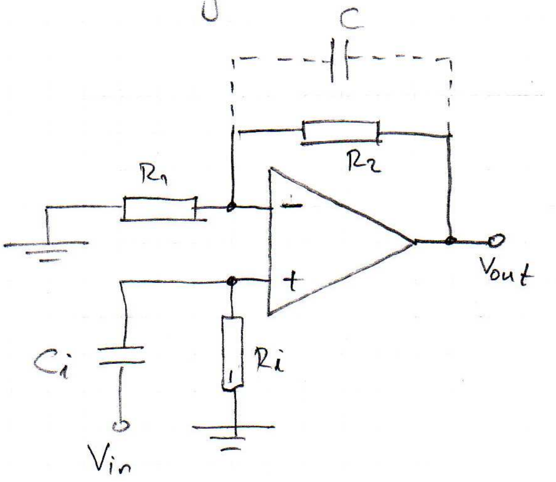
$$Z_2 = X_{C_2} \| R_2$$

$$|Z_{in}| = |Z_1| = \left|R_1 + \frac{1}{j\omega C_1}\right|$$





AC neinvertirajuće

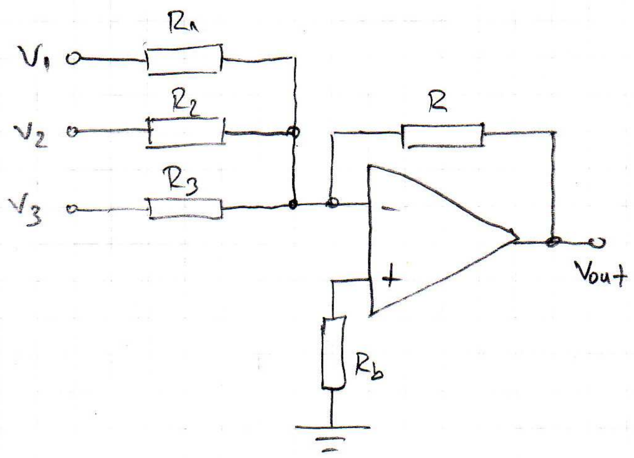


$$f_1 = \frac{1}{2\pi C_i R_i}$$

SKLOPOVI ZA REALIZACIJU LINEARNIH ANALOGNIH FUNKCIJA

ZBRAJANJE

Invertirajuće zbrajalo

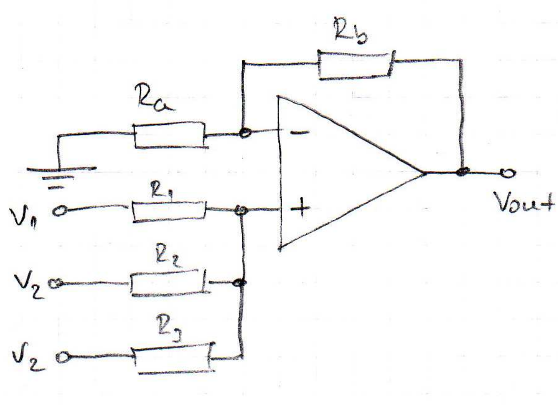


$$V_{out} = -\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right) \cdot R$$

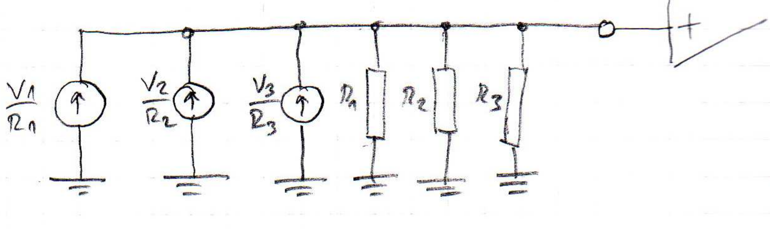
predznak

$R_b \approx R_1 \| R_2 \| R_3 \| R$ za smanjenje smetnji

Neinvertirajuće



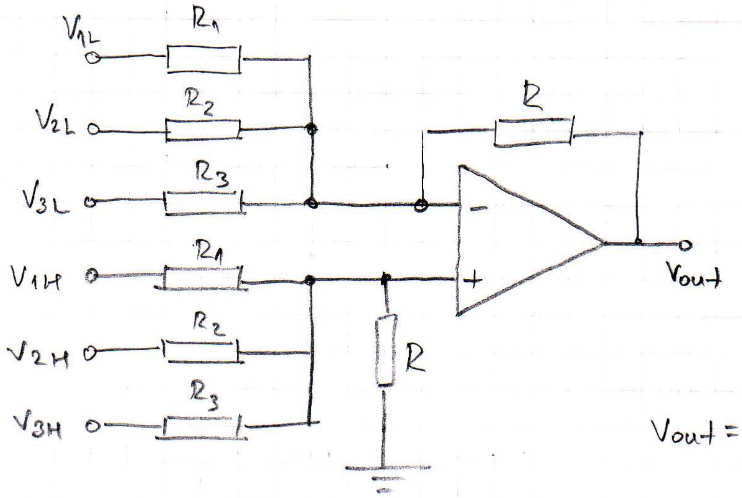
nadomjesna shema



$$V_{out} = \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right) R_p \left(1 + \frac{R_b}{R_a}\right)$$

$$R_p = R_1 \| R_2 \| R_3$$

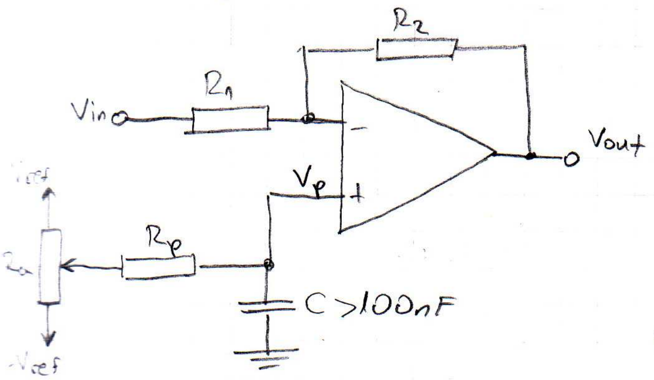
Zbrajalo za diferencijalne signale



$$V_{out} = (V_{1H} - V_{1L})\frac{R_1}{R_1} + (V_{2H} - V_{2L})\frac{R}{R_2} + (V_{3H} - V_{3L})\frac{R}{R_3}$$

POMAK ISTOSMJERNE RAZINE

Invertirajuće

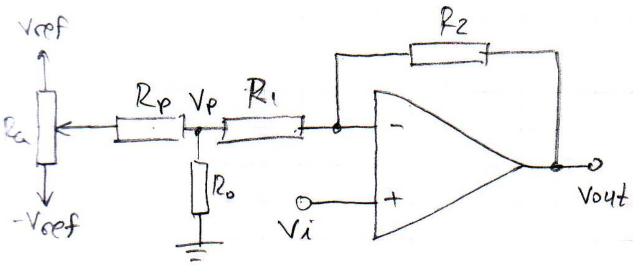


R_p - zaštita za pojačalo, u slučaju da R_a ode u krajnji položaj → Vref direkt na ulaz pojačala

C - otklanja VF smetnje, DC komponenti ne smeta

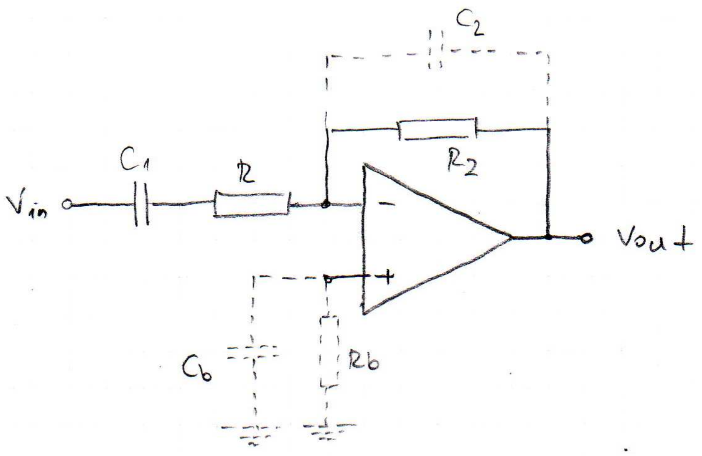
$$V_{out} = -\frac{R_2}{R_1} V_i + \underbrace{V_p\left(1 + \frac{R_2}{R_1}\right)}_{\text{DC komponenta}}$$

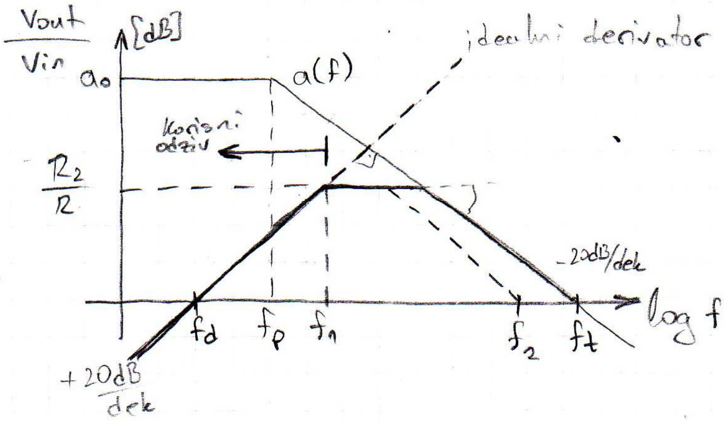
Neinvertirajuće



$$V_{out} = V_i\left(1 + \frac{R_2}{R_1 + R_0}\right) - V_p\frac{R_2}{R_1}$$

DERIVIRANJE





- sa R gušimo pojačanje kako bi osigurali stabilnost pojačala

- f_2 - utjecaj od C_2

- od f_1 prema niže je iskoristivi odziv

$$f_1 = \frac{1}{2\pi C_1 R}$$

$$\frac{V_{out}}{V_{in}} = \frac{-\frac{R_2}{Z_1}}{1+\frac{1}{a\beta}}$$ ← uz zanemarenje C_b, R_b, C_2

$$\beta = \frac{Z_1}{R_2 + Z_1}$$

$$Z_1 = R + X_{C_1} = R + \frac{1}{j\omega C_1}$$

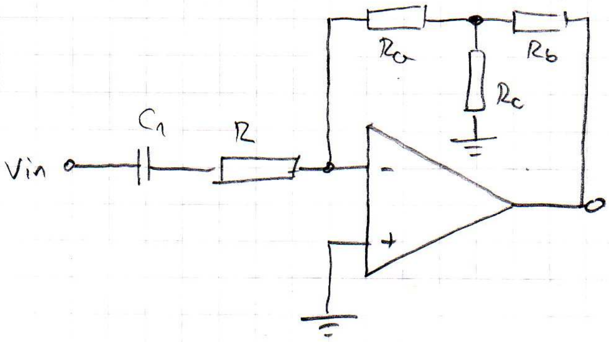
$$a = \frac{a_0}{1+j\frac{f}{f_p}}$$

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{-R_2 C_1 s}{1+s\left(RC+\frac{1}{a_0 2\pi f_p}\right)+s^2\frac{C_1(R+R_2)}{a_0 2\pi f_p}}$$

- U korisnom području $f < f_1$

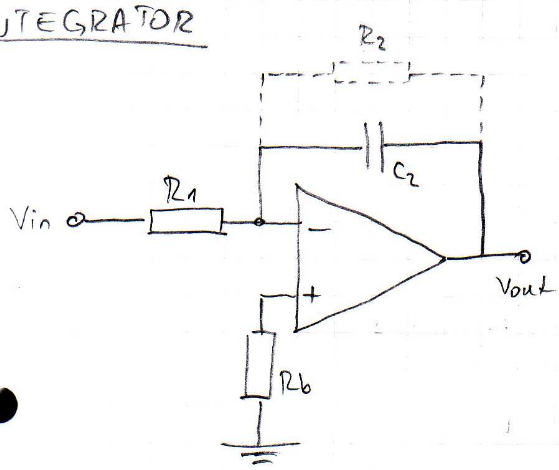
$$V_{out} = -R_2 C_1 \frac{dv_i}{dt}$$

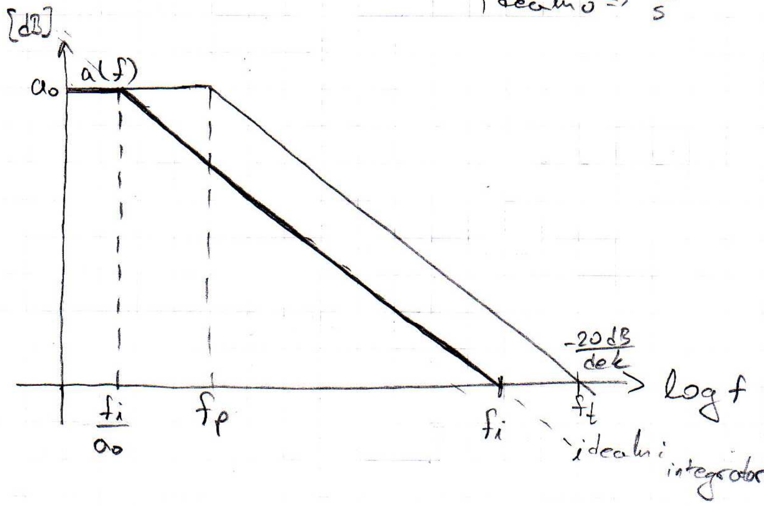
- Ako je potrebna vrlo velika vremenska konstanta $\Longrightarrow$



INTEGRATOR

idealno => "$\frac{1}{s}$"





- za "praktične" integratore $f_i \ll f_t$

$$\frac{V_{out}}{V_{in}} = -\frac{1}{R_1 C_2 s} \cdot \frac{1}{1 + \frac{s + 2\pi f_p}{a_0 2\pi f_p} \cdot \frac{s + R_1 C_2 s}{R_1 C_2 s}}$$

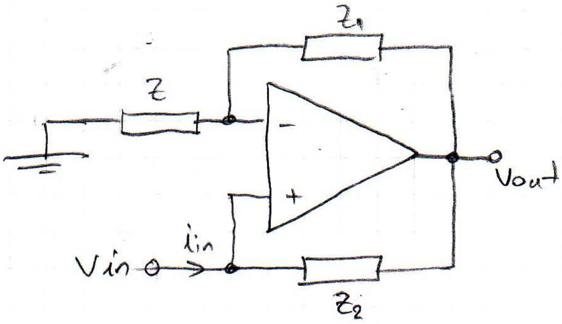
$$\omega_i = \frac{1}{R_1 C_2} \Rightarrow f_i = \frac{1}{2\pi R_1 C_2}$$

- Za $f \ll f_i$

$$\boxed{\frac{V_{out}(s)}{V_{in}(s)} = -\frac{1}{\frac{1}{a_0} + \frac{s}{\omega_i}} \quad \circ\!\!-\!\!\!-\!\!\bullet \quad V_{out}(t) = -\frac{1}{\tau}\int_{t_0}^{t_0+T} V_{in}(t)\,dt + V_0}$$

$\tau = R_1 C_1$

NEGATIVNI KONVERTOR IMPEDANCIJE (NIC)

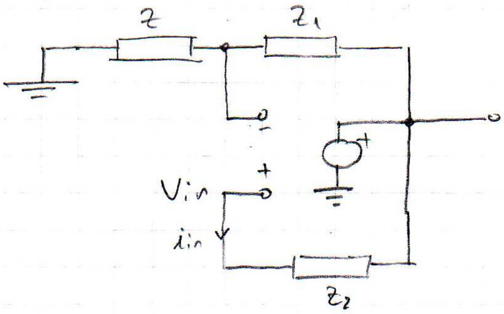


$$V_{out} = V_{in}\left(1 + \frac{Z_1}{Z_2}\right)$$

$$V_{in} - V_{out} = i_{in} Z_2$$

$$\Rightarrow Z_{in} = -Z\,\frac{Z_2}{Z_1}$$

nadomjesna shema



$$V_{out} = a(V_+ - V_-) = a\left(V_{in} - V_{out}\frac{Z}{Z+Z_1}\right)$$

$$-\frac{V_{out}}{Z+Z_1} + \underbrace{\frac{V_{in}-V_{out}}{Z_2}}_{i_{in}} = i$$

$$V_{out} = a\left(V_{in} - V_{out}\frac{Z}{Z+Z_1}\right)$$

$$V_{out}\left(1 + \frac{Za}{Z+Z_1}\right) = a\cdot V_{in} \quad \Rightarrow \quad V_{out} = \frac{a\cdot V_{in}}{1 + \frac{Z\cdot a}{Z+Z_1}} = \frac{V_{in}}{\frac{1}{a} + \frac{Z}{Z+1}}$$

$$\lim_{a\to\infty} V_{out} = \left(1 + \frac{Z_1}{Z_2}\right)V_{in}$$

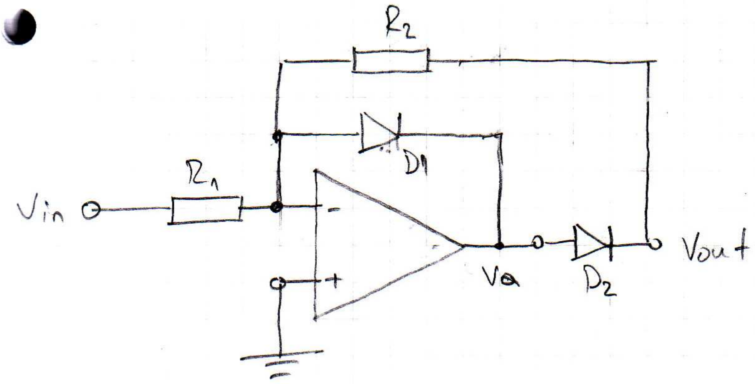
$$i_{in} = \frac{V_{in} - V_{out}}{Z_2} = \frac{V_{in}}{Z_2} - \frac{1}{Z_2}\left(1 + \frac{Z_1}{Z}\right)V_{in}$$

$$i_{in} = V_{in}\left[\frac{1}{Z_2} - \frac{1}{Z_2}\left(1 + \frac{Z_1}{Z}\right)\right]$$

$$Z_{in} = \frac{V_{in}}{i_{in}} = \frac{1}{\frac{1}{Z_2} - \frac{1}{Z_2}\left(1+\frac{Z_1}{Z}\right)} = \frac{Z\cdot Z_2}{Z - Z\left(1 + \frac{Z_1}{Z_2}\right)} = \frac{Z\cdot Z_2}{Z - Z - Z_1} = \underline{-Z\cdot\frac{Z_2}{Z_1}}$$

AC/DC PRETVORBA

Precizni poluvalni ispravljač



za $V_{in}>0$, $V_a \rightarrow$ negativan

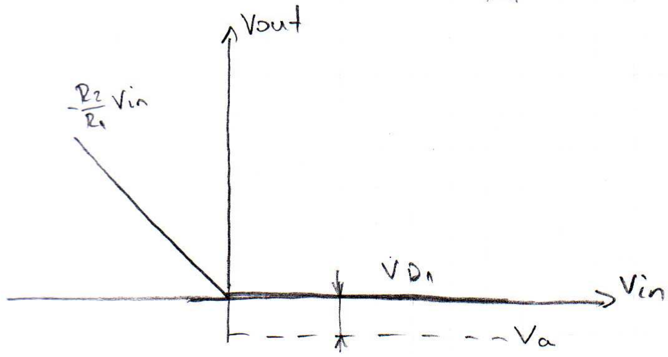
D1 vodi; D_2 ne vodi

R_2 - ne teče struja

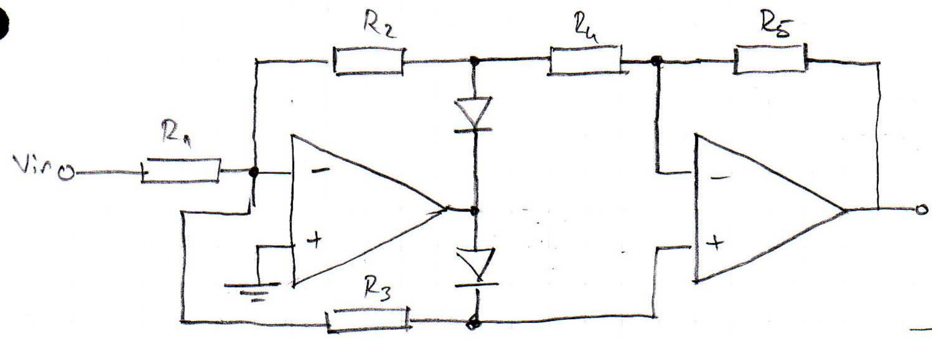
$V_{in}<0$, V_a - pozitivan, D_1 ne vodi, D_2 vodi,

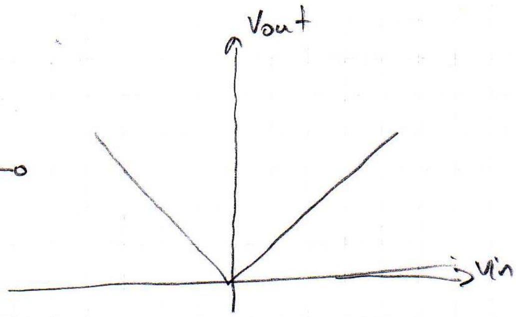
povratna veza zatvorena kroz R_2

$$V_{out} = -\frac{R_2}{R_1} V_{in}$$



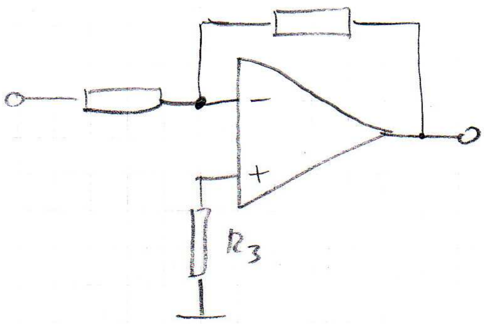
Punovalni ispravljač





ZADATCI

1.



$$A = -\frac{R_2}{R_1} \Rightarrow R_2$$

$$R_{ul} = R_1$$

$$\Rightarrow R_3 = R_1 \| R_2$$

⋮

$$\frac{du_{iz}}{dt} = 1\,\frac{V}{\mu s}$$

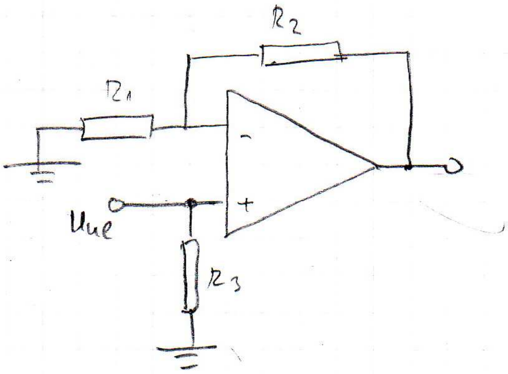
$$f_{max} = \frac{\left(\frac{du_{iz}}{dt}\right)_{max}}{2\pi \cdot U_{max}} = 19{,}9\,kHz$$

$$U_{iz_{max}} = 8$$

2.

$A = 10$
$R_{ul} = 10k\Omega$
$f = 10\,kHz$
$f_p = 10\,Hz$
$a_0 = 70\,dB$
$r_d = 1M\Omega$

$A|_{f=}$



$$A = 1 + \frac{R_2}{R_1} \Rightarrow \frac{R_2}{R_1} = 9 \Rightarrow R_2 = 9R_1$$

$$R_{ul} = R_3$$

$$R_3 = R_1 \| R_2$$

$$\frac{R_1 R_2}{R_1 + R_2} = R_{ul} \Rightarrow R_1 = 10\,\frac{R_{ul}}{9} = 11{,}11\,k\Omega$$

$$R_2 = 100\,k\Omega \quad , \quad R_3 = 10\,k\Omega$$

$$a = \frac{a_0}{1 + j\frac{f}{f_p}} \quad , \quad a = \frac{a_0}{\sqrt{1 + \left(\frac{f}{f_p}\right)^2}}$$

$$20 \log a_0 = 70\,dB$$

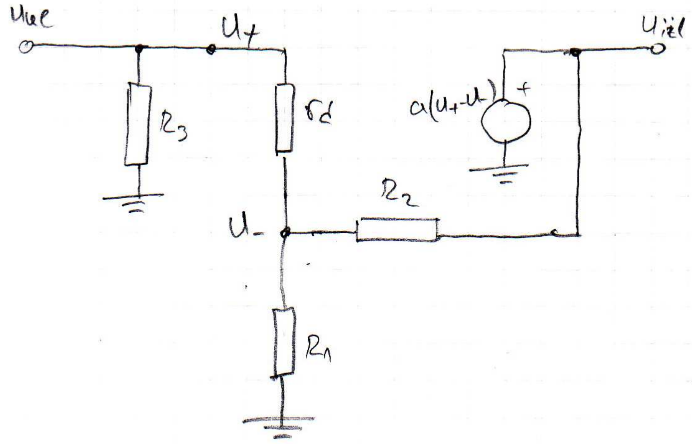
$$a_0 = 10^{\frac{70}{20}} = 10^{3{,}5} = 3{,}16 \cdot 10^3$$

$$a = \frac{a_0}{\sqrt{1 + \left(\frac{10\,kHz}{10\,Hz}\right)^2}} = 3{,}16$$

$$\boxed{A = \frac{\left(1 + \frac{R_2}{R_1}\right) a}{1 + a + \frac{R_2}{R_1} + \frac{R_2}{r_d}}} = 2{,}38$$

ŠALABAHTER

nadomjesna shema



$$\left.\begin{aligned} &\frac{U_+-U_-}{r_d} - \frac{U_-}{R_1} + \frac{U_{izl}-U_-}{R_2} = 0 \\ &U_+ = U_{ul} \\ &U_{iz} = a(U_+-U_-) \end{aligned}\right\} A$$

Dodavanjem izvora s unutarnjim otporom R_g

$R_3 \| R_g$

$$U_{iz,pom} = \left\{ U_f + I_{ul}\left[(R_3\|R_g) - (R_1\|R_2)\right] + I_{pom}\frac{(R_3\|R_g)+(R_1\|R_2)}{2} \right\}$$

$T_{min} = 5°C$
$T_{max} = 35°C$
$T_0 = 15°C$

$\Delta T_1 = -10°C$
$\Delta T_2 = 20°C$

$$\frac{\Delta U}{\Delta T} = \left[\left|\frac{dU_f}{dT}\right| + \left(\frac{dI_{of}}{dT}\right)\cdot R_3\right]\cdot\left(1+\frac{R_2}{R_1}\right)$$

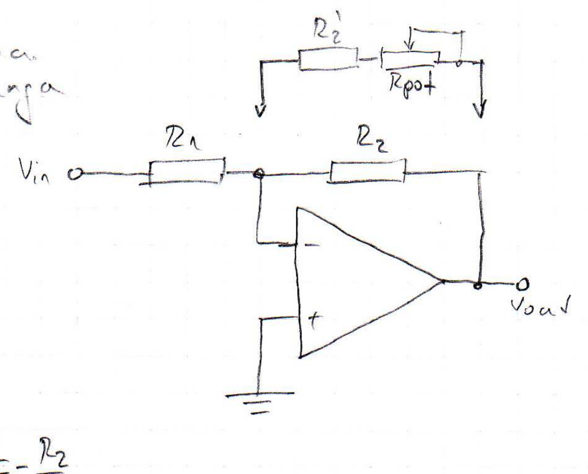
$10\frac{\mu V}{°C}$, $50\frac{\mu A}{°C}$

$$\Delta U_1 = \Delta T_1 \cdot [\quad] = -1{,}25\,mV$$

$$\Delta U_2 = \Delta T_2 \cdot [\quad] = +2{,}5\,mV$$

$$-1{,}25 \leq \Delta U \leq 2{,}5\,V$$

promjena pojačanja



$$V_{out} = -\frac{R_2}{R_1}V_{in}$$

R_1 - ne mijenjamo

R_2 - može

$$A_{min} = -\frac{R_2}{R_1}$$

$$A_{max} = -\frac{R_2+R_{pot}}{R_1}$$