ES04 - FREQUENCY COMPENSATION

28/09/2021

FREQUENCY RESPONSE

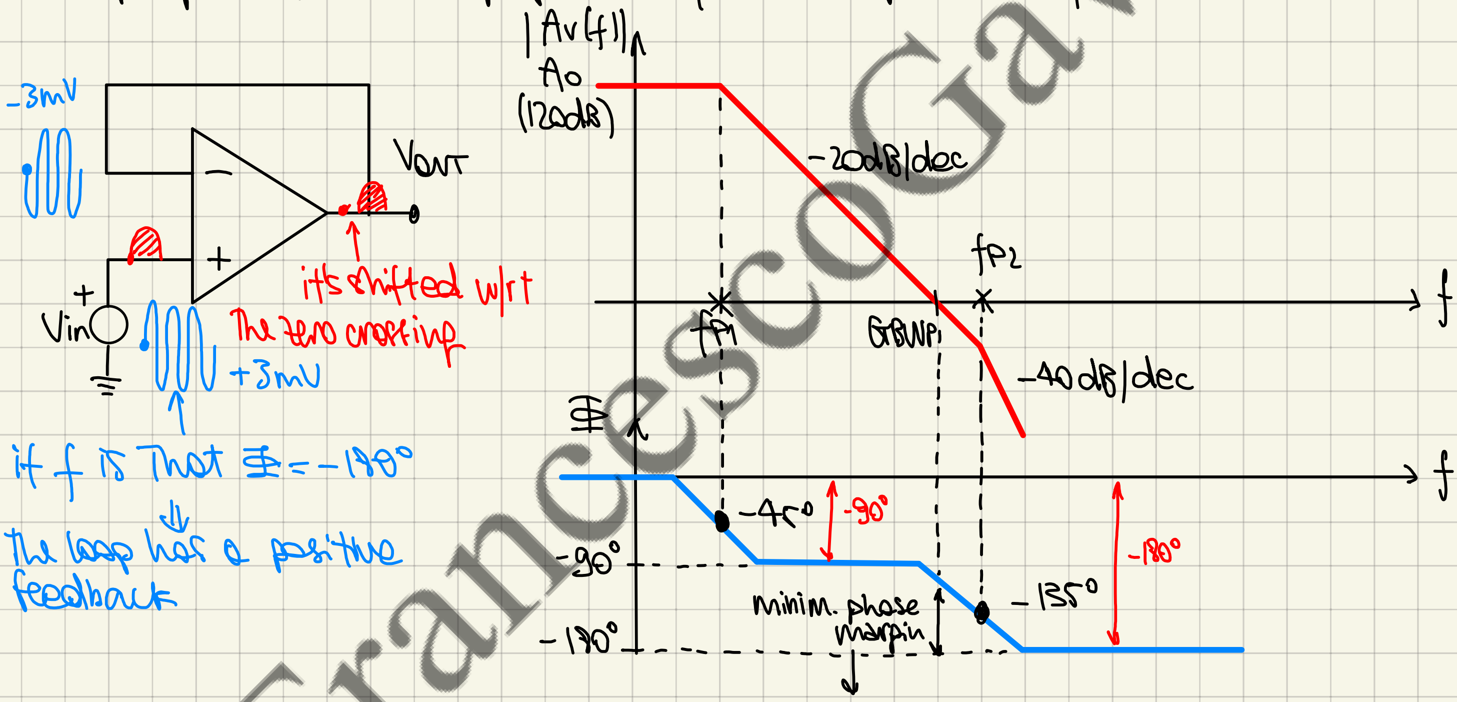
The frequency response study is a small-signal study, that is a study that analyzes components when they deviate a bit from their operating point and do not go out of their linear operation range, reaching the saturation or even the cut-off

OpAmps cannot operate w/ an open loop, but they have to be used in a negative FB configuration w/ the output signal coming back to the inverting OpAmp pin.
The "loop closure" leads to a reduction of the OpAmp gain, but at the same time it makes the OpAmp gain more precise, widens the BW, reduces the output impedance, raises the input impedance (seen from the positive terminal).

A noticeable disadvantage of the FB is that it may cause the instability of the stage.

- OPEN-LOOP FREQUENCY RESPONSE

The OpAmp introduces amplification, but also phase shift.



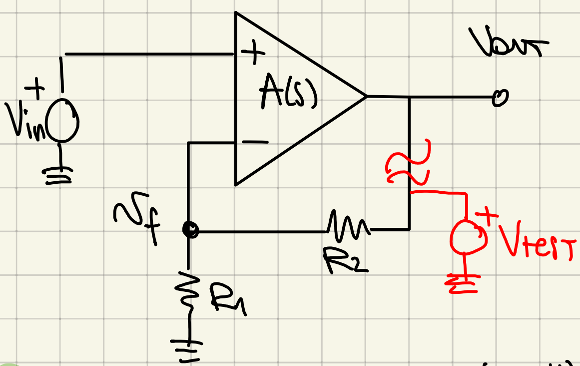
if f is that Φ = -180°
⇓
the loop has a positive feedback

$\phi_m \simeq 180° - 100° = 80°$

ϕ_m is the residual phase before the loop becomes positive, and so unstable

Commonly we say that an OpAmp is compensated if the 2nd pole of its open-loop gain A(s) is at a frequency higher than the intersection of $G_{loop}(s)$ and the 0dB axis

• NON-INVERTING STAGE



1. FEEDBACK GAIN

$$\boxed{\beta = \frac{V_f}{V_{TEST}}} = \frac{R_1}{R_1+R_2}$$

2. LOOP GAIN

$$\boxed{G_{loop} = -A(s)\cdot\beta} = -A(s)\,\frac{R_1}{R_1+R_2}$$

3. REAL GAIN → BEWARE (IMP!!): This is valid only for the NI config.

$$\boxed{G_{NI} = \frac{A}{1-A\cdot\beta} = \frac{A}{1+G_{loop}} = \frac{A}{\beta\left(\frac{1}{\beta}-A\right)} = \begin{cases} \text{if } \frac{1}{\beta} \ll A \ (G_{loop}\gg 1) \longrightarrow \underbrace{G_{NI} \simeq \frac{1}{\beta}}_{*\ \text{IDEAL GAIN}} \\ \text{if } \frac{1}{\beta} \gg A \ (G_{loop}\ll 1) \longrightarrow G_{NI} \simeq A \end{cases}}$$

* we love this gain bcz it's independent of the OpAmp itself

Gloop ASSESSMENT AND REAL GAIN EXTRACTION

In order to assess Gloop, to check FB quality and stage stability, and to be able to draw the real closed-loop frequency response and not just the ideal one, do follow these hints:

1. Draw A(s) (the freq. response of the OpAmp)

2. Compute β(s) (No Laplace, just asymptotic analysis @DC and @HF) and draw 1/β(s) (remember: poles of β(s) lift up, zeros of β(s) put down 1/β(s))

3. The split between A(s) and 1/β(s) is Gloop(s):
   - The larger the split (i.e. Gloop), the better the feedback quality (remember: if $G_{loop} \gg 1 \rightarrow G \simeq 1/\beta$: ideal gain)
   - @ $f = f^*$ where $A(f^*) = 1/\beta\,(f^*) \rightarrow G_{loop}(f^*) = 1$

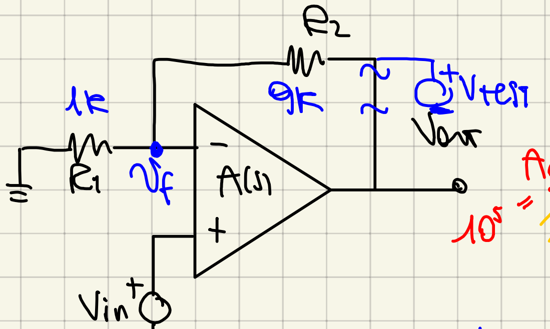
4. Draw the expected ideal gain (don't care about A(s) nor 1/β(s))

5. The real closed-loop frequency response:
   - follows the ideal one when "there is Gloop" (i.e. $G_{loop}(s) > 1$)
   - beyond f^* there is no more feedback, hence the real gain rolls off from the ideal trend, experiencing all following poles and zeros of A(s)

6. Stage stability depends on the "closure angle" between A(s) and 1/β(s) around f^*

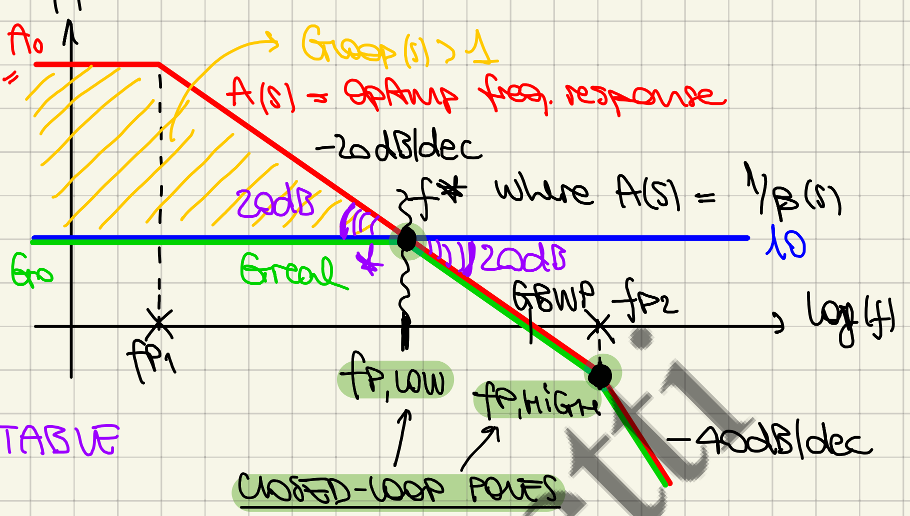
- STABLE → $\boxed{\text{20dB/dec before and after } f^*}$
- MARGINALLY STABLE → $\boxed{\text{20dB/dec before and 40dB/dec after } f^*\text{, or viceversa}}$
- UNSTABLE → $\boxed{\text{40dB/dec or higher before and after } f^*}$

Let's apply the procedure to the NI stage seen before:



$$\beta(s) = \frac{V_f}{V_{test}} = \frac{R_1}{R_1+R_2} = \frac{1}{10}$$

$$G_{ideal} = 1 + \frac{R_2}{R_1} = \frac{1}{\beta}$$

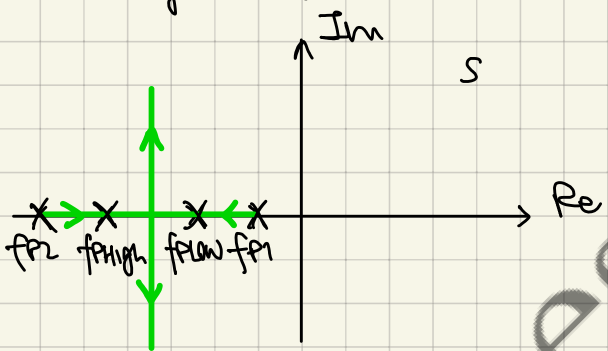


Notice: here β is DC (constant)

* closure angle = 20−20 → STABLE

$$f_{p1} \cdot A_0 = f^* \cdot 10 \rightarrow f^* = f_{p1} \frac{A_0}{10} = 10\,Hz \cdot \frac{100k}{10} = 100\,kHz$$

We can study this behavior also using the root locus:



Why does the "closure angle" matter on the stability?

a. Given that the split btw A(s) and 1/β(s) is Gloop(s)

b. The "closure angle" @ f* measures the slope of Gloop(s) versus freq. @ f*

c. If before f* the Gloop experienced:

- 1 pole → −20dB/dec slope @ f*
- 2 poles → −40dB/dec slope @ f*
- n poles → n × (−20dB/dec) slope @ f*
- 2 poles, 1 zero → −20dB/dec slope @ f*
- p poles, z zeros → (p−z) × (−20dB/dec) slope @ f*
- {1 pole before f*, 1 pole @ f*} → −20dB/dec slope before f*, −40dB/dec slope after f*

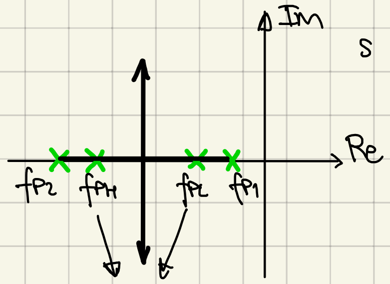
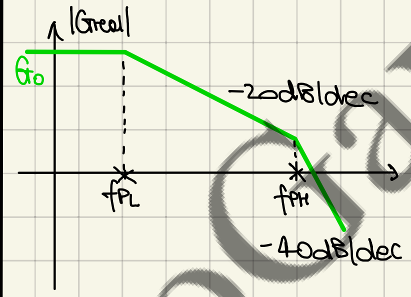
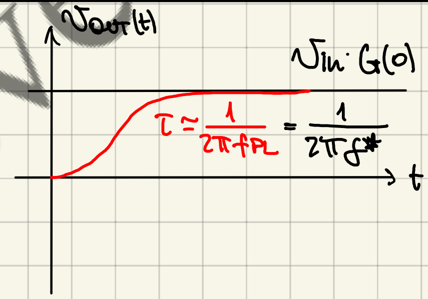
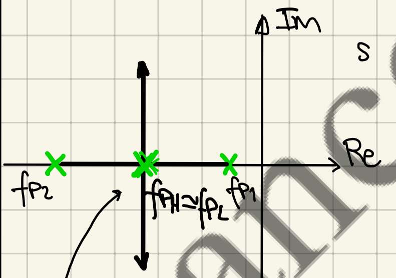
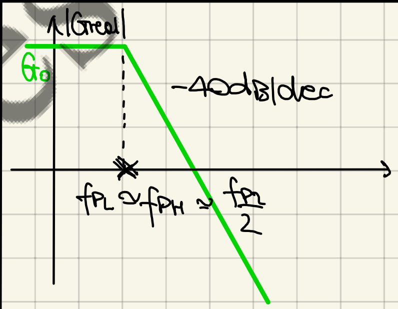
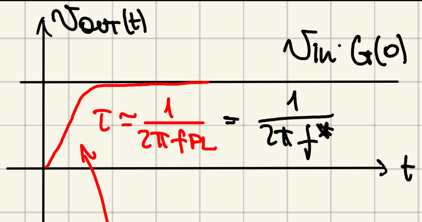
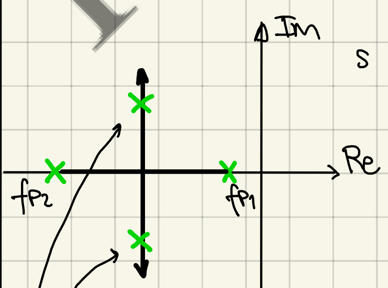
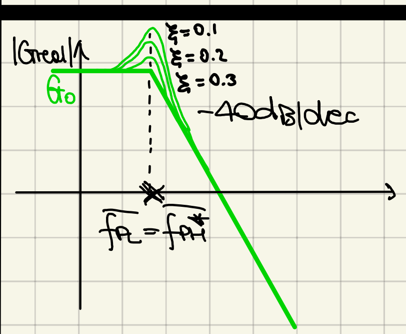
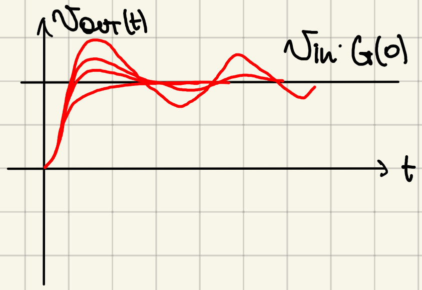
d. Each pole (zero) adds a phase shift of −90° (+90°) to the feedback signal after one decade from it; instead the pole (zero) adds just −45° (+45°) if the f* is coincident w/ the pole (zero) itself

e. Therefore, by measuring the "closure angle" it's possible to infer the difference $(p-z)$ and eventually the overall phase shift accumulated along the feedback path.

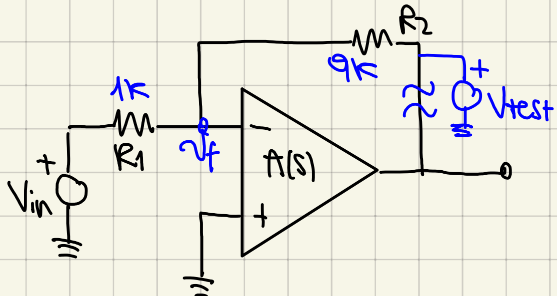
f. The stage is STABLE if the feedback stays negative and does not accumulate $-180°$ phase shift, in which case it turns to be positive and the stage is UNSTABLE

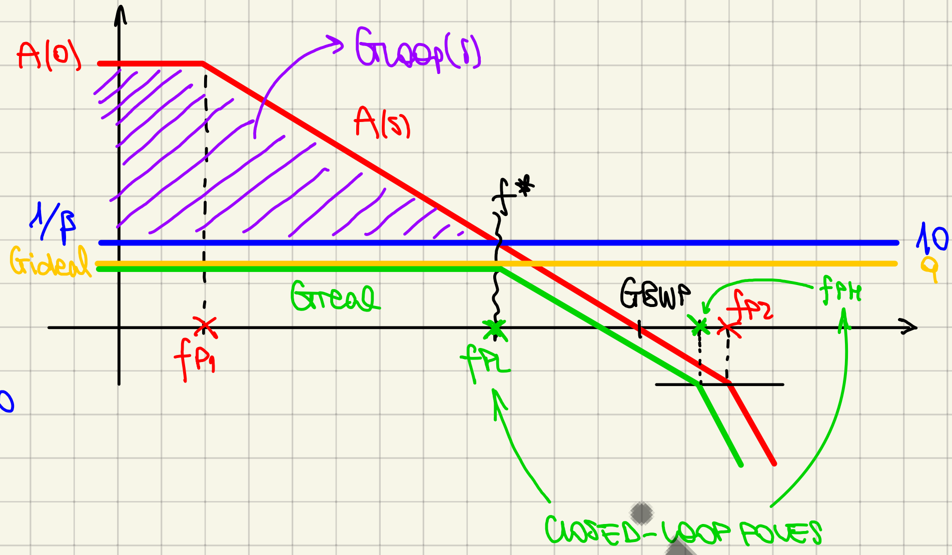
When G_{loop} is poor? when the attenuation introduced by the loop is really strong.
↓
ex: in the NI stage analyzed so far, G_{loop} is poor if $R_1 = 1k\Omega$ and $R_2 = 1M\Omega$

Let's look at other three examples:

	ROOT LOCUS	CLOSED-LOOP FREQ. RESPONSE	TIME RESPONSE
G_{loop} POOR ($1/\beta$ STRONG, β POOR)	 G_{real} has 2 real separated poles		
G_{loop} MODERATE ($1/\beta$ DECR., β INCR.)	 G_{real} has 2 real coincident poles		 faster than the previous case
G_{loop} STRONG ($1/\beta$ POOR, β STRONG)	 G_{real} has 2 complex conjugated poles		 overshootings and undershootings in time

- INVERTING STAGE





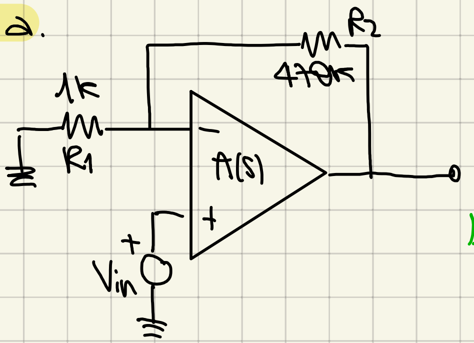
$$\frac{V_f}{V_{test}} = \beta = \frac{R_1}{R_1+R_2} = \frac{1}{10} \rightarrow \frac{1}{\beta} = 10$$

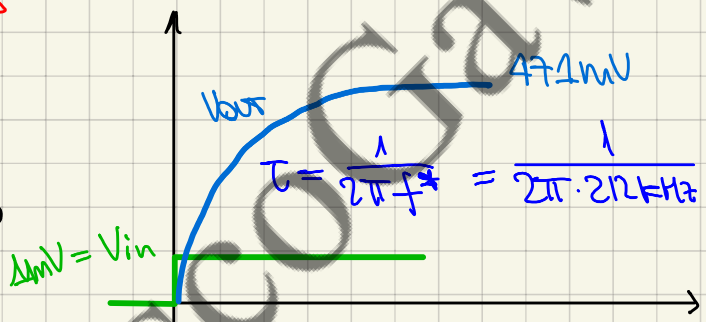
$$|G_{ideal}| = \left|-\frac{R_2}{R_1}\right| = |-9|$$

- if $f_{P2} > GBWP \rightarrow$ The OpAmp is "compensated"
- if $f_{P2} < GBWP \rightarrow$ The OpAmp is "uncompensated"

"UNCOMPENSATED" OPAMP

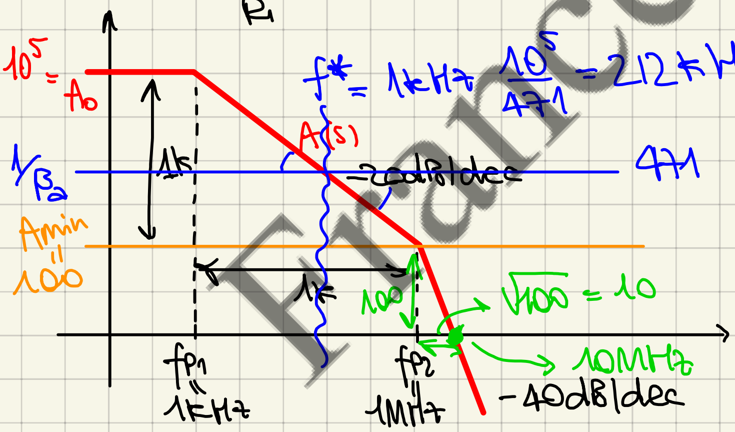
CASE a.





$$\tau = \frac{1}{2\pi f^*} = \frac{1}{2\pi \cdot 212\,kHz}$$

$$G_{ideal} = 1 + \frac{R_2}{R_1} = 471 > A_{min} \Rightarrow \text{STABLE}$$



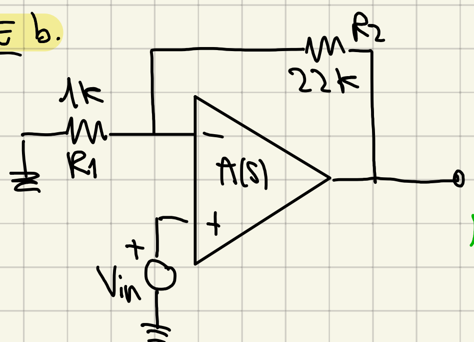
$f^* = 1\,kHz \cdot \frac{10^5}{471} = 212\,kHz < f_{P2}$

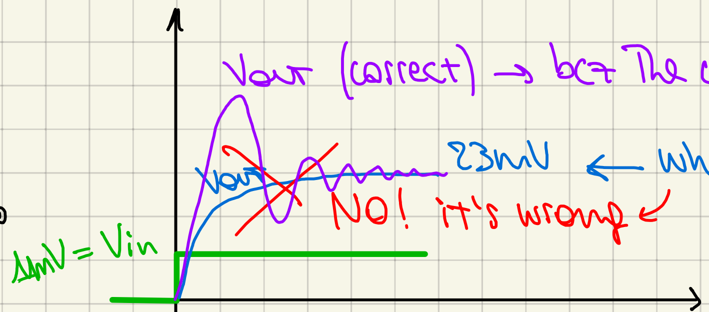
$\sqrt{100} = 10$

10MHz

closure angle$_{(a)}$ = 20-20 ⇒ STABLE (cvd)

CASE b.



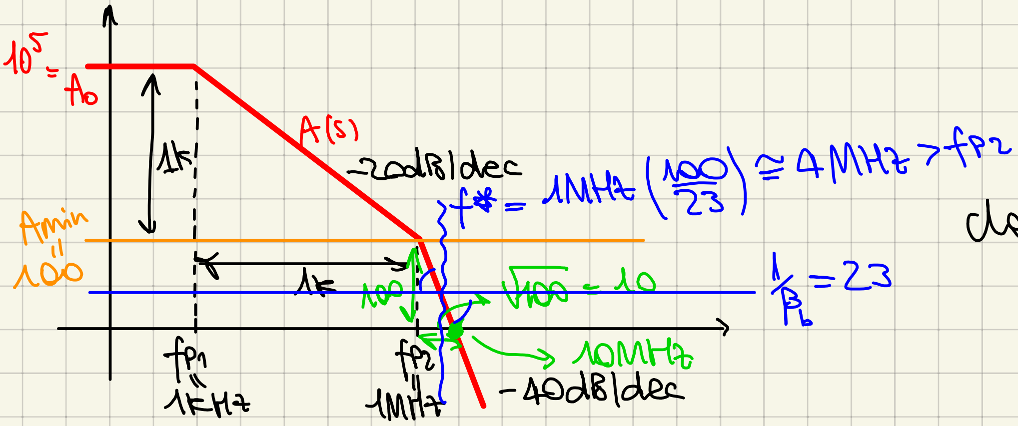


Vout (correct) → bcz The circuit is unstable!

23mV ← what I expect

NO! it's wrong

$$G_{ideal} = 1 + \frac{R_2}{R_1} = 23 < A_{min} \Rightarrow \text{UNSTABLE}$$



closure angle$_{(b)}$ = 40 - 40

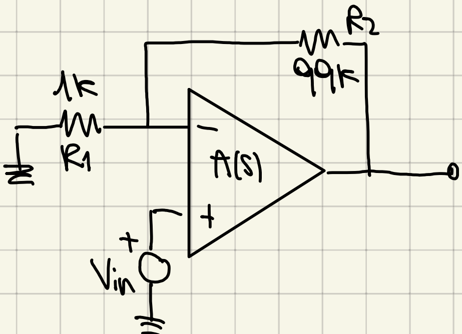
⇓

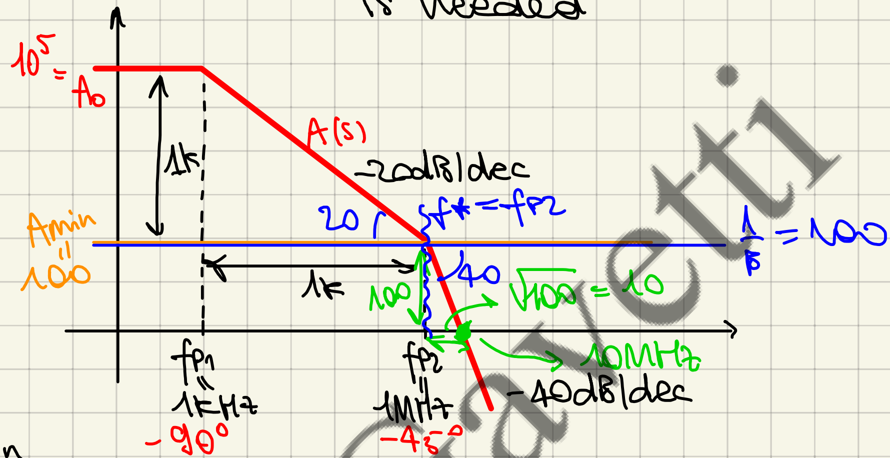
UNSTABLE!!

(wd)

compensation is needed

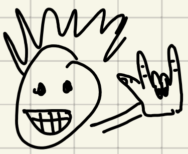
CASE c.





$G_{ideal} = 1 + \frac{R_2}{R_1} = 100 = A_{min}$

$\frac{1}{\beta} = 1 + \frac{R_2}{R_1} = 100$



(very happy)

closure angle$_{(c)}$ = 20 - 40

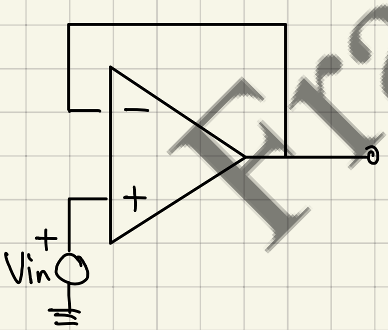
↓

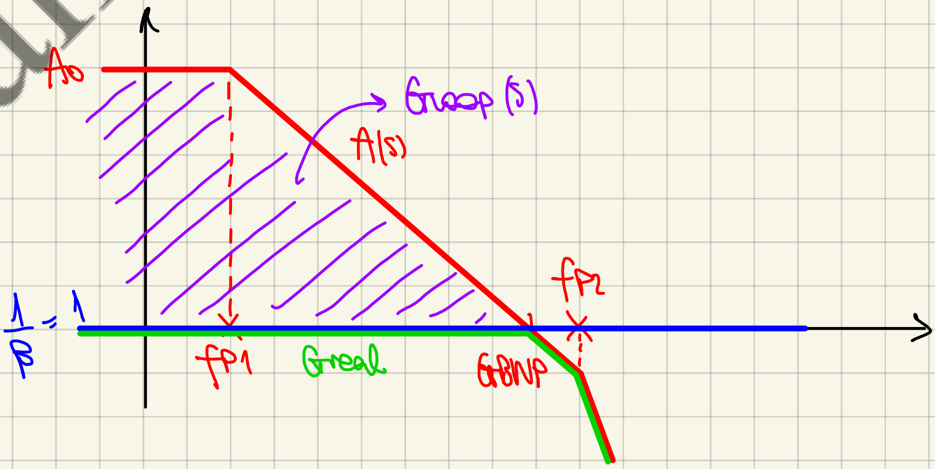
STILL STABLE!!

BEST CONDITION → The time response will be very fast even though there is a minor peaking

$PM = 180° - 90° - 45° = 45°$

NON-INVERTING STAGE: THE WORST CASE





$G_{ideal} = 1$

UNCOMPENSATED OPAMP = is an OpAmp that has the two poles before the frequency at which the gain ($A(s)$) becomes 1.

↓

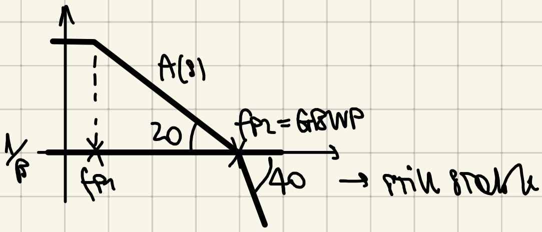
in this case it can be stable or unstable depending on where $1/\beta$ cuts $A(s)$

COMPENSATED OPAMP = is an OpAmp that has the 2nd pole f_{P2} at a frequency higher than the frequency at which the gain ($A(s)$) becomes 1

↓

The MAIN ADVANTAGE of a compensated OpAmp is that even if you connect the OpAmp in the worst possible way for stability that is $1/\beta = 1$ (so the BUFFER) the OpAmp, since it has $f_{P2} > GBWP$, is stable for sure

The manufacturer could design the OpAmp also to have $f_{P2} = GBWP$



HOW TO COMPUTE THE PHASE MARGIN

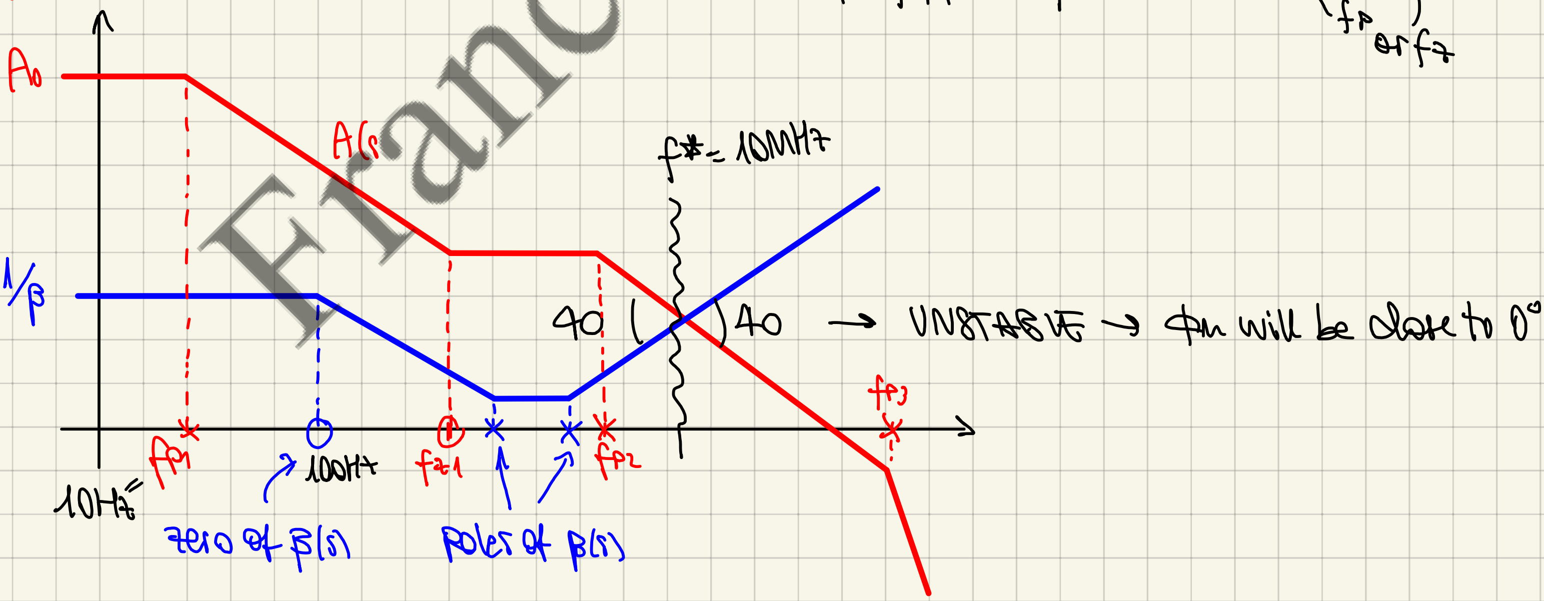
1. Plot $A(s)$
2. Plot $1/\beta(s)$
3. Find f^* (where $A(s) = 1/\beta(s)$)
4.

$$\Rightarrow \boxed{\phi_m = 180^\circ - \sum_i \operatorname{atan}\left(\frac{f^*}{f_{Pi}}\right) + \sum_j \operatorname{atan}\left(\frac{f^*}{f_{Zj}}\right)}$$

NOTICE: where f_{Pi} and $f_{Z,j}$ are all the poles and zeros of $A(s)$ and $\beta(s)$

Example:

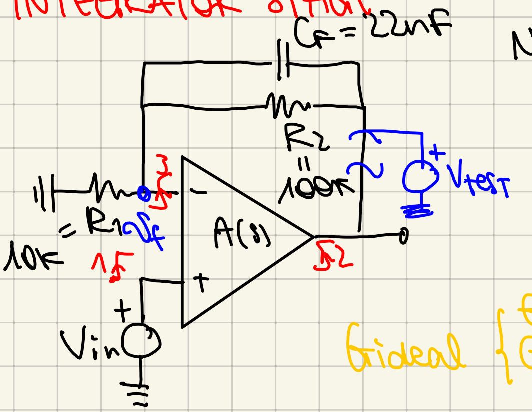
Notice: if $f_P, f_Z \ll f^* \rightarrow \operatorname{atan}\left(\frac{f^*}{f_P \text{ or } f_Z}\right) \simeq 90^\circ$



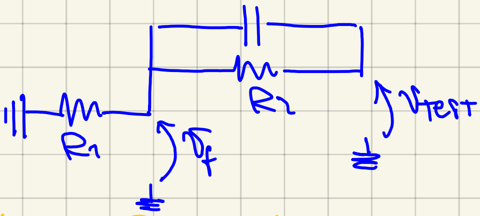
$$\phi_m = 180^\circ - \arctan\left(\frac{10MHz}{10Hz}\right) + \arctan\left(\frac{10MHz}{100Hz}\right)$$

ROLE OF C_F

INTEGRATOR STAGE



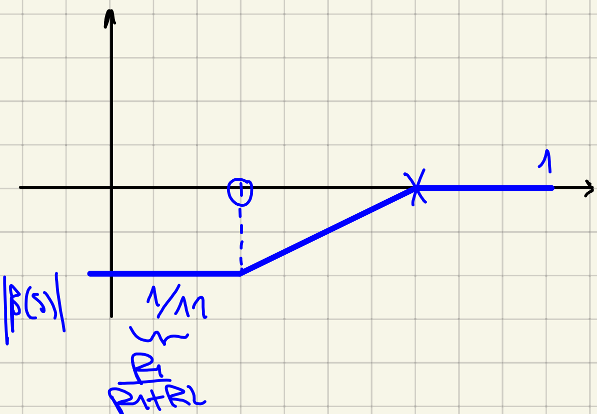
NEGATIVE FB

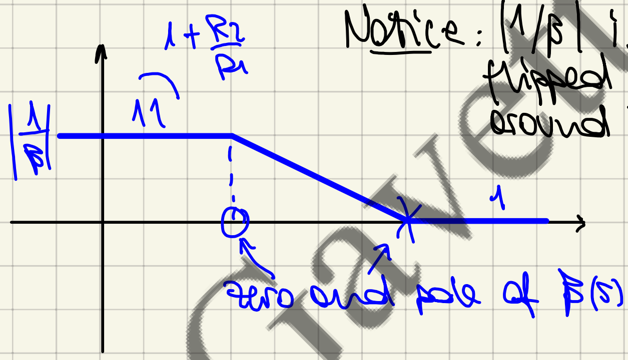


$$G_{ideal} \begin{cases} G_{ideal}(0) = 1 + R_2/R_1 = 11 \\ G_{ideal}(\infty) = 1 \end{cases}$$

@DC → C open → $\beta(0) = \frac{V_f}{V_{TEST}}(0) = \frac{R_1}{R_1+R_2} = \frac{1}{11}$

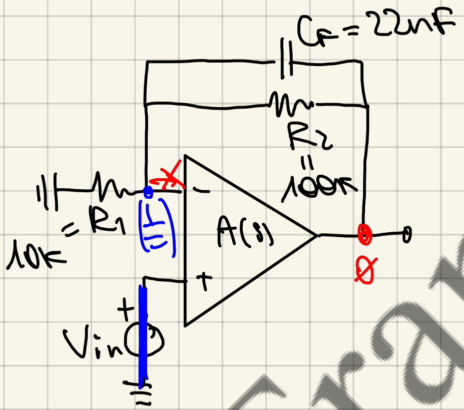
@HF → C close → $\beta(\infty) = 1$



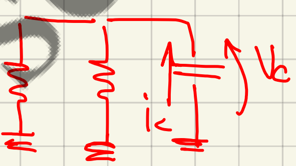


Notice: $|1/\beta|$ is simply $|\beta|$ flipped vertically around the 0dB axis

Now, let's compute the zero and the pole of the circuit; (not of β)

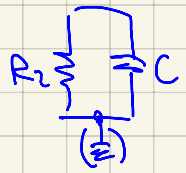


zero:

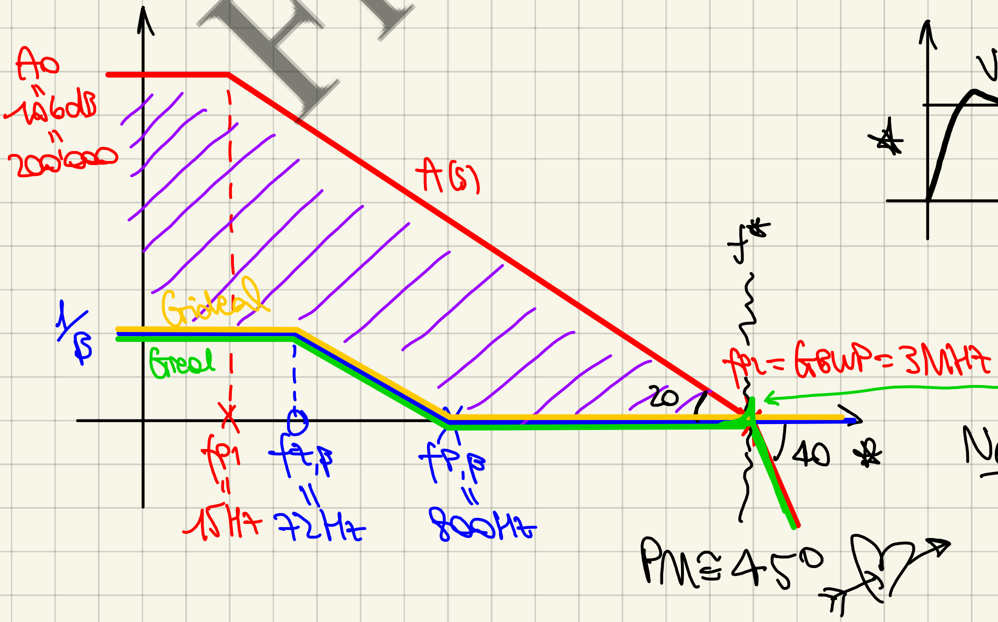


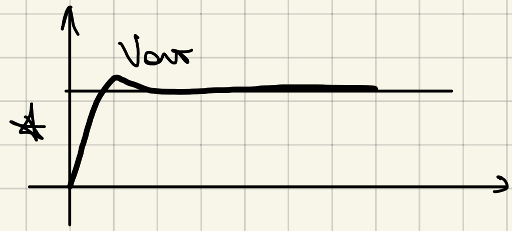
$$f_Z = \frac{1}{2\pi C_F R_1 // R_2}$$

pole:



$$f_P = \frac{1}{2\pi C_F R_2}$$





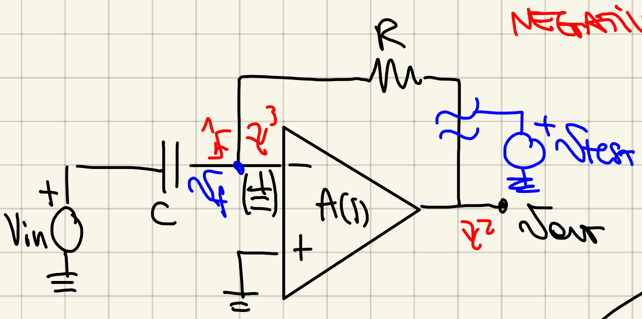
Notice: $\frac{1}{\beta}(s) = G_{ideal}(s)$

indeed it is a NON-INVERTING CONFIG

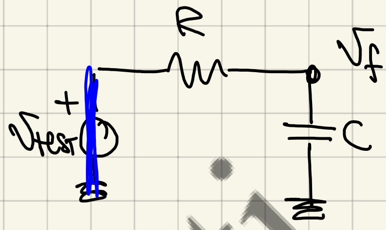
DERIVATOR STAGE

• IDEAL DERIVATOR

NEGATIVE FB



β should have a pole



$@DC \to C$ open $\to \beta(0) = 1 \to \frac{1}{\beta}(0) = 1$

$@HF \to C$ short $\to \beta(\infty) = 0 \to \frac{1}{\beta}(\infty) = \infty$

$$f_{p,\beta} = \frac{1}{2\pi CR}$$

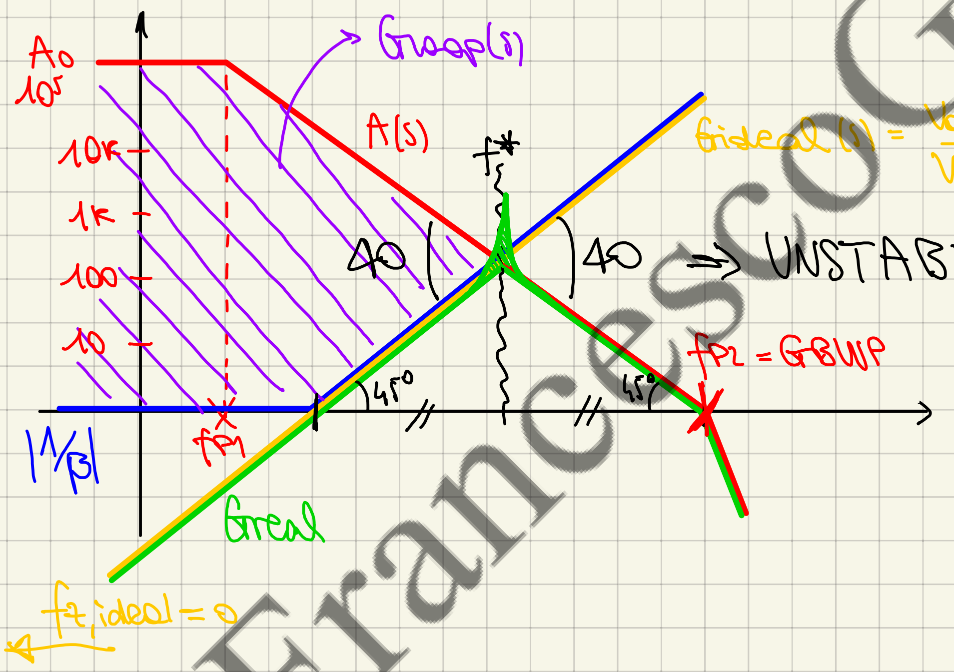
$G_{ideal} = ?$

$@DC \to G_{ideal}(0) = 0$

$@HF \to G_{ideal}(\infty) = \infty$

in the ideal gain there is no pole, there is only a zero at the origin

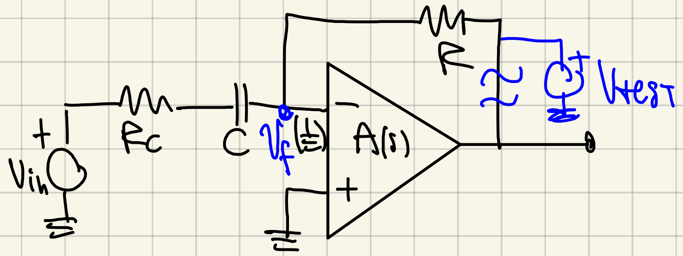
$f_{z,ideal} = 0$



$$G_{ideal}(s) = \frac{V_{out}}{V_{in}}\Big|_{ideal}(s) = -RCs$$

• REAL DERIVATOR

NEG FB



$@DC \to \beta(0) = 1$

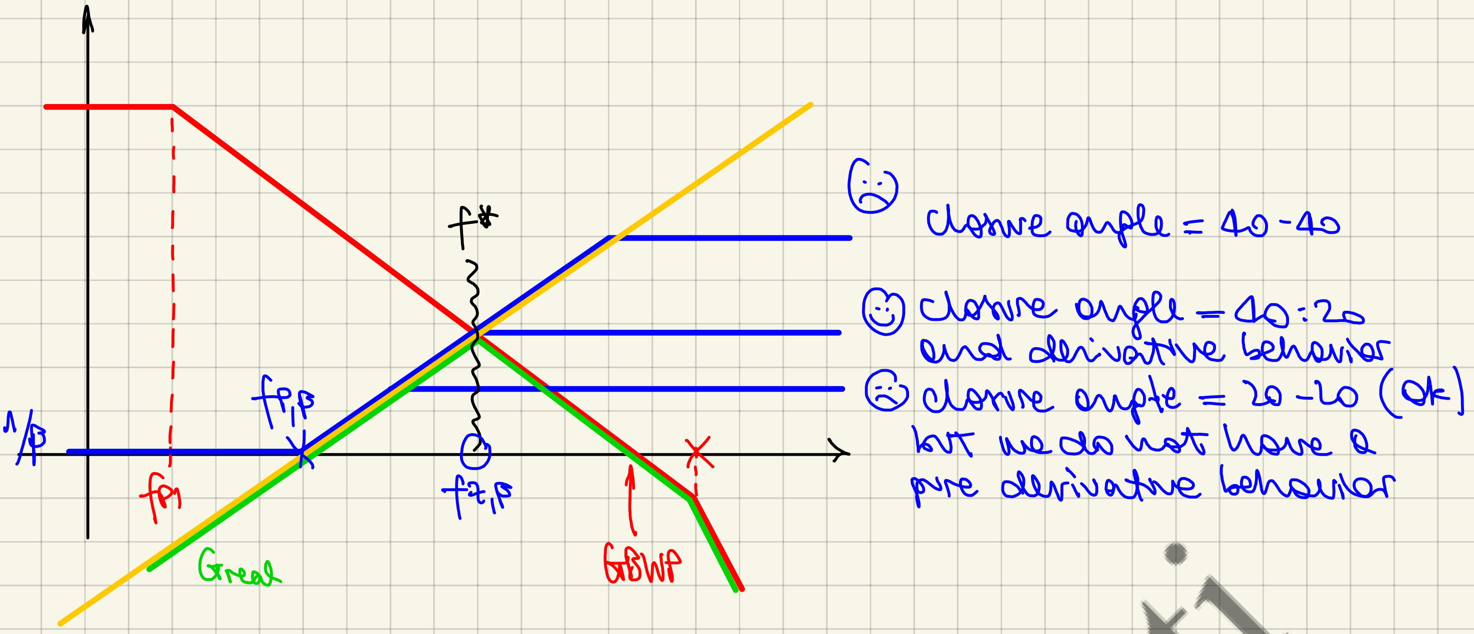
$@HF \to \beta(\infty) = \frac{R_C}{R_C + R}$

$$f_{p,\beta} = \frac{1}{2\pi C(R_C + R)}$$

G_{ideal}

$@DC \to G_{ideal}(0) = 0$

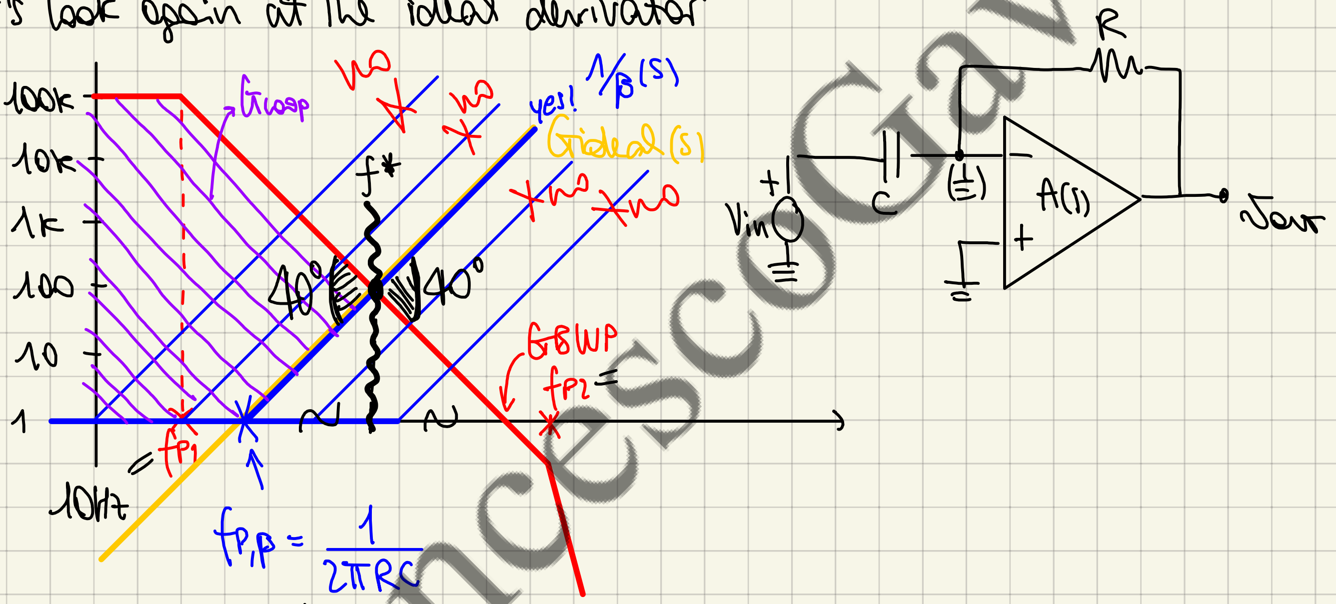
$@HF \to G_{ideal}(\infty) = -\frac{R}{R_C}$



ES04 - FREQUENCY COMPENSATION (2)

30/09/2021

Let's look again at the ideal derivator



The pole of β should be where Gideal(s) cuts the 0dB axis

f^* is in the middle btw $f_{p,\beta}$ and GBWP $\Rightarrow$ $\boxed{f^* = \sqrt{f_{p,\beta} \cdot GBWP}}$

closure angle = 40–40 → the circuit is UNSTABLE

$$PM = 180° - \operatorname{atan}\left(\frac{f^*}{f_{p1}}\right) - \operatorname{atan}\left(\frac{f^*}{f_{p,\beta}}\right) - \operatorname{atan}\left(\frac{f^*}{f_{p2}}\right)$$

$f^* \gg f_{p1}, f_{p,\beta} \Rightarrow PM \cong 180° - 90° - 90° - \operatorname{atan}\left(\frac{f^*}{f_{p2}}\right) \simeq 0°$

$\Rightarrow \operatorname{atan}\left(\frac{f^*}{f_{p2}}\right) \simeq 0° \rightarrow f_{p2} \gg f^*$

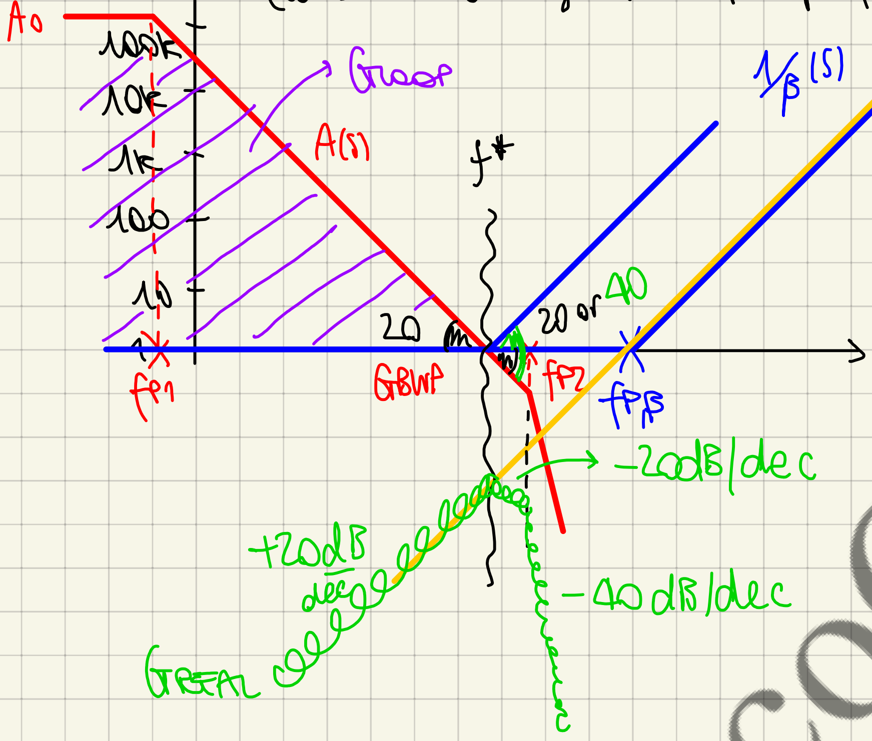
we should try to avoid this bad closure angle

How can we do that?

SOLUTION ①: we move $f_{p,\beta}$ at very high frequency

The GBWP stays @ a lower freq.

(let's also change the OpAmp for instance w/ an older one)

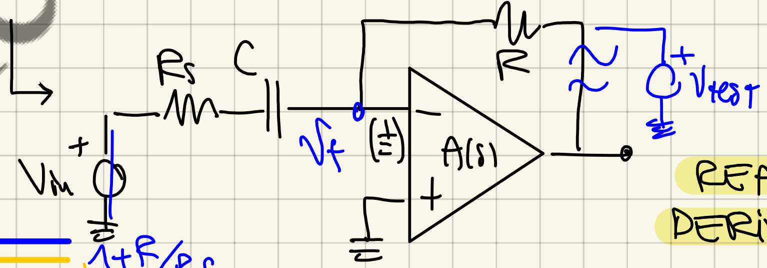


$$G_{REAL} = \begin{cases} G_{IDEAL} & \text{if } G_{loop} \gg 1 \\ G_{IDEAL} \cdot G_{loop} & \text{if } G_{loop} \ll 1 \end{cases}$$

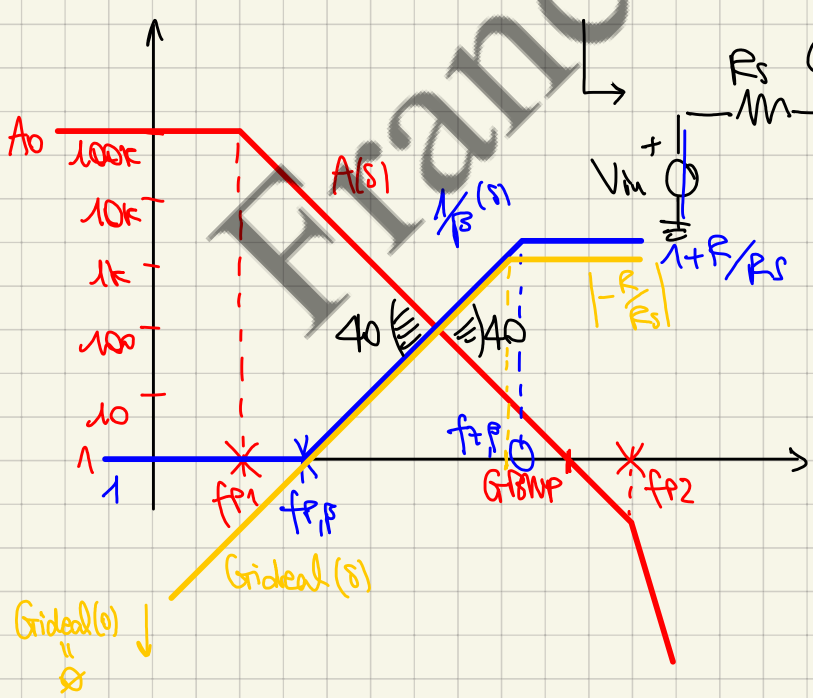
⇒ This is absolutely not a good derivator!! ☹

⇒ Move $f_{p,\beta}$ at very high frequency is not a good way to compensate!!

SOLUTION ②: we add a COMPENSATION RESISTOR R_C in series to the capacitor



REAL DERIVATOR



$G_{ideal}(0) = 0$

$G_{ideal}(\infty) = -R/R_S$

$\beta(0) = 1 \rightarrow \frac{1}{\beta}(0) = 1$

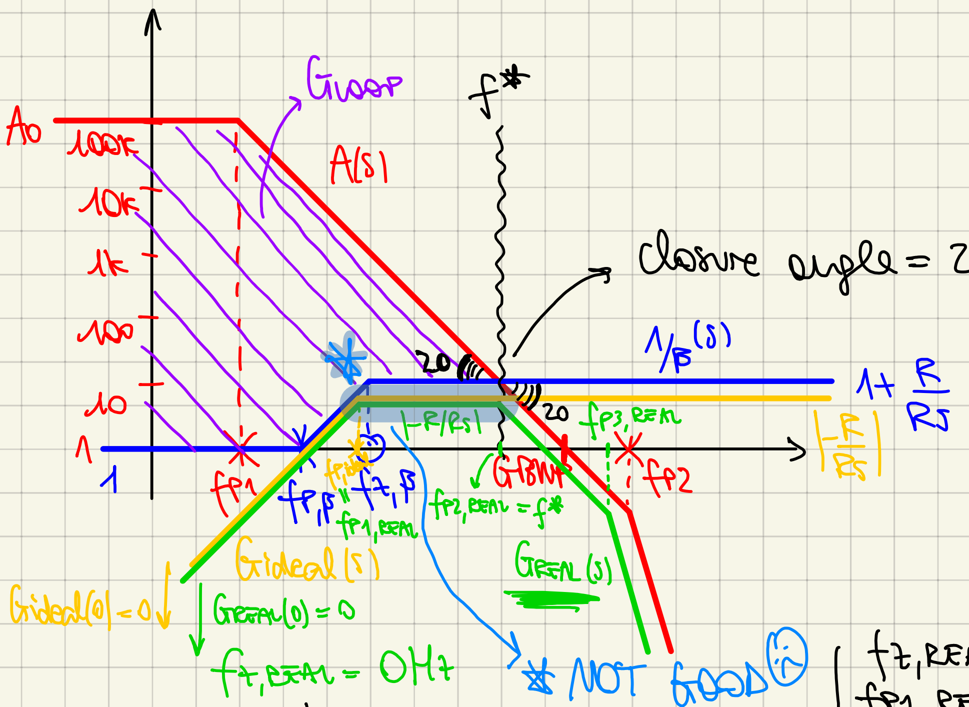
$\beta(\infty) = \frac{R_S}{R+R_S} \rightarrow \frac{1}{\beta}(\infty) = 1+\frac{R}{R_S}$

$f_{z,\beta} = \frac{1}{2\pi R_S C}$

$f_{p,\beta} = \frac{1}{2\pi C(R+R_S)}$

The closure angle is still bad!! ☹

• we can choose R_S in such a way that $1/\beta(s)$ cuts $A(s)$ when it is constant

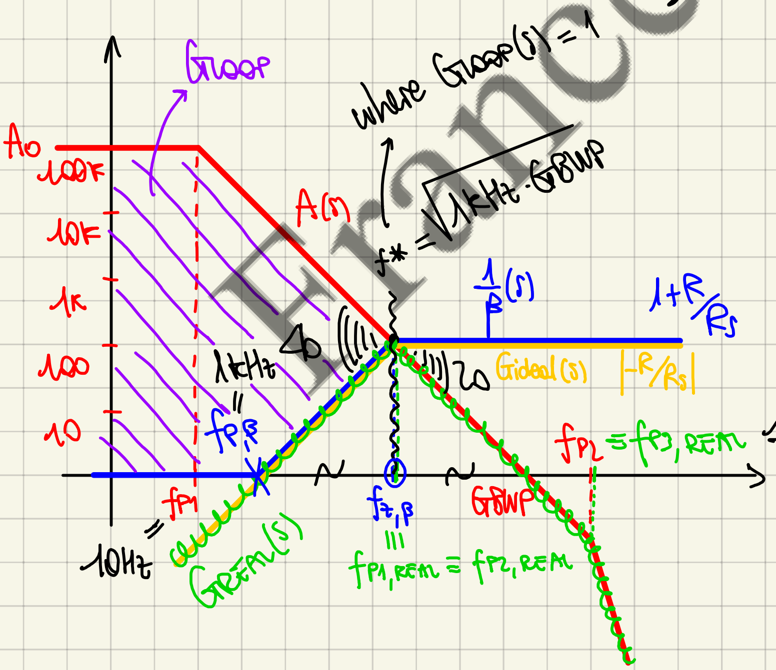


The real gain has 1 zero and 3 poles
$$\begin{cases} f_{z,REAL} = 0Hz \\ f_{P1,REAL} = f_{P,ideal} \simeq f_{z,\beta} \\ f_{P2} = f^* \\ f_{P3} \end{cases}$$
but slightly lower

Now the closure angle is good, the circuit is stable, but the customer is still not satisfied, bcz he asked us a derivator and we are taking to him a derivator till $f_{P1,REAL}$ but then it is an amplifier till $f_{P2,REAL}$ *

⇓ (FINAL SOLUTION)

• we can choose R_S in such a way that $G_{ideal}(s)$ $(\sim 1/\beta(s))$ cuts $A(s)$ @ f^*



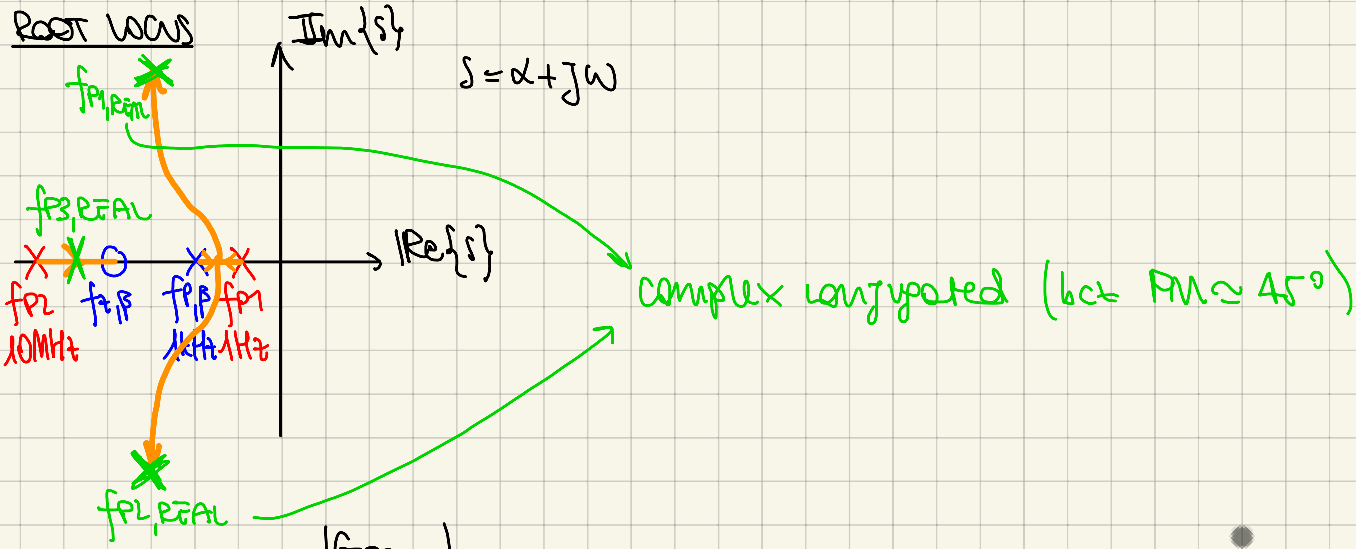
$$f_{P,\beta} = \frac{1}{2\pi C (R + R_S)}$$

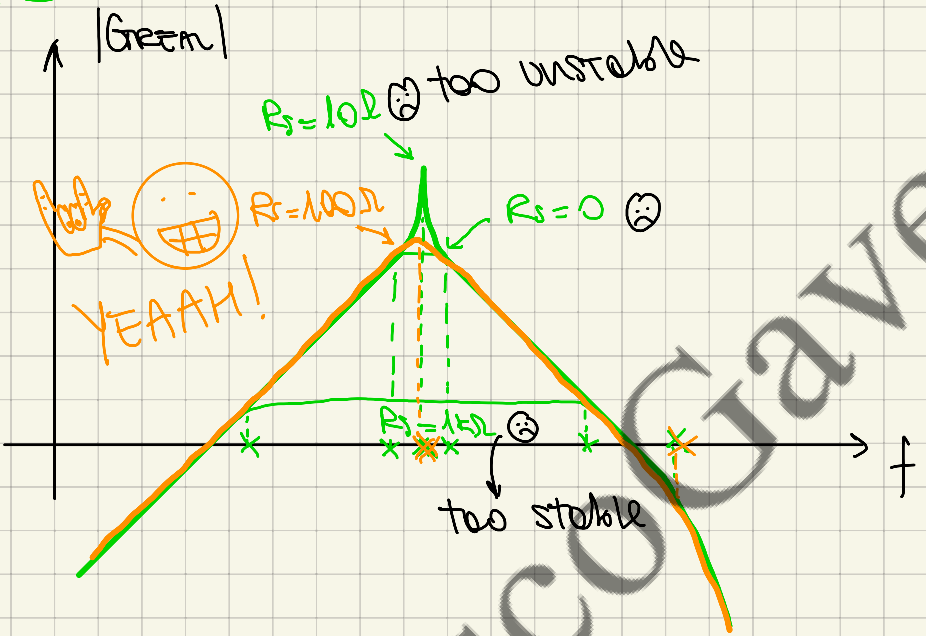
$$f_{z,\beta} = \frac{1}{2\pi C R}$$

closure angle = 40 - 20
↓
still stable
↓
we expect $\Phi_M \simeq 45°$

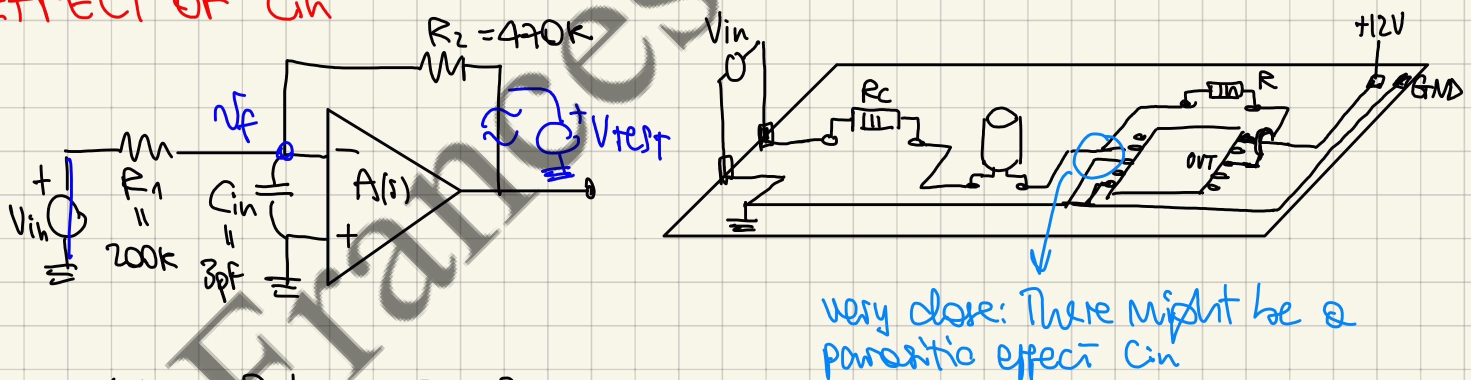
$$PM = 180° - \tan^{-1}\left(\frac{f^*}{f_{P1}}\right) - \tan^{-1}\left(\frac{f^*}{f_{P,\beta}}\right) + \tan^{-1}\left(\frac{f^*}{f_{z,\beta}}\right) - \tan^{-1}\left(\frac{f^*}{f_{P2}}\right)$$

$$= 180° - 90° - 90° + 45° - 0° \simeq 45°$$





EFFECT OF Cin



$G_{IDEAL}(0) = -R_2/R_1 \simeq -2.3$

$G_{IDEAL}(\infty) = -R_2/R_1$

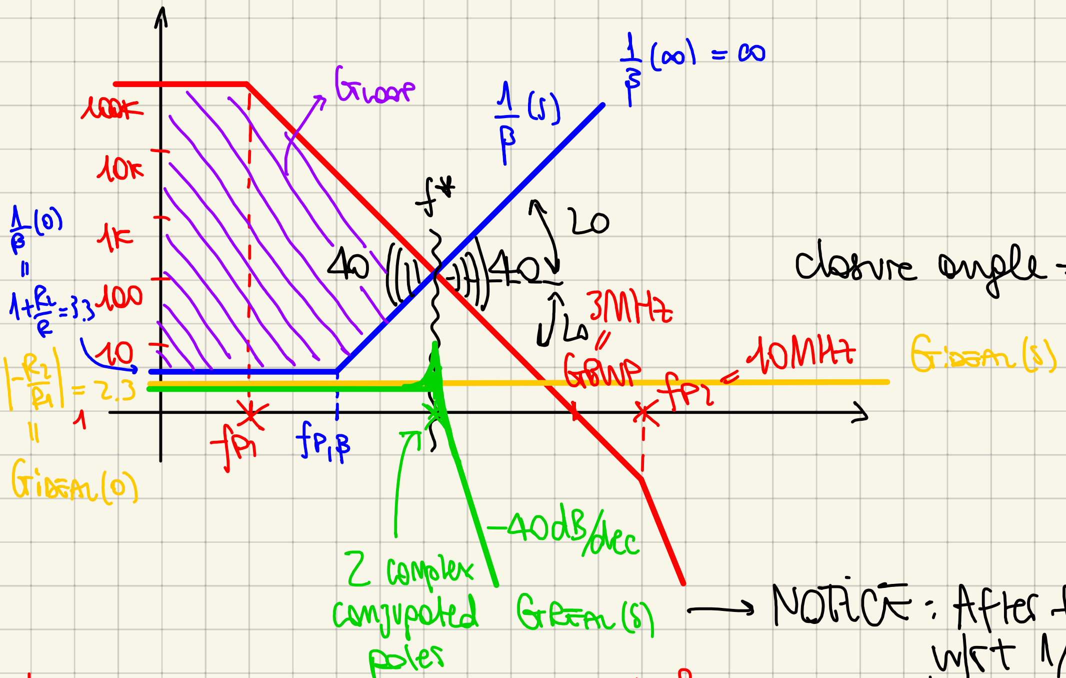
The capacitor Cin has no effect on G_{IDEAL} bc @DC it's open and v^- is @v.g. and @ HF it's short and v^- is @ ground, so nothing changes or we can say that, since Cin stays btw v.g. and ground, no current can flow through it so it doesn't influence G_{IDEAL} which remains constant.

$\beta(0) = \frac{R_1}{R_1+R_2} \simeq 0.3 \rightarrow \frac{1}{\beta}(0) = 1 + \frac{R_2}{R_1} \simeq 3.3$

$\beta(\infty) = 0 \rightarrow \frac{1}{\beta}(\infty) = \infty$

β(s) must have a pole

$f_{P,\beta} = \frac{1}{2\pi C\, R_1 \| R_2}$



closure angle = 40−40 ⇒ UNSTABLE

→ NOTICE: After f^* $A(s)$ dies by −40dB/dec w/r t $1/\beta(s)$ so G_{REAL} will die by −40dB/dec more w/r t G_{IDEAL}

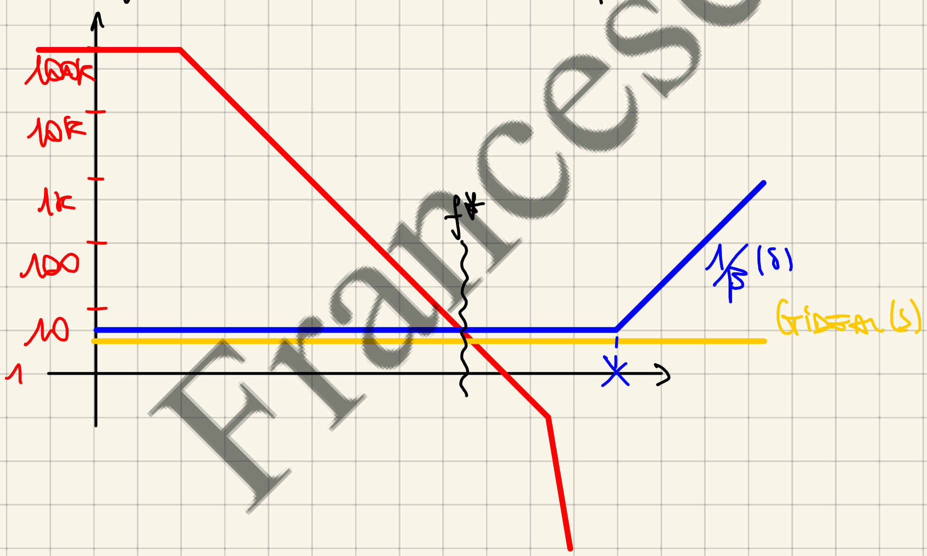
How can we compensate the circuit?

let's move $f_{P,\beta}$ to a very high frequency by changing the resistors

$$f_{P,\beta} = \frac{1}{2\pi C_{in}(R_1 \| R_2)} \quad \text{and} \quad |G_{IDEAL}| = \left|-\frac{R_2}{R_1}\right| = 2.3$$

instead of choosing $R_2 = 470k$ and $R_1 = 200k$, let's choose: $\begin{cases} R_2 = 4.7k\Omega \\ R_1 = 2k\Omega \end{cases}$

In this way we keep the same ideal gain but we increase a lot the pole frequency $f_{P,\beta}$ such that now $1/\beta(s)$ cuts $A(s)$ when it is constant



A best way to compensate, as we have previously seen, is having $1/\beta(s)$ that cuts $A(s)$ in such a way that we have 40−20 or 20−40 as closure angle

How can we obtain that in this case?

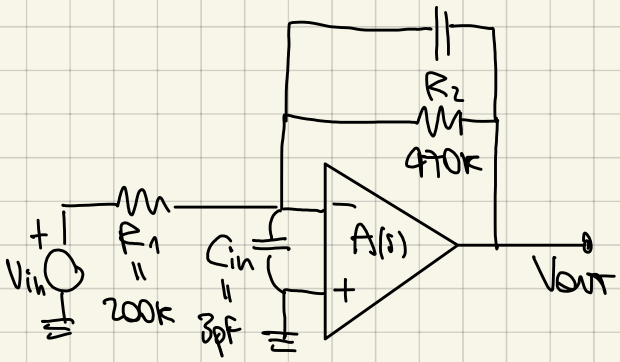
SOLUTION 1

In principle we would like to add a resistor in series to C_{in}, but we can't since very often C_{in} is a parasitic term

↳ NOT POSSIBLE !! ☹

SOLUTION 2

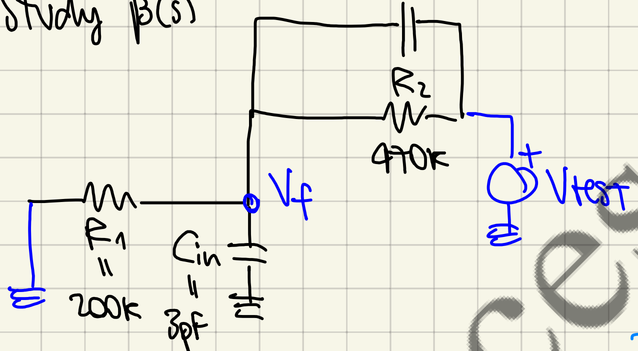
Another way to obtain the desired closure angle (and so to compensate) is to add a COMPENSATION CAPACITOR in parallel to the feedback resistor R_2



1. Study $G_{IDEAL}(s)$ REMEMBER: As we told before, Cin has no effects on it since the FB is negative and it is btw V_f and ground

$$\left.\begin{array}{l} G_{IDEAL}(0) = -R_2/R_1 = -2.3 \\ G_{IDEAL}(\infty) = 0 \end{array}\right\} f_{P,i} = \frac{1}{2\pi C_c R_2} =$$

2. Study $\beta(s)$

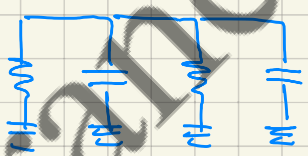


@DC $\to \beta(0) = \frac{R_1}{R_1+R_2} \to \frac{1}{\beta}(0) = 1 + \frac{R_2}{R_1} = 3.3$

~~@HF $\to \beta(\infty) = 0 \to \frac{1}{\beta}(\infty) = \infty$~~ WRONG

$\beta(\infty) = \dots\dots = \frac{C_c}{C_{in}+C_c}$????

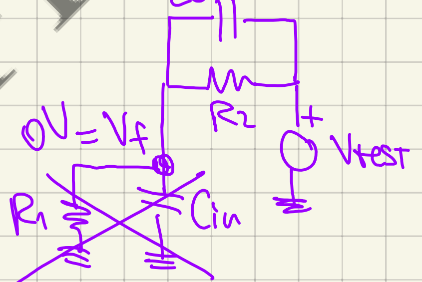
- POLES of $\beta(s)$



2 dependent capacitors $\to$ 1 pole

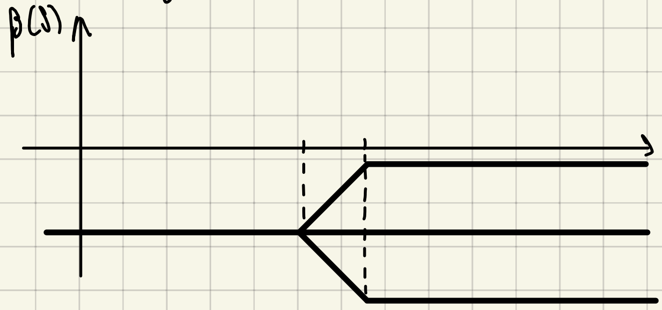
$$f_{P,\beta} = \frac{1}{2\pi (C_{in}+C_c) R_1 \| R_2} =$$

- ZEROS of $\beta(s)$ $0V = V_f$



$$f_{z,\beta} = \frac{1}{2\pi C_c R_2} =$$

Depending on the pole and zero frequencies we can have 3 possibilities:

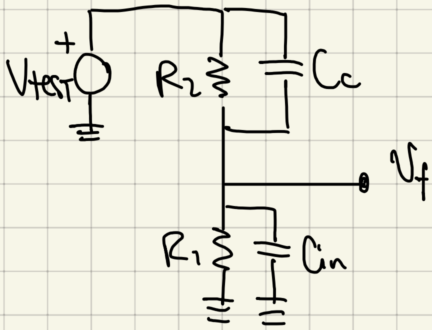


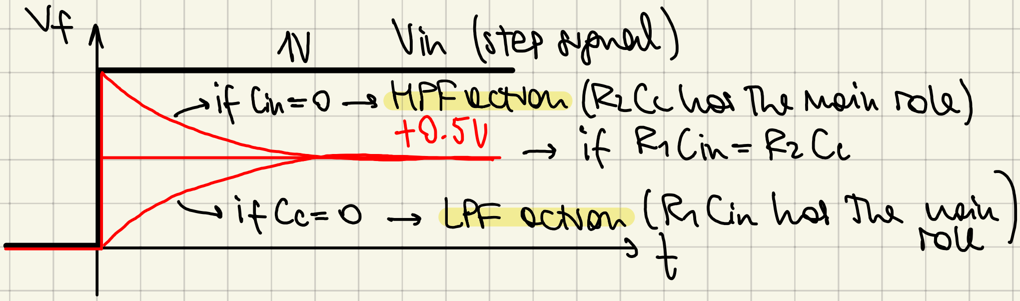
$\to f_{z,\beta} < f_{P,\beta}$

$\to f_{z,\beta} = f_{P,\beta}$ (POLE-ZERO CANCELLATION)

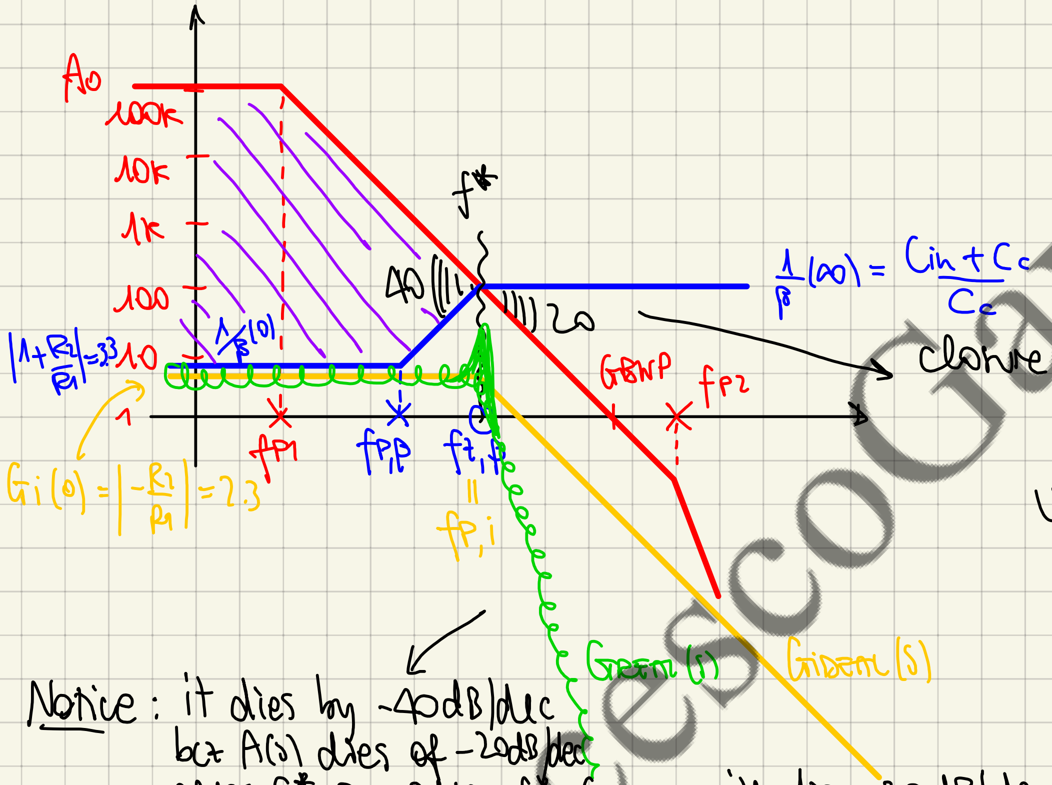
$\to f_{z,\beta} > f_{P,\beta}$

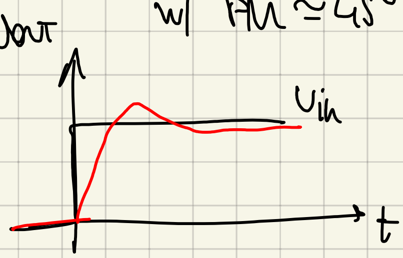
In the time domain instead we can notice that:





In conclusion, in the freq. domain we'll have





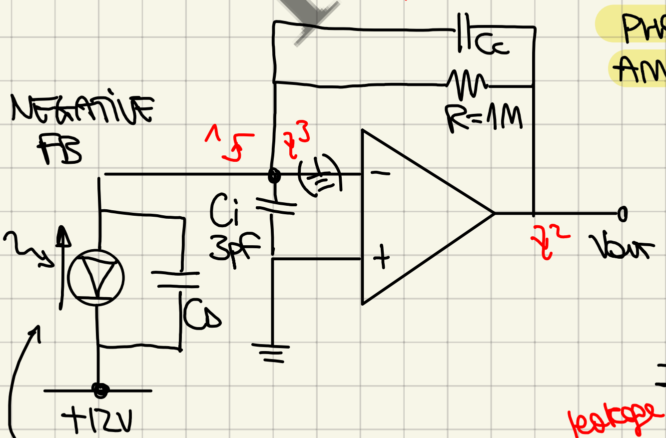
Notice: it dies by -40dB/dec
bcz A(s) dies of -20dB/dec
after f^*, so after f^* G_{REAL} will die -20dB/dec more than G_{IDEAL}
(which dies by -20dB/dec)

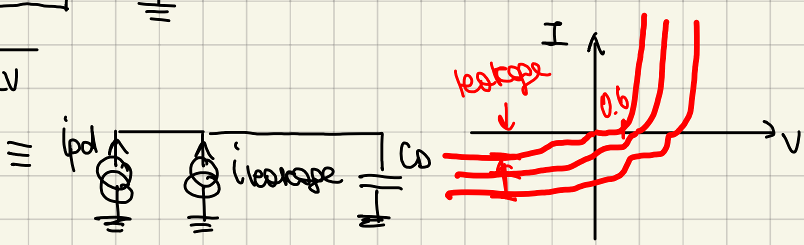
ES04 - FREQUENCY COMPENSATION (3)

05/10/2021

TRANSIMPEDANCE AMPLIFIER

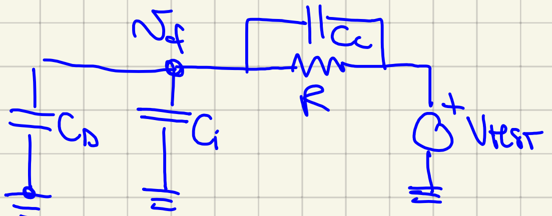
PHOTODIODE AMPLIFIER





$G_{IDEAL} = ?$ $\quad$ @DC $\rightarrow G_{IDEAL}(0) = -R$; @HF $\rightarrow G_{IDEAL}(\infty) = 0$ $\quad \Big\} \; f_{p,i} = \dfrac{1}{2\pi C_c R}$

$\beta(s) = ?$

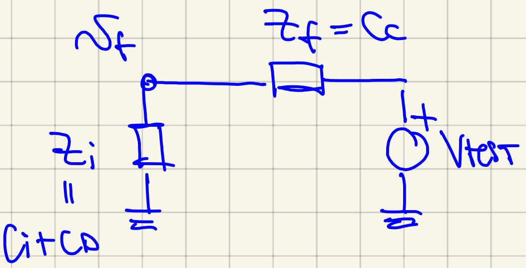


$(I_R = 0 \rightarrow V_R = 0 \rightarrow V_f = V_{test})$

@DC $\rightarrow \beta(0) = 1 \rightarrow \dfrac{1}{\beta}(0) = 1$

@HF $\rightarrow \beta(\infty) = ?$

$\begin{cases} V_{test} = V_f \\ V_f = 0 \end{cases} \rightarrow \beta(\infty) = \left[\dfrac{0}{0}\right]$ F.I.

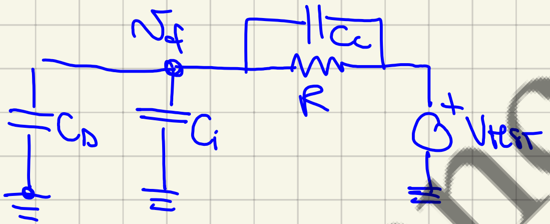


$$\beta(\infty) = \frac{Z_i}{Z_i + Z_f} = \frac{\frac{1}{s(C_i+C_D)}}{\frac{1}{s(C_i+C_D)} + \frac{1}{sC_c}} =$$

$$= \frac{\cancel{s}C_c\cancel{(C_i+C_D)}}{[\cancel{s}C_c + \cancel{s}(C_i+C_D)]\cancel{s(C_i+C_D)}} = \frac{C_c}{C_c + (C_i+C_D)}$$

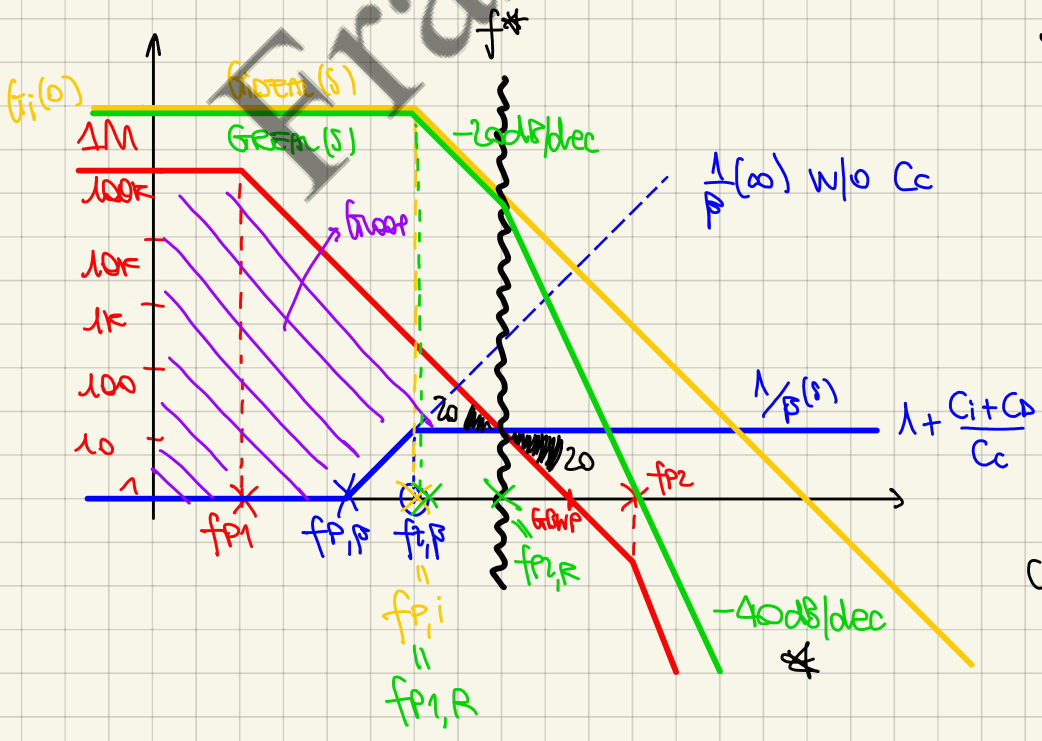
$$\Rightarrow \frac{1}{\beta}(\infty) = 1 + \frac{C_i+C_D}{C_c}$$

$$\begin{cases} 1/\beta(0) = 1 \\ 1/\beta(\infty) = 1 + \dfrac{C_i+C_D}{C_c} \end{cases}$$



$$f_{p,\beta} = \frac{1}{2\pi(C_c + C_i + C_D)R}$$

$$f_{z,\beta} = \frac{1}{2\pi C_c R}$$



* After f^* $A(s)$ dies by -20dB/dec w/rt $1/\beta(s)$

$\downarrow$

This means that after f^* $G_{REAL}(s)$ will die by -20dB/dec more than what $G_{IDEAL}(s)$ does

$\downarrow$

So after f^* $G_{REAL}(s)$ will die by -40dB/dec

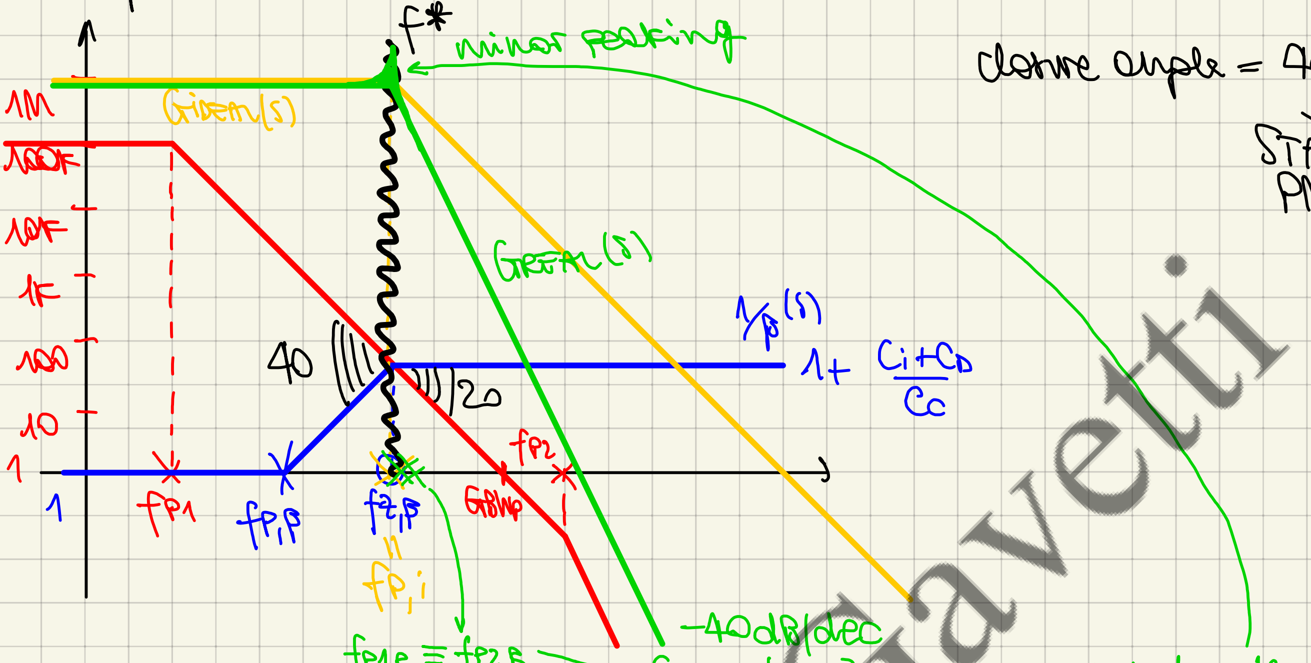
closure angle $= 20 - 20$

$\Downarrow$

STABLE

The circuit is stable, but is the customer satisfied?
Not at all, bcz the transimpedance amplifier doesn't show a constant gain up to f^*

As we have already seen the best choice is to place $f_{z,\beta}$ (and so $f_{p,i}$) where $1/\beta(s)$ cuts $A(s)$

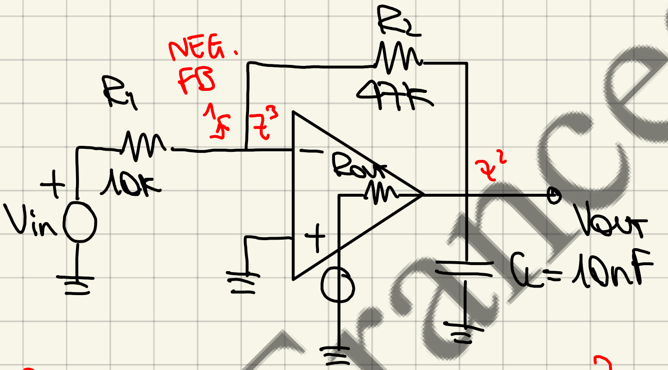


closure angle = 40-20
⇓
STABLE w/ PM ≅ 45°

Now the customer is satisfied bcz Greal remains constant up to f^*

EFFECT OF C_{OUT}

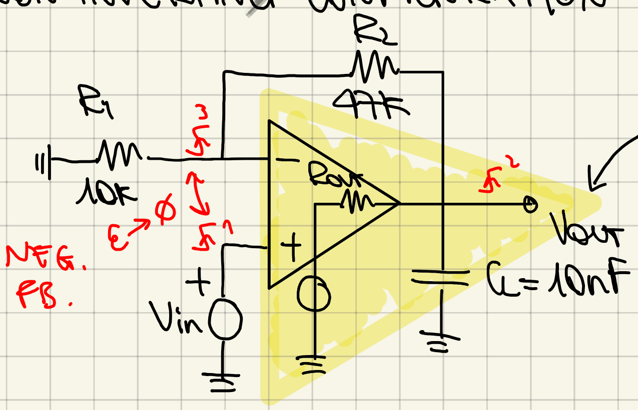
- INVERTING CONFIGURATION



In case of absolutely ideal OpAmp ($R_{OUT}=0$) C_L has no effects
↓
it has no poles at all bcz it's in parallel w/ a voltage generator w/ zero impedance (an ideal one), so once we turn it off C_L will be btw 2 grounds
→ C_L causes no instability

But, what happens if $R_{OUT} \neq 0$?

- NON-INVERTING CONFIGURATION



METHOD ①
↓
Considering C_L inside A

$$\tilde{A}(s) \simeq A(s) \cdot \frac{1/sC_L}{R_o + 1/sC_L} = A(s) \cdot \frac{1}{1+sC_LR_o}$$

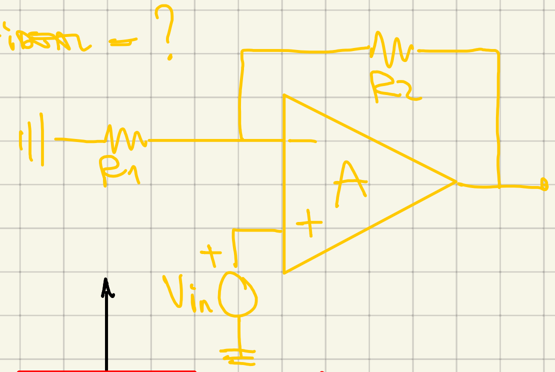
$$f_{OUT} = \frac{1}{2\pi C_L R_o} \quad \text{(additional pole)}$$

$\beta(s) = ?$

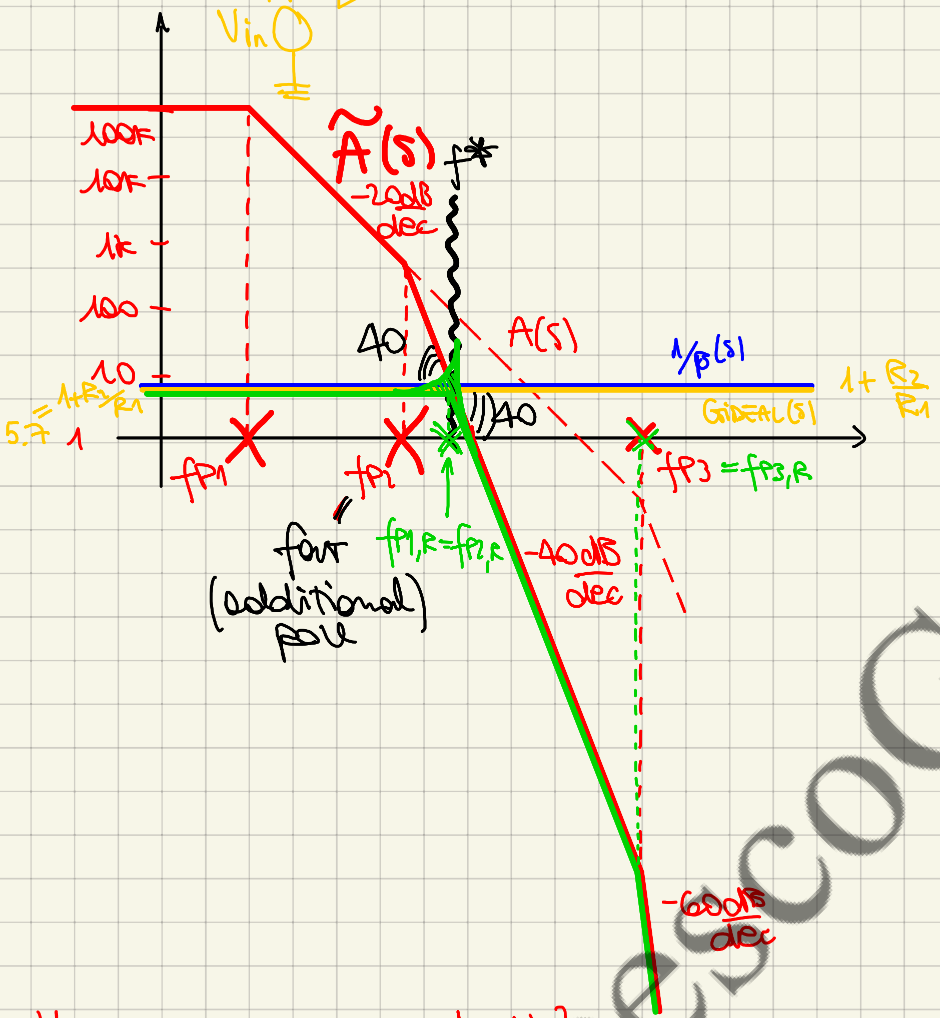
$$\beta(0) = \beta(\infty) = \frac{R_1}{R_1+R_2}$$

$$\rightarrow \frac{1}{\beta}(s) = 1 + R_2/R_1 \quad \text{(constant)}$$

$G_{IDEAL} = ?$



$G_{IDEAL}(s) = 1 + \frac{R_2}{R_1} = 5.7$



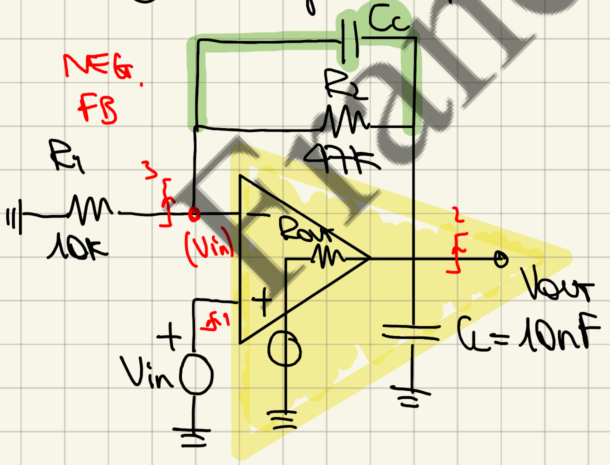
closure angle = 40 - 40

$\Downarrow$

UNSTABLE

How can we compensate it?

SOLUTION (1): adding a compensation capacitor in parallel to the feedback resistor

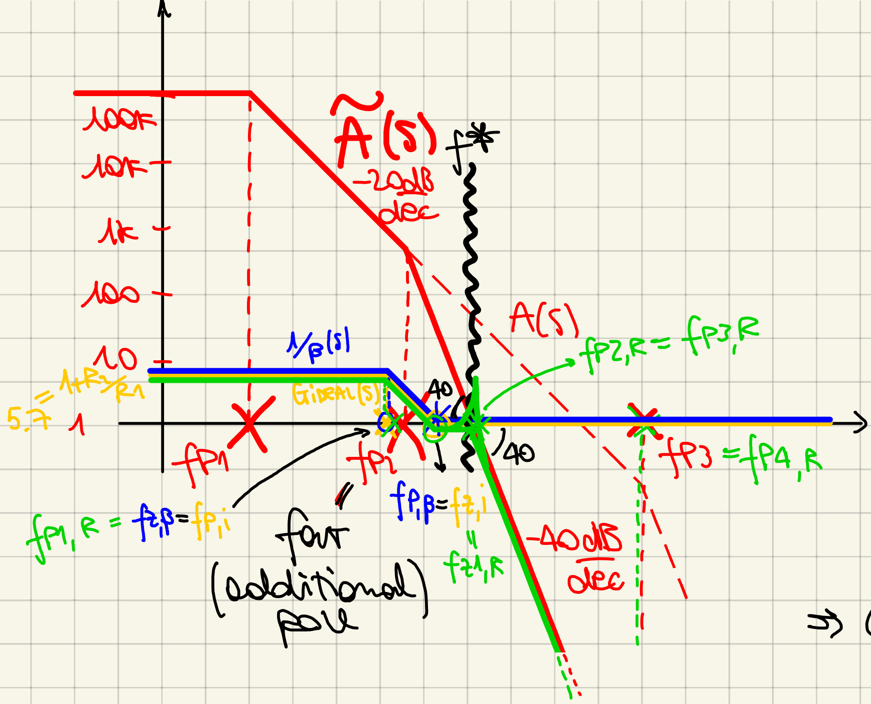


$G_{IDEAL}(0) = 1 + R_2/R_1$

$G_{IDEAL}(\infty) = 1$

$$f_{p,i} = \frac{1}{2\pi C_c R_2}$$

$$f_{z,i} = \frac{1}{2\pi C_c (R_1 \| R_2)}$$



closure angle = 40 - 40

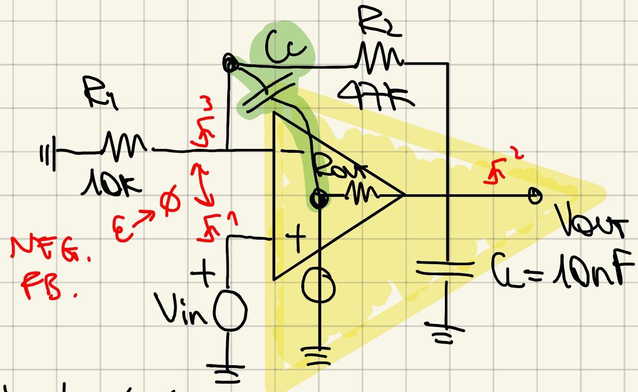
↓

UNSTABLE ☹

This solution doesn't work!

⇒ C_c in parallel to R_2 is not enough!

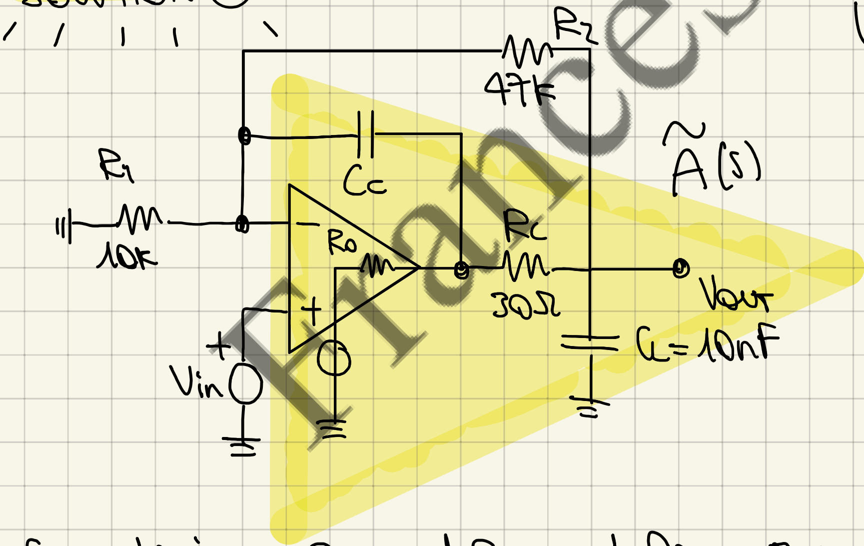
SOLUTION ②



BUT WE CANNOT ACCESS TO THE OPAMP IN THIS WAY !! ☹

This solution doesn't work too!

SOLUTION ③



let's size $\begin{cases} R_c \simeq R_o \\ C_c = C_L \, 2 \frac{R_o}{R_2} = 13\,pF \end{cases}$

Considering R_o and R_c much lower than R_1 and R_2 we get:

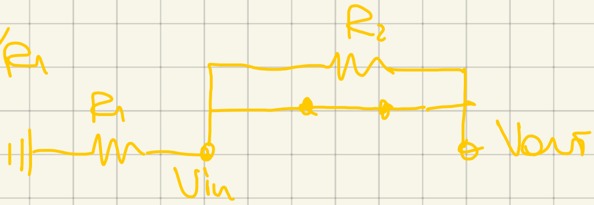
$$\tilde{A}(s) = A(s) \cdot \underbrace{\frac{1}{1 + s C_L (R_o + R_c)}} \cdot \underbrace{\frac{1}{1 + s C_c (R_1 \| R_2)}}$$

$$f_{out} = \frac{1}{2\pi C_L (R_o + R_c)} = 265\,kHz$$

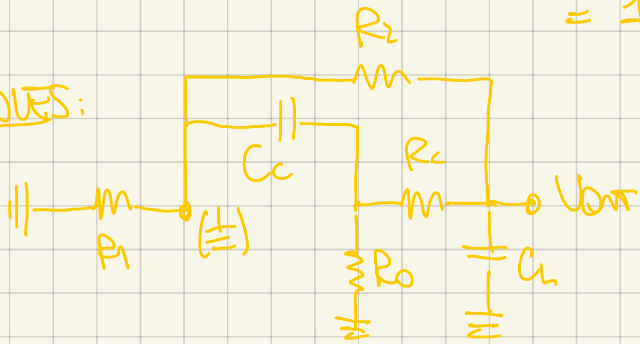
$$f_{NEW} = \frac{1}{2\pi C_c (R_1 \| R_2)} =$$

$G_{IDEAL}(s) = ?$ $\rightarrow$ $G_{IDEAL}(0) = 1 + R_2/R_1$

$G_{IDEAL}(\infty) = ? = 1$



POLES:



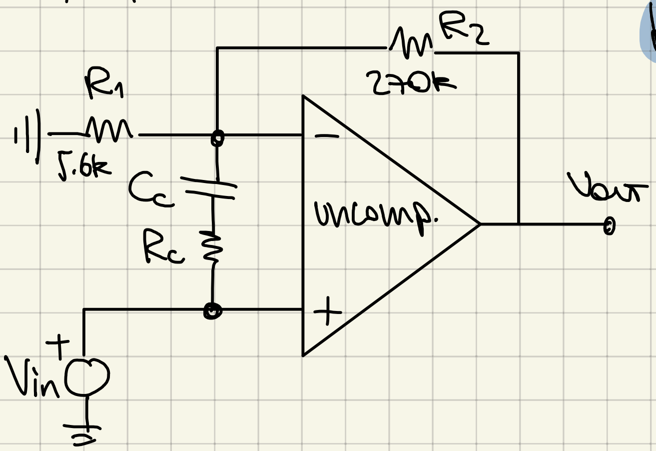
$$f_{P1,i} = \frac{1}{2\pi C_c (R_c + R_o)}$$

$$f_{P2,i} = \frac{1}{2\pi C_L (R_c \| R_2)}$$

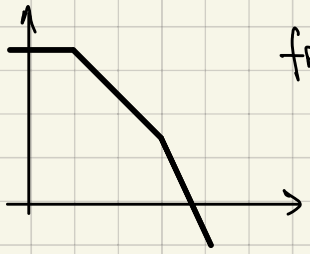
??

TO COMPLETE!!

SOLUTION ④ → NEGATIVE FEEDBACK COMPENSATION



Hp: let's suppose $A(s)$ is an uncompensated OpAmp



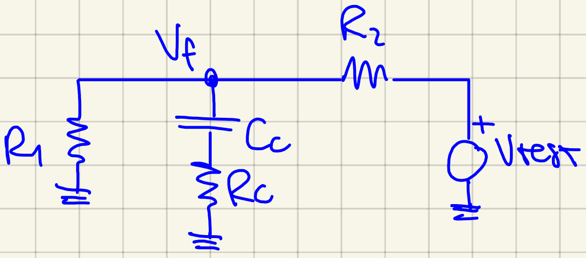
$f_{P2} < GBWP$

$G_{IDEAL}(s) = ?$ @DC → $G_i(0) = 1 + R_2/R_1 = 5.8$

@HF → $G_i(\infty) = 1 + R_2/R_1$

(G_{ideal} has neither poles nor zeros, it's constant)

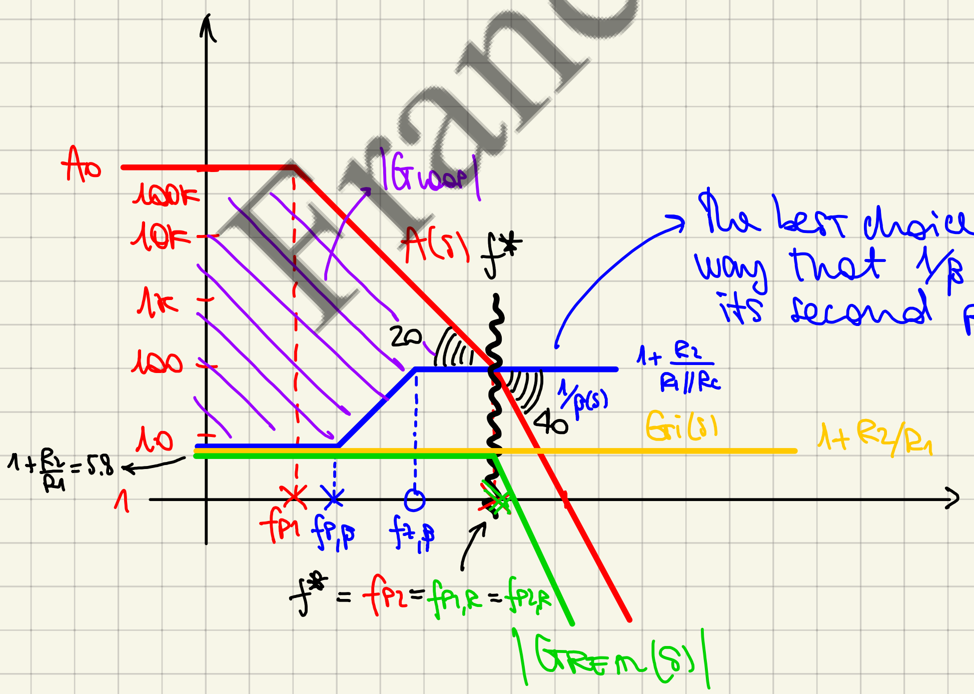
$\beta(s) = ?$ @DC → $\beta(0) = 1 + R_2/R_1 = 5.8$



@HF → $\beta(\infty) = \frac{R_1 || R_c}{R_1 || R_c + R_2}$

$\Rightarrow \frac{1}{\beta}(\infty) = 1 + \frac{R_2}{R_1 || R_c} =$

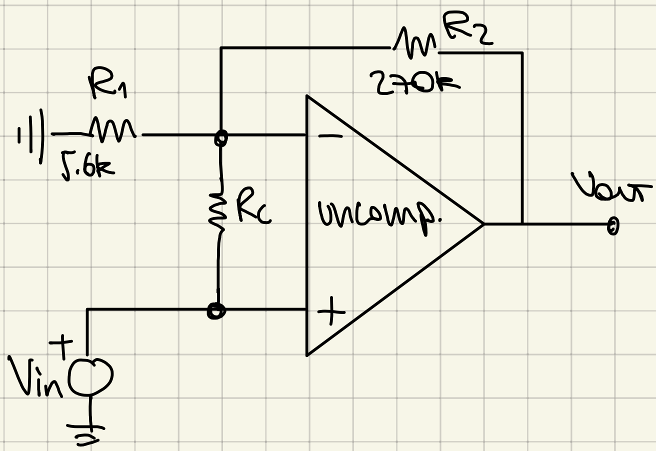
$f_{P,\beta} = \frac{1}{2\pi C_c (R_c + R_1 || R_2)} = \quad < \quad f_{Z,\beta} = \frac{1}{2\pi C_c R_c} =$



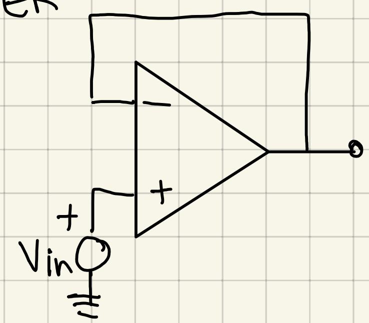
→ The best choice is to size the circuit in such a way that $1/\beta(s)$ intersects $A(s)$ where its second pole happens

$\Rightarrow f^* = f_{P2}$

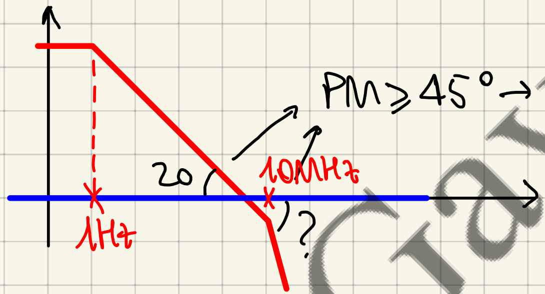
Possible simplification → REMOVE C_c



BUFFER

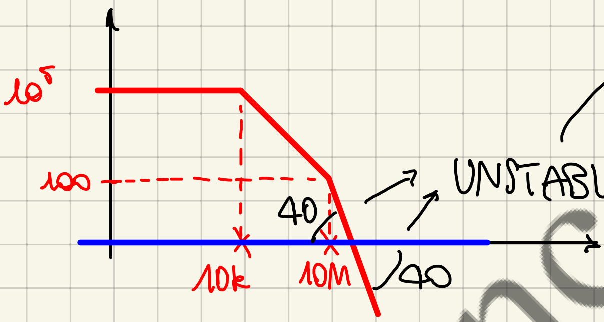


• compensated OpAmp



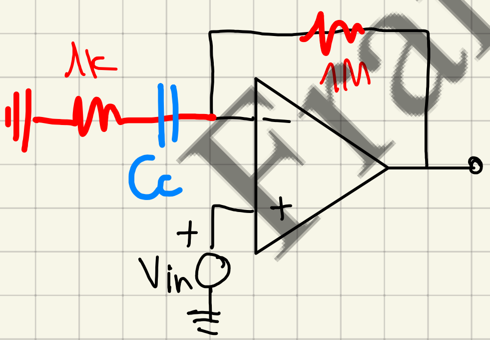
PM ≥ 45° → stable

• uncompensated OpAmp

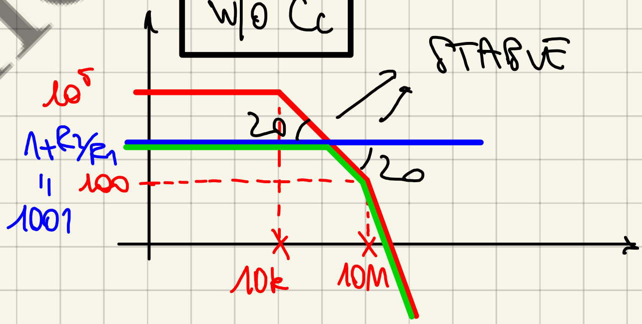


UNSTABLE

if we want to use an uncompensated OpAmp we have to regain stability

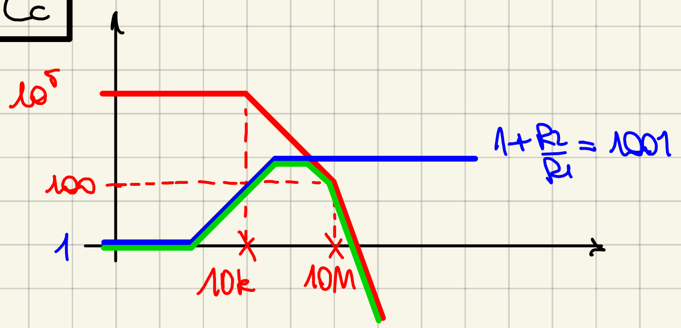


$\boxed{\text{w/o } C_c}$

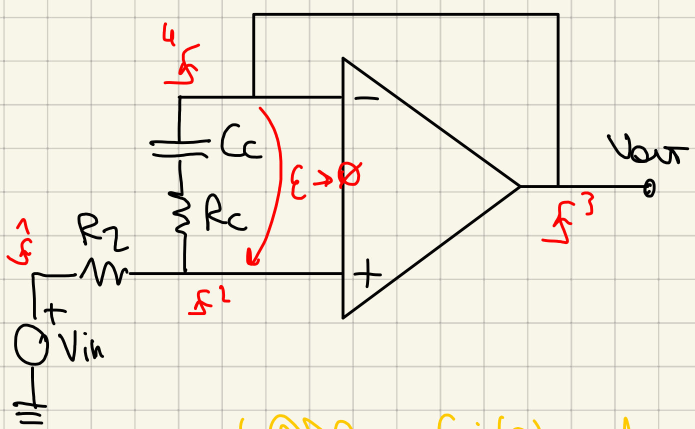


STABLE

$\boxed{\text{w/ } C_c}$



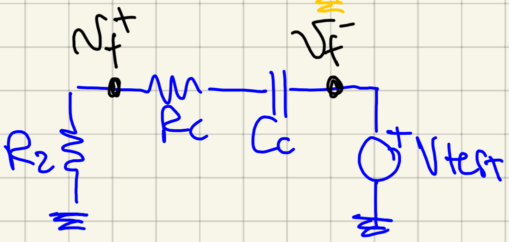
SOLUTION ⑤ → POSITIVE FEEDBACK COMPENSATION



$$G_{ideal}(s) = \begin{cases} @DC \rightarrow G_i(0) = 1 \\ @HF \rightarrow \end{cases}$$

$V_{out} = V_{in}$ $\quad G_i(\infty) = 1$

$\beta(s) = ?$

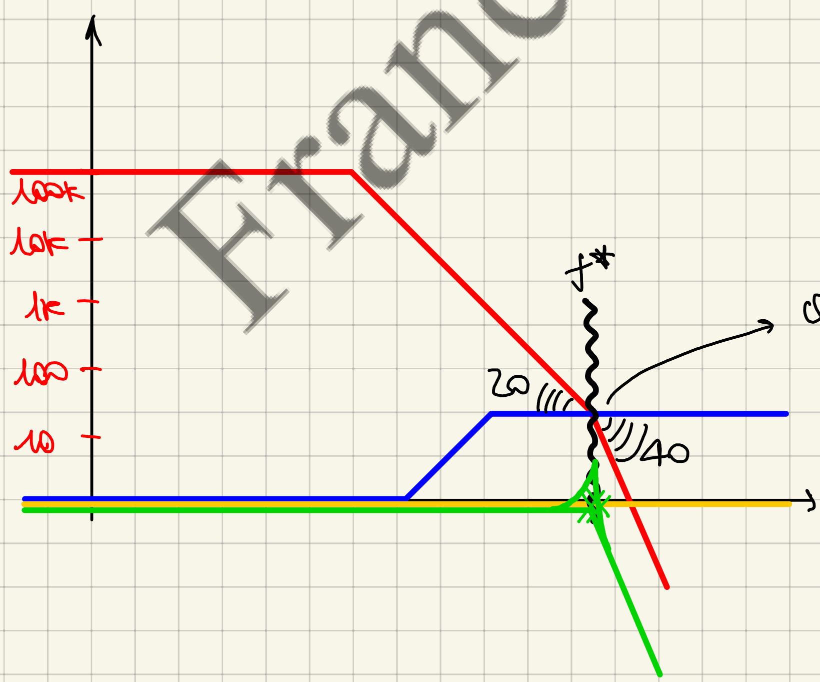


$@DC \rightarrow \beta(0) = \beta^-(0) - \beta^+(0) = 1 - 0 = 1$

$\Rightarrow \frac{1}{\beta}(0) = 1$

$@HF \rightarrow \beta(\infty) = \beta^-(\infty) - \beta^+(\infty) = 1 - \frac{R_2}{R_2+R_c} = \frac{R_c}{R_2+R_c}$

$\rightarrow \frac{1}{\beta}(\infty) = 1 + \frac{R_2}{R_c}$



closure angle = 20 − 40

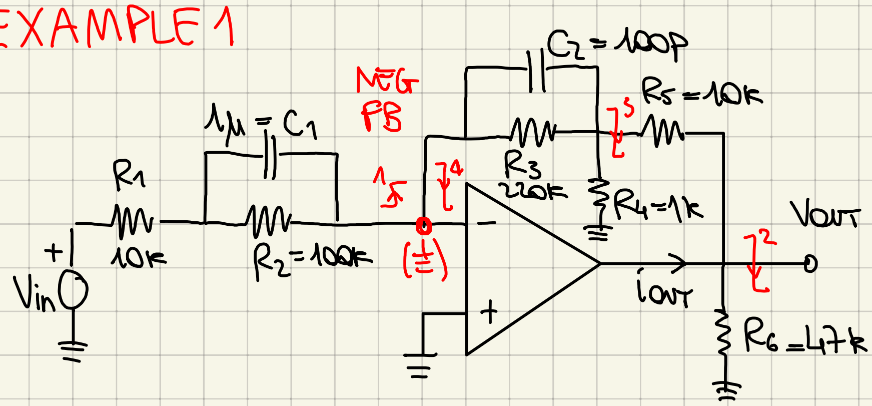
↓

STABLE

and highest f*

PM ≃ 45°

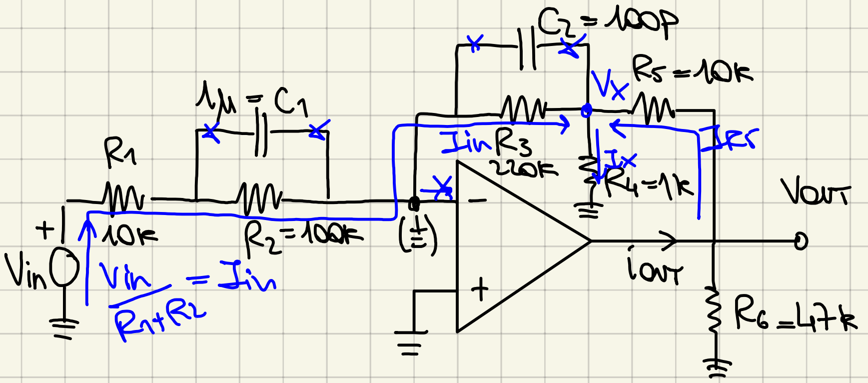
EXAMPLE 1



$R_1 = 10k\Omega$
$R_2 = 100k\Omega$
$R_3 = 220k\Omega$
$R_4 = 1k\Omega$
$R_5 = 10k\Omega$
$R_6 = 47k\Omega$

$C_1 = 1\mu F$
$C_2 = 100pF$

Ⓐ Plot The ideal $V_{out}(f)/V_{in}(f)$ gain



$I_{in} = V_{in}/R_1+R_2$

$V_x = -I_{in}R_3 = -V_{in}\frac{R_3}{R_1+R_2}$

$I_x = V_x/R_4$

$I_{R5} = I_x - I_{in}$

@ DC → C open

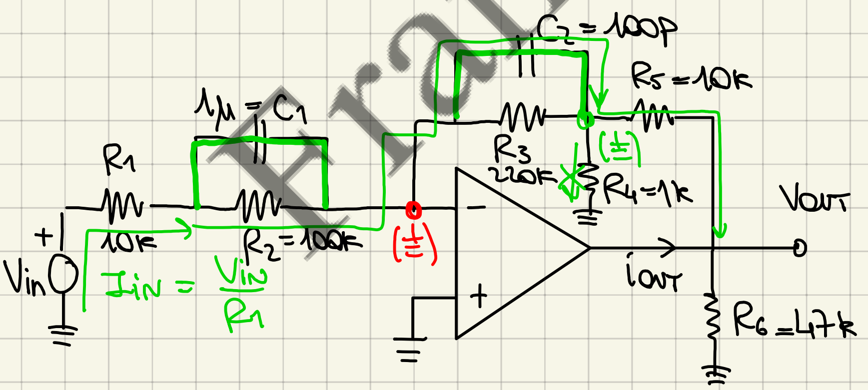
$V_{out} - V_x = I_{R5} \cdot R_5$

$V_{out} = V_x + (I_x - I_{in})R_5 = V_x + (V_x/R_4 - V_x/R_3)R_5$

$\overset{!}{=} V_x\left[1 + \frac{R_5(R_3+R_4)}{R_3R_4}\right] = -V_{in}\frac{R_3}{R_1+R_2}\left[1 + \frac{R_5(R_3+R_4)}{R_3R_4}\right]$

$G_i(0) = -\frac{R_3}{R_1+R_2}\left[1 + \frac{R_5(R_3+R_4)}{R_3R_4}\right] \simeq -22.1$

@HF → C close

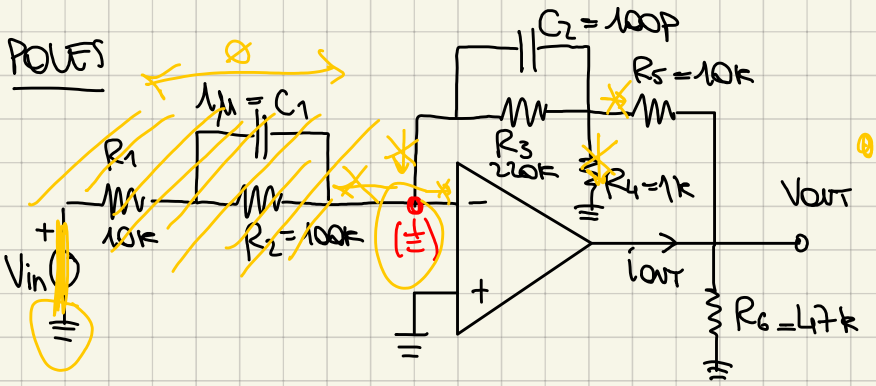


$V_{out} = -I_{in}R_5$

$\overset{!}{=} -V_{in}\frac{R_5}{R_1}$

$G_i(\infty) = -\frac{R_5}{R_1} = -1$

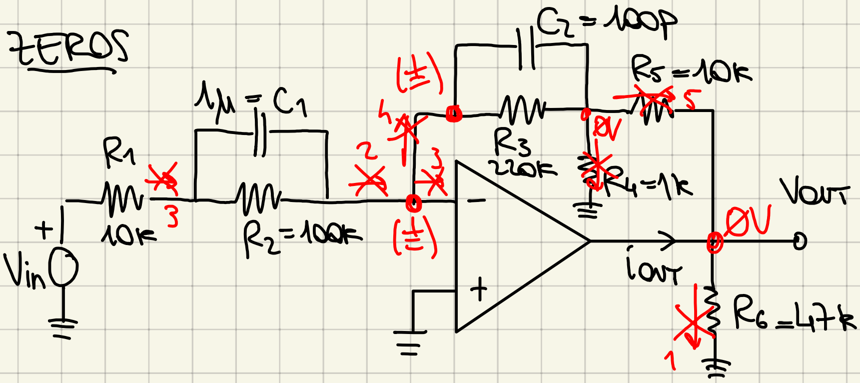
POLES



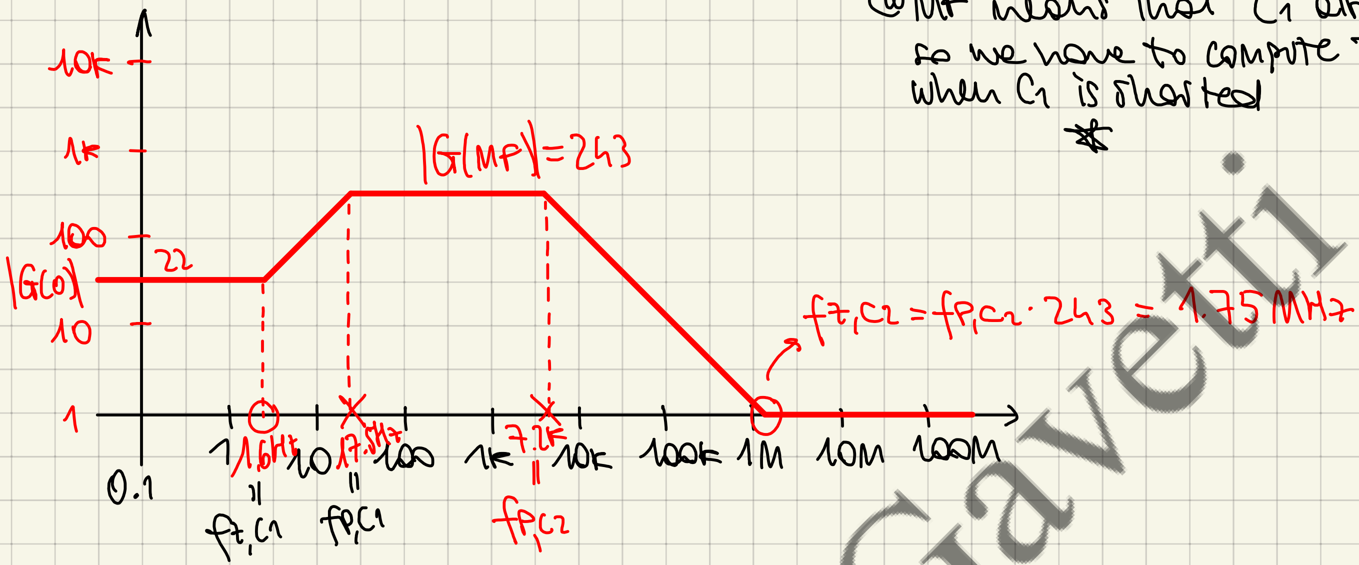
$f_{P,C_1} = \frac{1}{2\pi C_1(R_1 \| R_2)} = 17.5Hz$

$f_{P,C_2} = \frac{1}{2\pi C_2 R_3} = 7.2kHz$

ZEROS

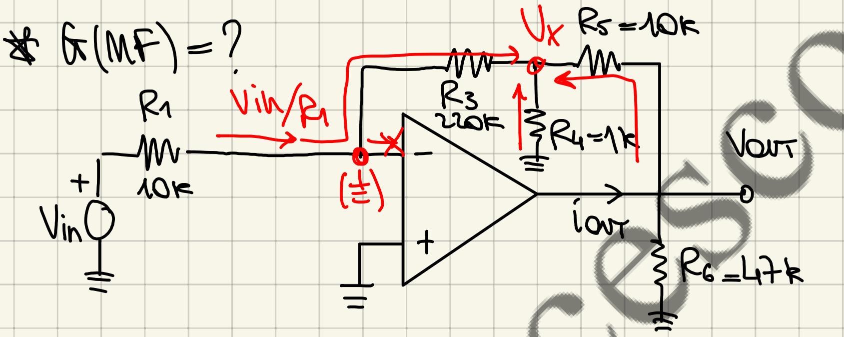


$$f_{z,C_1} = \frac{1}{2\pi C_1 R_2} \simeq 1.6\,Hz$$



@MF means that C_1 already acted so we have to compute the gain when C_1 is shorted *

* $G(MF) = ?$



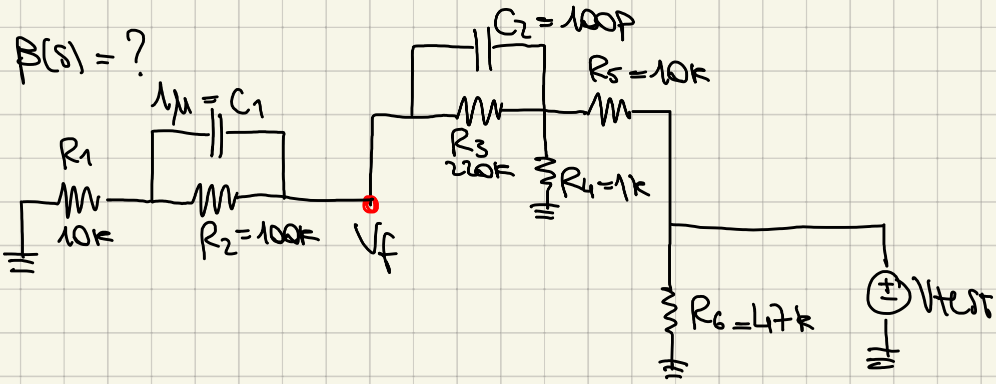
$$\begin{cases} V_{OUT} - V_x = -\left(-\frac{V_x}{R_4} + \frac{V_{in}}{R_1}\right) R_5 \\ V_x = -\frac{V_{in}}{R_1} R_3 \end{cases}$$

$$V_{OUT} = -V_{in}\frac{R_3}{R_4} + V_x\frac{R_5}{R_4} - V_{in}\frac{R_5}{R_1} =$$

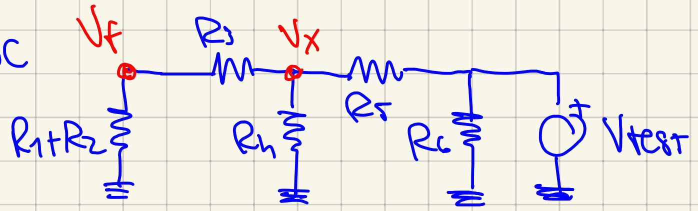
$$= -V_{in}\frac{R_3}{R_1} - V_{in}\frac{R_3 R_5}{R_1 R_4} - V_{in}\frac{R_5}{R_1}$$

$$= -V_{in}\left(\frac{R_3R_4 + R_3R_5 + R_4R_5}{R_1R_4}\right) \Rightarrow G(MF) = -\frac{R_3R_4 + R_3R_5 + R_4R_5}{R_1R_4} = -243$$

$\beta(s) = ?$



@DC

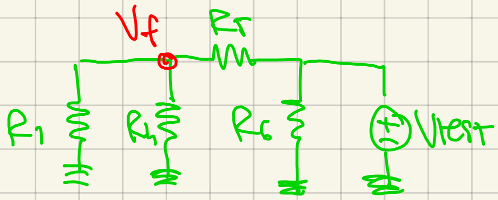


$$V_f = V_x \frac{R_1+R_2}{(R_1+R_2)+R_3}$$

$$V_x = V_{TEST} \frac{(R_1+R_2+R_3)\|R_4}{(R_1+R_2+R_3)\|R_4+R_5}$$

$$\beta(0) = \frac{R_4\|(R_1+R_2+R_3)}{R_4\|(R_1+R_2+R_3)+R_5} \cdot \frac{R_1+R_2}{R_1+R_2+R_3} \simeq \frac{1}{33} \Rightarrow \frac{1}{\beta}(0) = 33$$

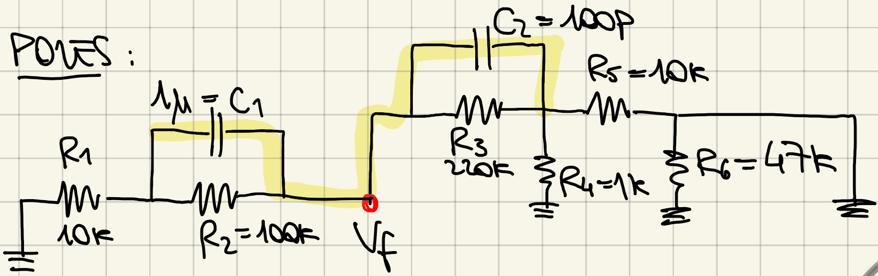
@HF



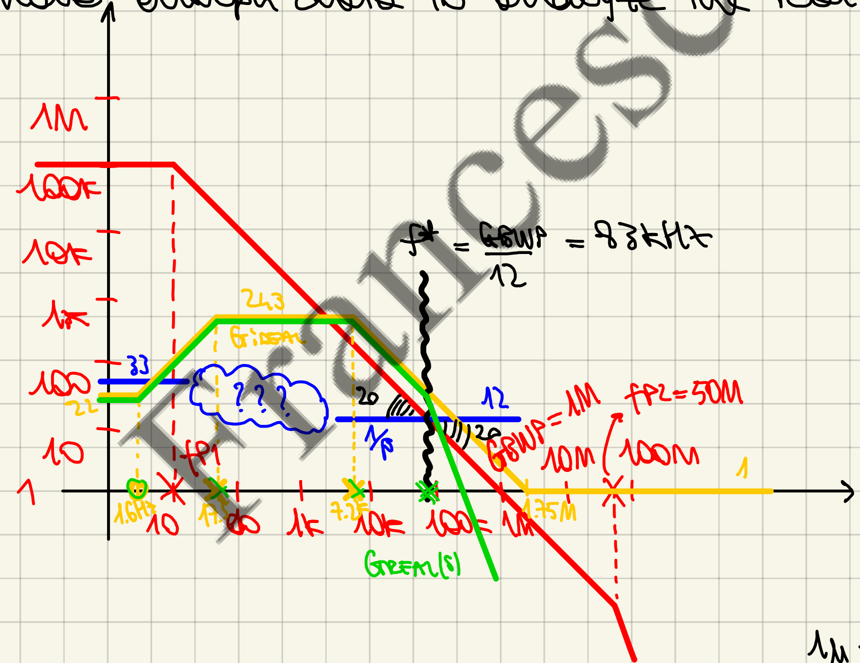
$$V_f = V_{TEST} \frac{R_1\|R_4}{R_1\|R_4+R_5}$$

$$\beta(\infty) = \frac{R_1\|R_4}{R_1\|R_4+R_5} \simeq \Rightarrow \frac{1}{\beta}(\infty) \simeq 12$$

POLES :

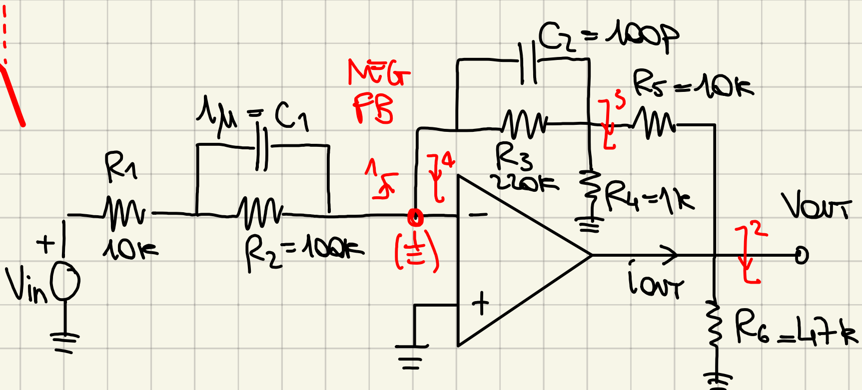


We can see that C_1 and C_2 are dependent to each other $\Rightarrow$ just 1 pole
&
we should use the τ_0, τ_{∞} METHOD, but we don't need to do so
we have enough data to analyze the real behavior of the circuit in an intuitive way



Ⓑ Compute i_{OUT} when $V_{in} = -100mV$

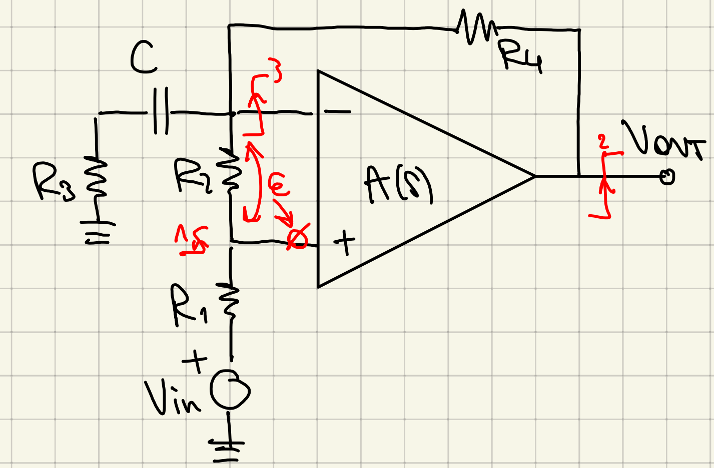
$V_{in} = -100mV \rightarrow$ it means that we are @DC



EXAMPLE 2

$A_0 = 100\,dB = 10^5$
$GBWP = 100\,MHz$

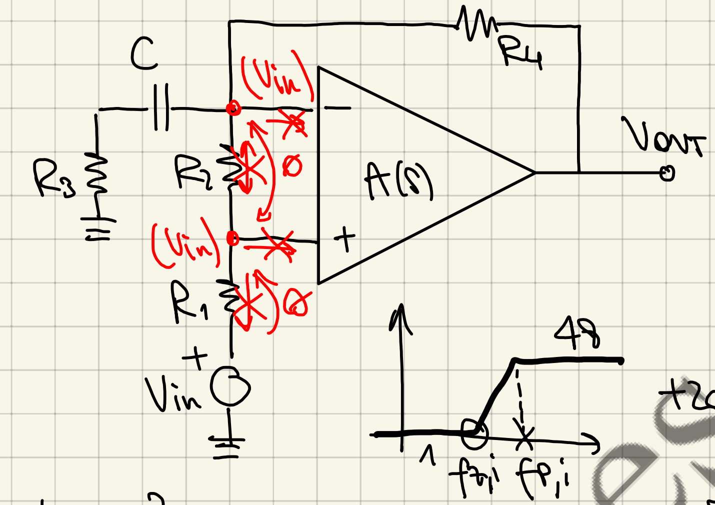
$R_1 = 22\,k\Omega \quad R_2 = R_3 = 1\,k\Omega \quad R_4 = 47\,k\Omega$
$C = 1\,nF$



Ⓐ Plot the Bode diagram of the ideal and real $V_{out}(f)/V_{in}(f)$

$G_{IDEAL} = ?$

ideally if $G_{loop} \to \infty \Rightarrow \varepsilon \to \emptyset$
$\Rightarrow$ no current flows through R_2



@DC $\rightarrow$ $\boxed{G_{IDEAL}(0) = 1}$

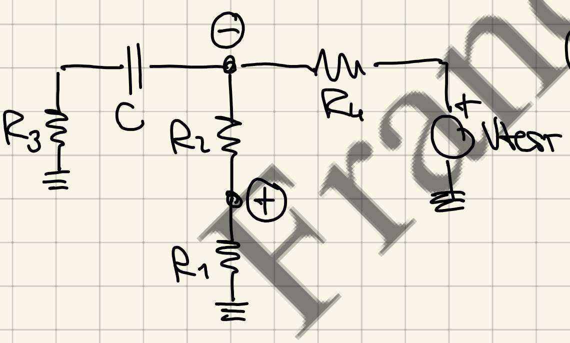
@HF $\rightarrow$ $\boxed{G_{IDEAL}(\infty) = 1 + \frac{R_4}{R_3} = 48}$

$f_{p,i} = \frac{1}{2\pi C R_3} = 160\,kHz$

$+20\,dB/dec \rightarrow \frac{f_{z,i}}{1} = \frac{f_{p,i}}{48} \rightarrow f_{z,i} = \frac{160\,kHz}{48} = 3.3\,kHz$

$\beta(s) = ?$

$v_f = v_f^- - v_f^+$



@DC $\rightarrow \beta(0) = \beta^-(0) - \beta^+(0) =$

$= \frac{R_1 + R_2}{R_1 + R_2 + R_4} - \frac{R_1}{R_1 + R_2 + R_4} =$

$= \frac{R_2}{R_1 + R_2 + R_4} = -\frac{1}{70}$

NEG. FB

$\Rightarrow \boxed{\frac{1}{\beta}(0) = -70}$

@HF $\rightarrow \beta(\infty) = \beta^-(\infty) - \beta^+(\infty) = \frac{R_3 \| (R_1 + R_2)}{R_3 \| (R_1 + R_2) + R_4}\left(1 - \frac{R_1}{R_1 + R_2}\right) =$

$= \frac{R_3 \| \cancel{(R_1 + R_2)}}{R_3 \| \cancel{(R_1 + R_2)} + R_4} \cdot \frac{R_2}{R_1 + R_2} \simeq \frac{1}{48} \cdot \frac{1}{23} =$

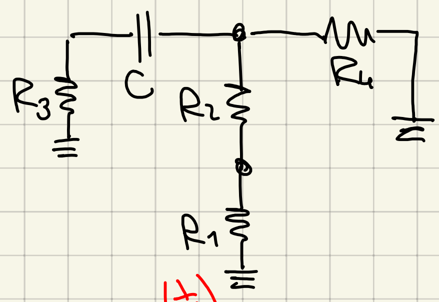
neg

neg

$R_3 \ll R_1 + R_2 = 23\,k\Omega$

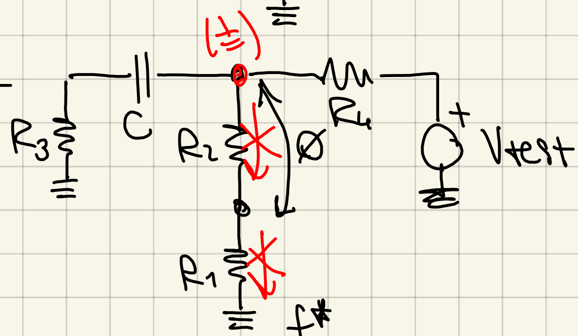
$\Rightarrow \boxed{1/\beta(\infty) = -48 \cdot 23 = -1104}$

POLES of β



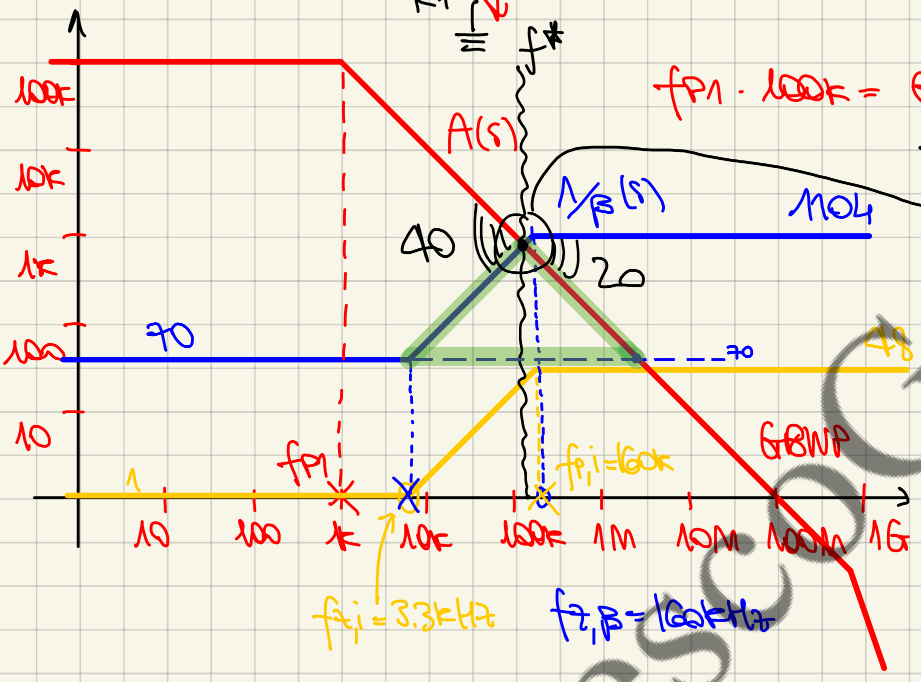
$$f_{p,\beta} = \frac{1}{2\pi C\left[R_3 + (R_2+R_1)\|R_4\right]} = \;\simeq$$

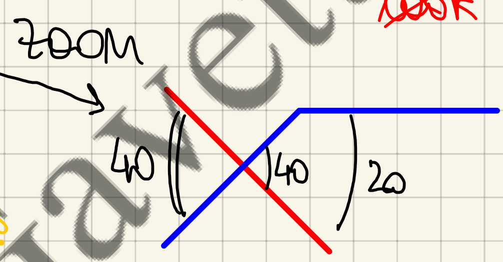
ZEROS of β



$$f_{z,\beta} = \frac{1}{2\pi C R_3} = 160\text{kHz}$$

$$f_{p1} \cdot 100k = GBWP \cdot 1 \rightarrow f_{p1} = \frac{100M}{100k} = 1k$$





$$f^* = \sqrt{f_{p,\beta} \cdot \hat{f}}$$

$$\hat{f} \cdot 48 = GBWP \cdot 1$$

$$\hat{f} = GBWP/70 \simeq 1.42\text{ MHz}$$

$$\Downarrow$$

$$f^* = \sqrt{160\text{kHz} \cdot 1.42\text{ MHz}} \stackrel{!}{=}$$

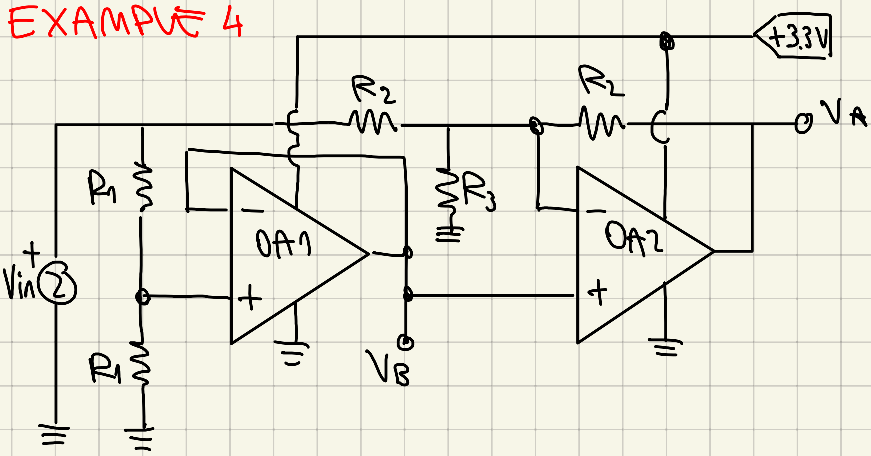
$$PM = 180° - \tan^{-1}\left(\frac{f^*}{f_{p1}}\right) - \tan^{-1}\left(\frac{f^*}{f_{p,\beta}}\right) + \tan^{-1}\left(\frac{f^*}{f_{z,\beta}}\right)$$

$$= 180° - 90° - 90° +$$

ES04 - FREQUENCY COMPENSATION (4)

06/10/2021

EXAMPLE 4



$A_d = 100\,dB = 10^5$

$GBWP = 100\,MHz$

$R_1 = 47\,k\Omega$

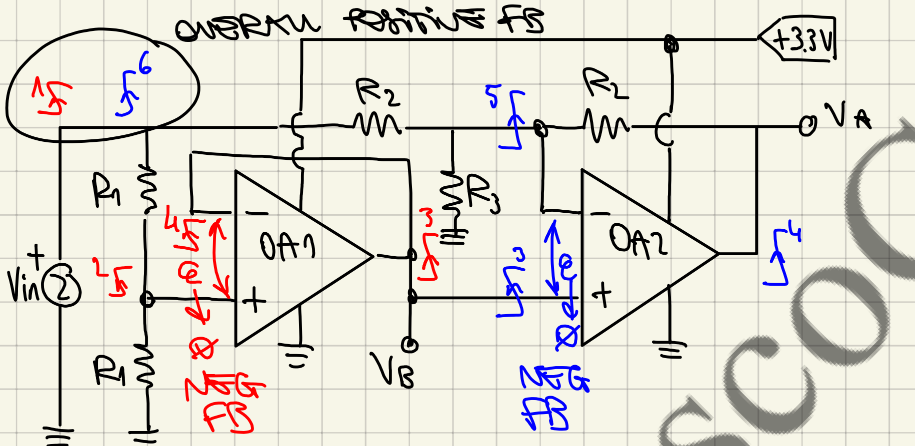
$R_2 = 220\,k\Omega$

$R_3 = 110\,k\Omega$

(A) Compute the real $V_A(f)/V_{in}(f)$ and $V_B(f)/V_{in}(f)$ gain and the input impedance

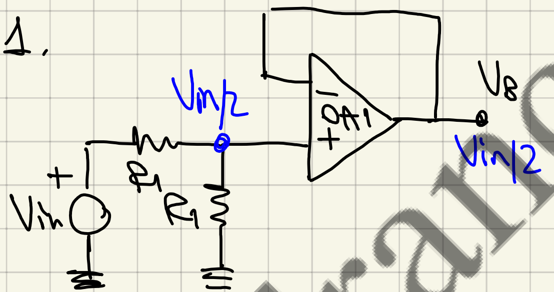
FEEDBACK ASSESSMENT

OVERALL POSITIVE FB



Two negative feedback loops that forms a global positive feedback loop

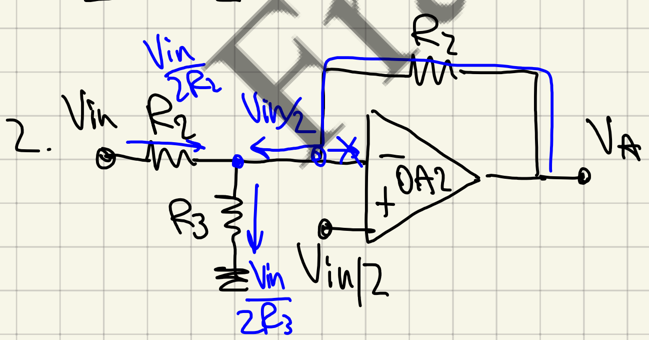
1.



$\beta_1(s) = 1$

$\frac{V_B}{V_{in}} = \frac{1}{2}$

2.

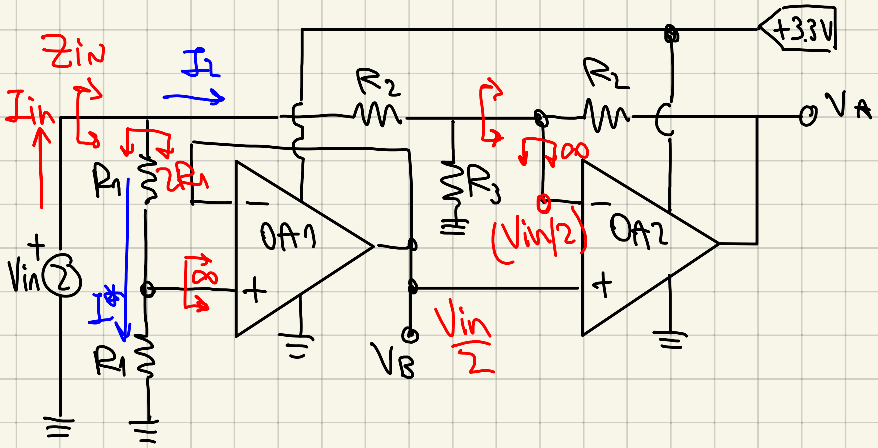


$G_{ideal}(s) = ?$

$$V_A - \frac{V_{in}}{2} = \left(\frac{V_{in}}{2R_3} - \frac{V_{in}}{2R_2}\right) \cdot R_2$$

$$V_A = \frac{V_{in}}{2}\left(\cancel{1} + \frac{R_2}{R_3} - \cancel{1}\right)$$

$$\frac{V_A}{V_{in}} = \frac{1}{2}\frac{R_2}{R_3}$$



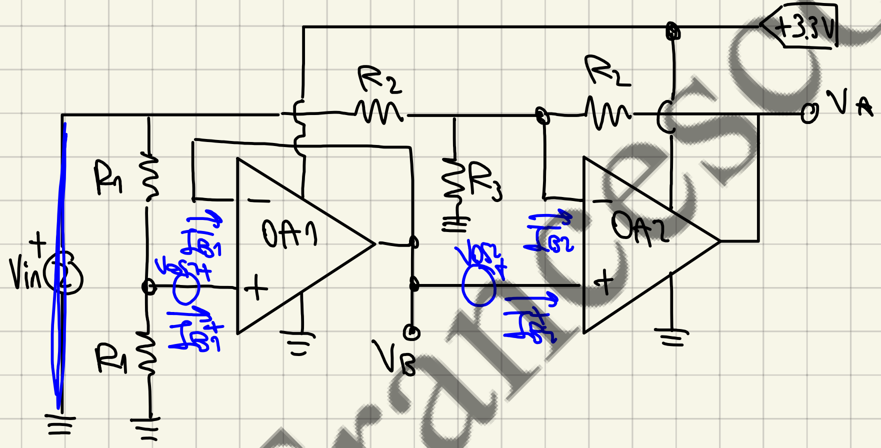
$$Z_{in} = \frac{V_{in}}{I_{in}} =$$

$$I_{in} = I^* + I_2 \quad \text{where} \begin{cases} I^* = \dfrac{V_{in}}{2R_1} \\ I_2 = \dfrac{(V_{in} - V_{in}/2)}{R_2} = \dfrac{V_{in}}{2R_2} \end{cases}$$

$$\Rightarrow \frac{I_{in}}{V_{in}} = \frac{1}{2R_1} + \frac{1}{2R_2} = \frac{1}{2\, R_1 \| R_2}$$

$$\Rightarrow Z_{in} = \frac{V_{in}}{I_{in}} = 2(R_1 \| R_2) = 2R_1 \| 2R_2$$

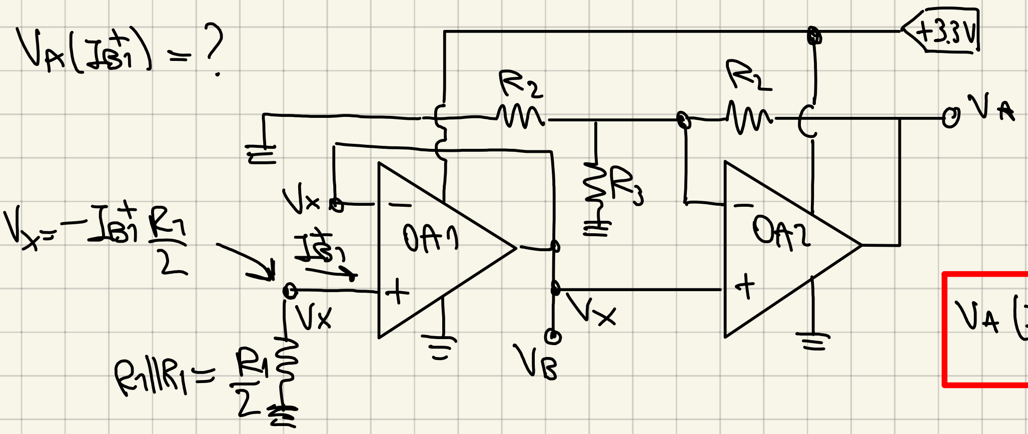
(B) Compute the output static error on V_A, due to $I_B = 10nA$ and $V_{os} = 5mV$ of both OpAmps



$$V_A(\varepsilon) = V_A(V_{os1}) + V_A(V_{os2}) + V_A(I_{B1}^-) + V_A(I_{B1}^+) + V_A(I_{B2}^-) + V_A(I_{B2}^+)$$

$$V_A(V_{os1}) = ? \quad V_{os1} = V_A \frac{R_2 \| R_3}{R_2 \| R_3 + R_2} \rightarrow \boxed{V_A(V_{os1}) = V_{os}\left(1 + \frac{R_2}{R_2 \| R_3}\right) = V_A(V_{os2})}$$

$$V_A(I_{B1}^+) = ?$$

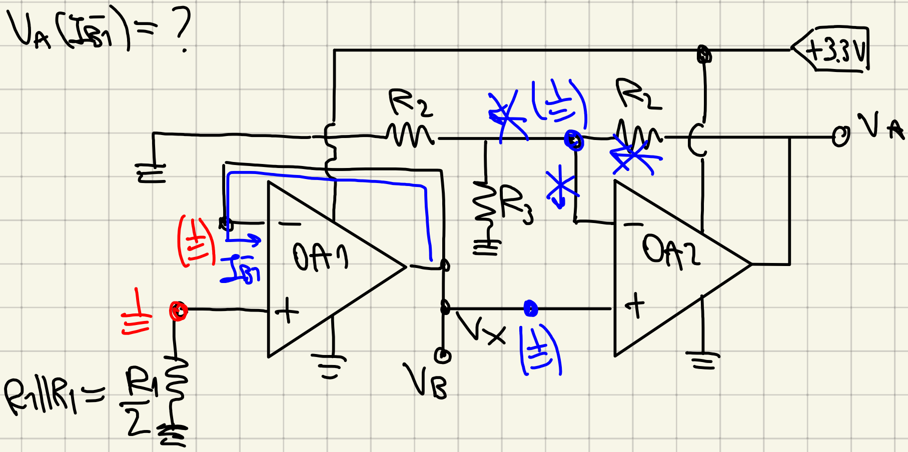


$$V_x = V_A \frac{R_2 \| R_3}{R_2 \| R_3 + R_2}$$

$$V_A = V_x \left(1 + \frac{R_2}{R_2 \| R_3}\right)$$

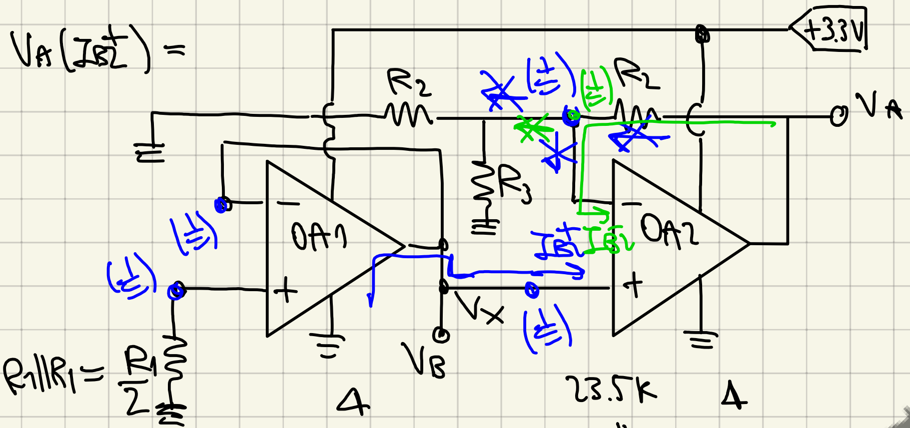
$$\boxed{V_A(I_{B1}^+) = I_{B1}^+ \left[-\frac{R_1}{2}\left(1 + \frac{R_2}{R_2 \| R_3}\right)\right]}$$

$V_A(I_{B1}^-) = ?$



$\Rightarrow \boxed{V_A(I_{B1}^-) = \varnothing}$

$V_A(I_{B2}^+) =$



$\boxed{V_A(I_{B2}^+) = \varnothing}$

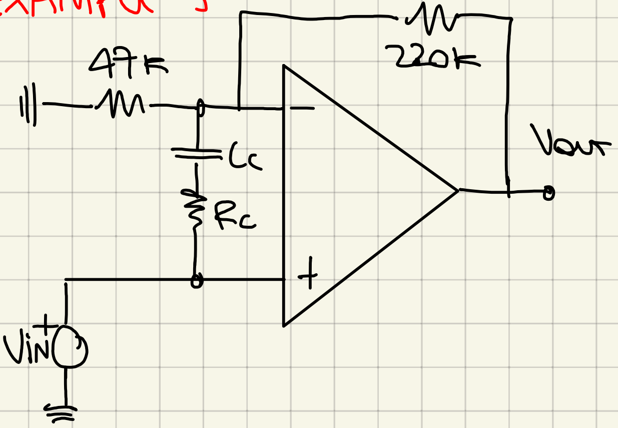
$\boxed{V_A(I_{B2}^-) = I_{B2}^- R_2}$

$$V_A(\varepsilon) = \pm 2 V_{OS} \overbrace{\left(1 + \frac{R_2}{R_2 \| R_3}\right)}^{4} - I_{B1}^+ \overbrace{\frac{R_1}{2}}^{23.5k} \overbrace{\left(1 + \frac{R_2}{R_2 \| R_3}\right)}^{4} + I_{B2}^- R_2 =$$

$$= \pm 2 \cdot 5mV \cdot 4 + 10nA \left[220k - 23.5k \cdot 4\right] =$$

$$= \pm 40mV + 1.26mV$$

EXAMPLE 5



Uncompensated OpAmp w/

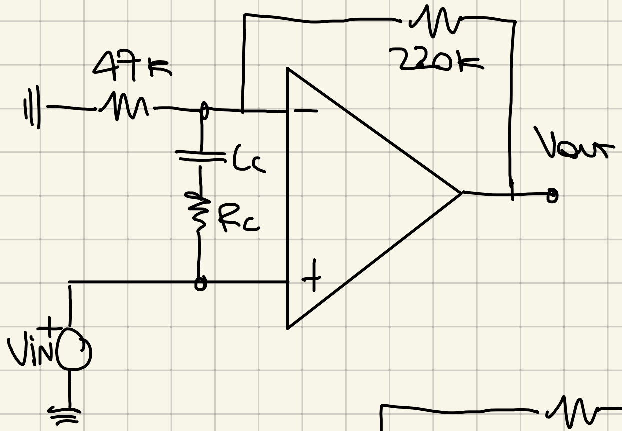
$A_0 = 120\,dB = 10^6 = 1M$

$f_0 = 5\,kHz$

$f_1 = 50\,MHz$

$I_B = 1\,nA$, $V_{os} = 3\,mV$

Ⓐ Without C_c and R_c compute stability and PM

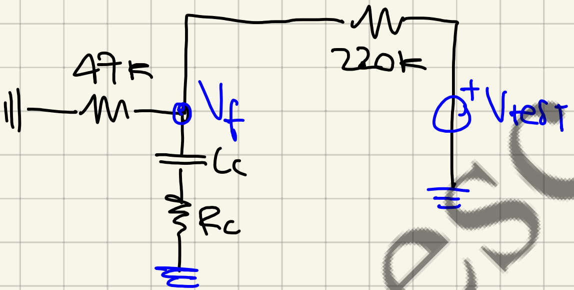


$G_i(s) = ?$

$G_i(0) = 1 + \frac{220k}{47k} \simeq 5.68$

$G_i(\infty) = 1 + \frac{220k}{47k} \simeq 5.68$

$\beta(s) = ?$



$\beta(0) = \frac{47k}{47k + 220k}$

$\Rightarrow \frac{1}{\beta}(0) = 1 + \frac{220k}{47k} \simeq 5.68$

$\beta(\infty) = \frac{47k \| R_c}{47k \| R_c + 220k} \Rightarrow \frac{1}{\beta}(\infty) = 1 + \frac{220k}{R_c \| 47k}$

⇓

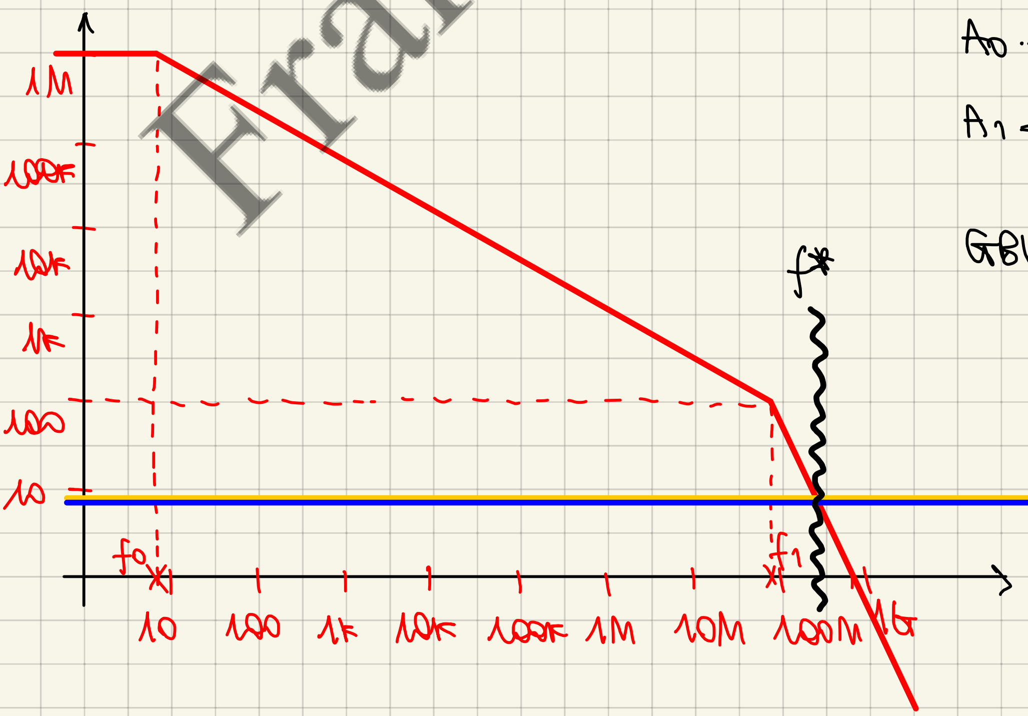
w/o C_c and R_c

$\Rightarrow \frac{1}{\beta}(s) = 5.68$

$A_0 \cdot f_0 = A_1 \cdot f_1$

$A_1 = \frac{A_0 f_0}{f_1} = \frac{10^6 \cdot 5k}{50M} = 100$

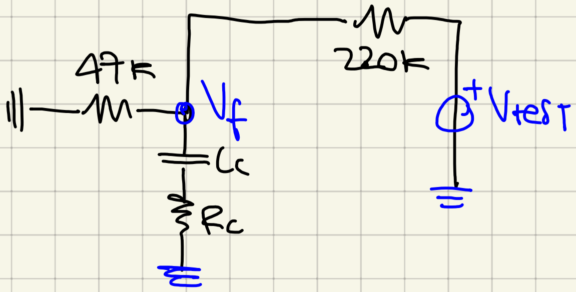
$GBWP = f_1 \sqrt{A_1} = 10 f_1 = 500\,MHz$



$$f^* = \frac{\sqrt{A_1}\cdot f_1}{\sqrt{5.68}} = \frac{10 f_1}{\sqrt{5.68}} = \frac{500M}{\sqrt{5.68}} \simeq 210MHz$$

$$PM = 180° - \tan^{-1}\left(\frac{f^*}{f_0}\right) - \tan^{-1}\left(\frac{f^*}{f_1}\right) = 180 - 90° - 77° \simeq 13°$$

(B) Properly size C_c and R_c to obtain $PM = 90°$



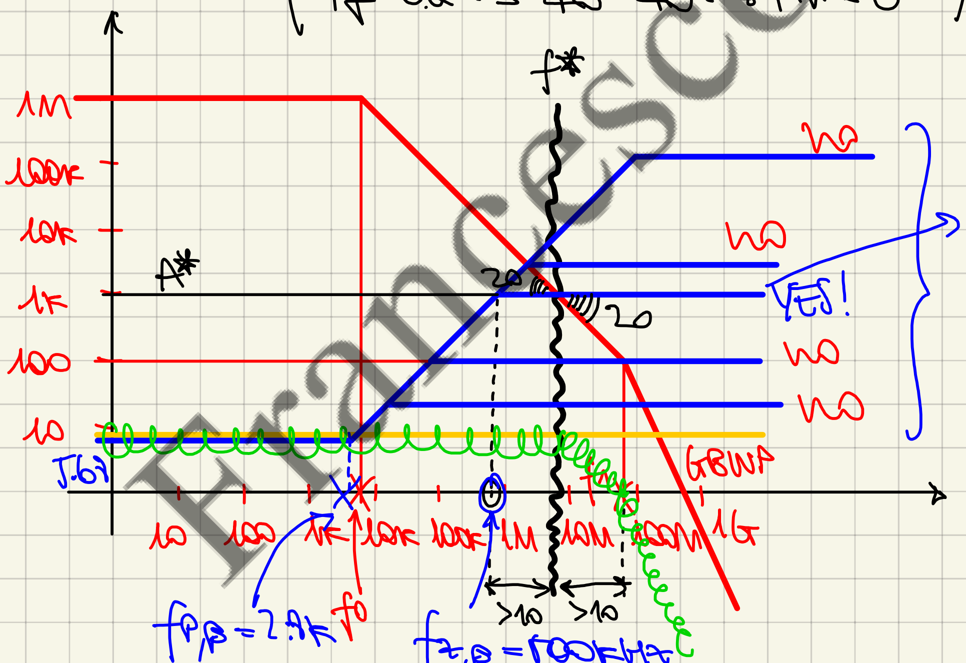
$$f_{p,\beta} = \frac{1}{2\pi C_c\left[R_c + 47k \| 220k\right]}$$

$$f_{z,\beta} = \frac{1}{2\pi C_c R_c}$$

$$PM = 180° - 90° - 77° - \tan^{-1}\left(\frac{f^*}{f_{p,\beta}}\right) + \tan^{-1}\left(\frac{f^*}{f_{z,\beta}}\right) = 90°$$

$f^* = ?$ Notice: to have $PM = 90°$ → we need a 20-20 closure angle

$$\begin{pmatrix} \text{if C.A.} = 20-40 \to PM \simeq 45° \\ \text{if C.A.} = 40-40 \to PM \simeq 0° \end{pmatrix}$$



$$\frac{1}{\beta}(\infty) = 1k$$

$$1 + \frac{220k}{47k \| R_c} = \frac{1}{\beta}(\infty)$$

In order to have a closure angle of 20-20

$$f^* = \frac{f_1}{10} = 5MHz$$

$$f_{z,\beta} = \frac{f^*}{10} = \frac{f_1}{100} = \frac{50M}{100} = 500kHz = \frac{1}{2\pi C_c R_c}$$

$$f^*\cdot A^* = f_1\cdot A_1 \Rightarrow A^* = \frac{f_1 A_1}{f^*} = \frac{50M\cdot 100}{5M} = 1000 = 1k$$

$$\Rightarrow \frac{1}{\beta}(\infty) = 1 + \frac{220k}{47k \| R_c} = 1k$$

$$\Rightarrow \frac{220k}{47k \| R_c} \simeq 1k \quad \rightarrow \quad \frac{47k \cdot R_c}{47k + R_c} = 220$$

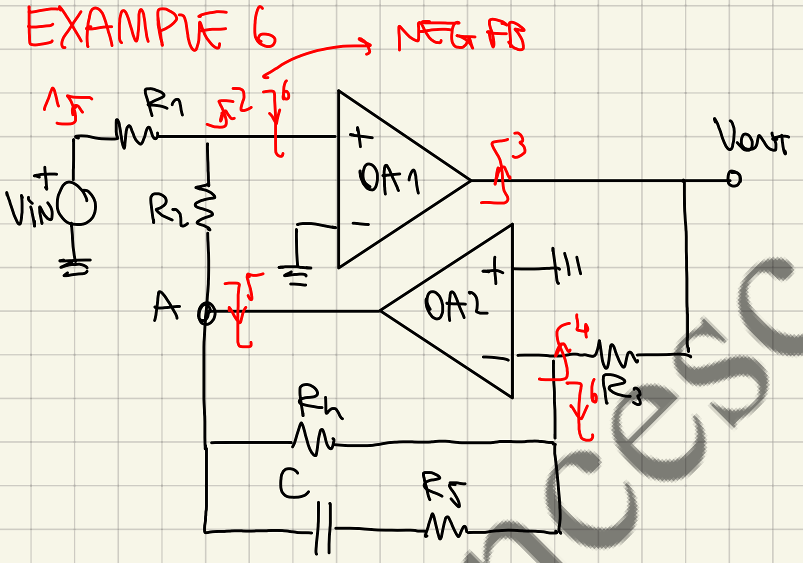
$$47k\,R_c - 220\,R_c = 47k \cdot 220$$

$$R_c = \frac{47k \cdot 220}{47k - 220} \simeq 220\,\Omega$$

$$\frac{1}{2\pi C_c R_c} = 500kHz \quad \rightarrow \quad C_c = \frac{1}{2\pi\, 220 \cdot 500k} \simeq 1.45nF$$

$$f_{p,\beta} = \frac{1}{2\pi C_c \left[R_c + 47k \| 220k\right]} \simeq 2.8k$$

EXAMPLE 6

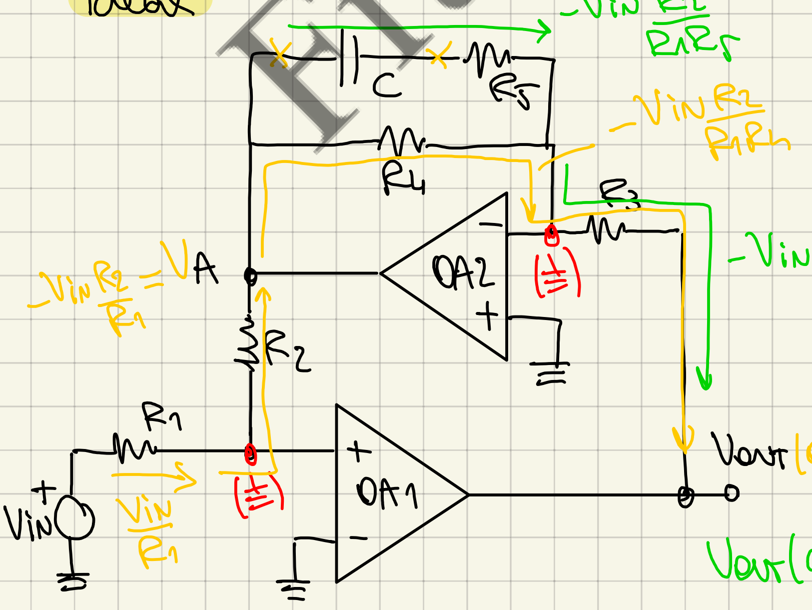


$A_0 = 120dB = 10^6$
GBWP = 20MHz

$I_B = 10nA$, $V_{os} = 5mV$

$R_1 = 1k$ $\quad$ $C = 10nF$
$R_2 = 50k$
$R_3 = 2k$
$R_4 = 50k$
$R_5 = 1k$

Ⓐ Plot the Bode diagram of the $V_{out}(f)/V_{in}(f)$ real gain, when OA2 is still ideal



$G_{ideal}(s) = ?$

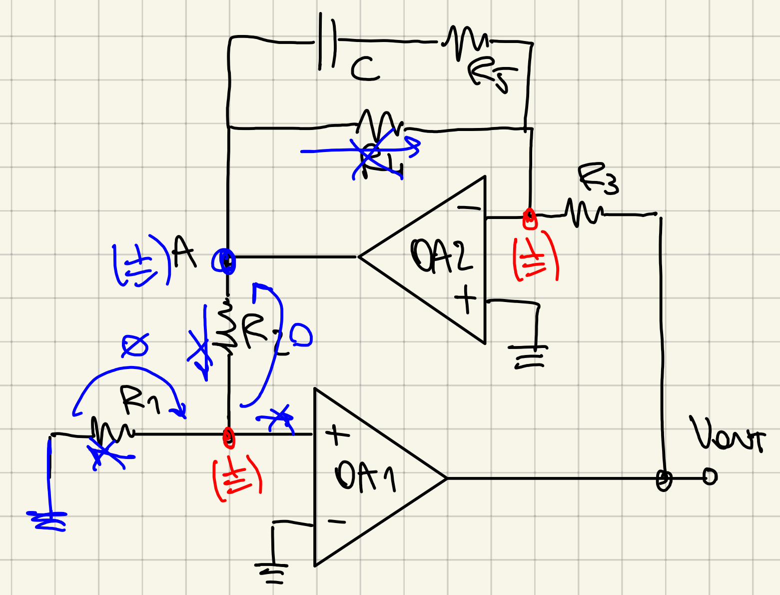
$$G_i(0) = \frac{R_2 R_3}{R_1 R_h} = \frac{50k \cdot 2k}{1k \cdot 50k} = 2$$

$$V_{out}(0) = V_{in}\,\frac{R_2 R_3}{R_1 R_h}$$

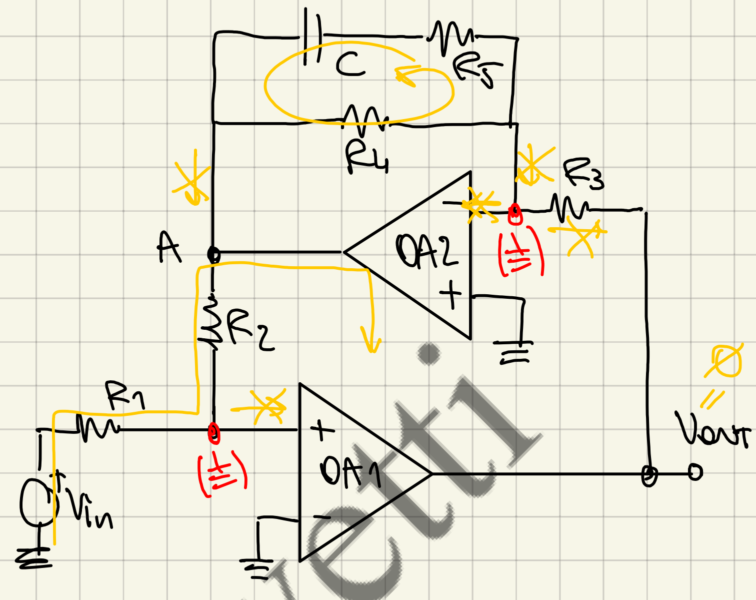
$$V_{out}(\infty) = \frac{R_2 R_3}{R_1}\left(\frac{1}{R_h} + \frac{1}{R_5}\right)$$

$$G_i(\infty) = \frac{R_2 R_3}{R_1}\left(\frac{1}{R_4} + \frac{1}{R_5}\right) = \frac{50k \cdot 2k}{1k}\left(\frac{1}{50k} + \frac{1}{1k}\right) = 102$$

POLE

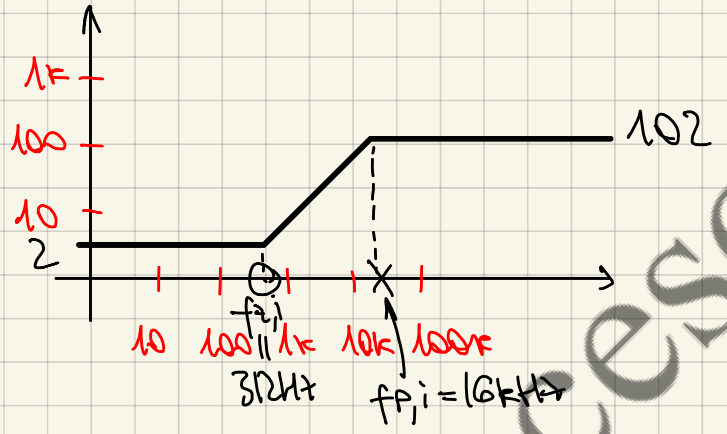


ZERO

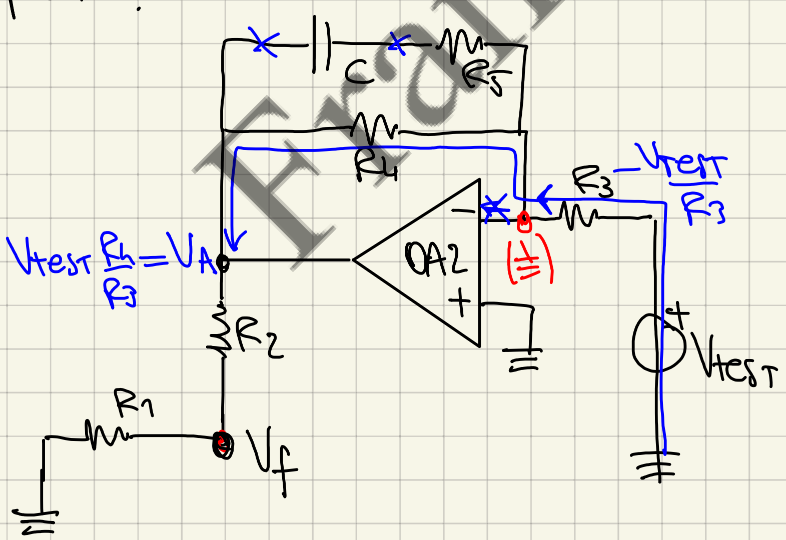


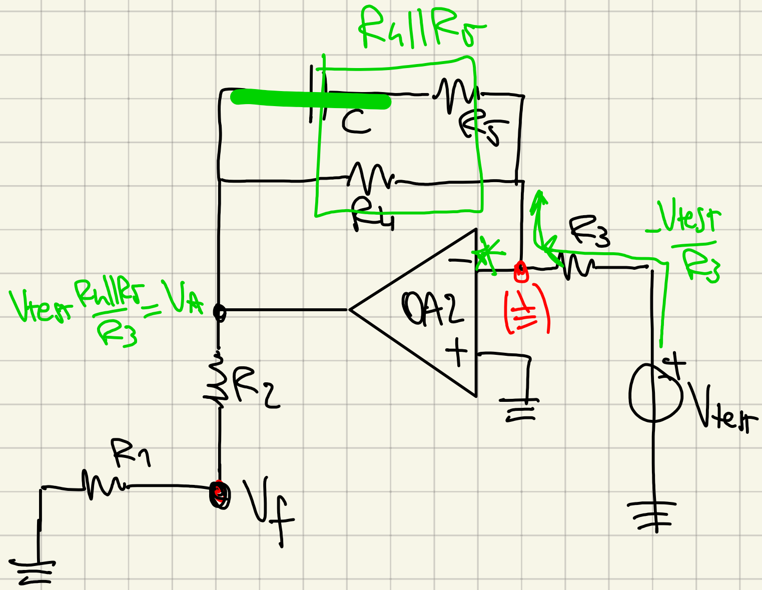
$$f_{p,i} = \frac{1}{2\pi C R_5} \cong 16\,kHz$$

$$f_{z,i} = \frac{1}{2\pi C (R_4 + R_5)} = 312\,Hz$$



$\beta(s) = ?$





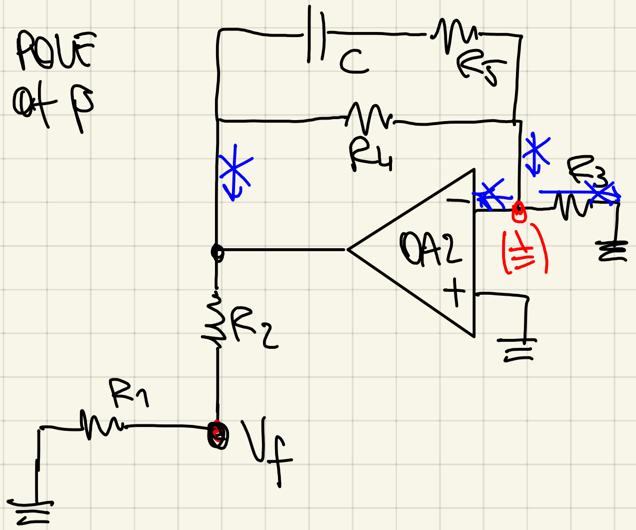
$$\beta(0) = ? = \frac{R_4}{R_3} \cdot \frac{R_1}{R_1 + R_2} = 0.5$$

$$\Rightarrow \frac{1}{\beta}(0) = 2$$

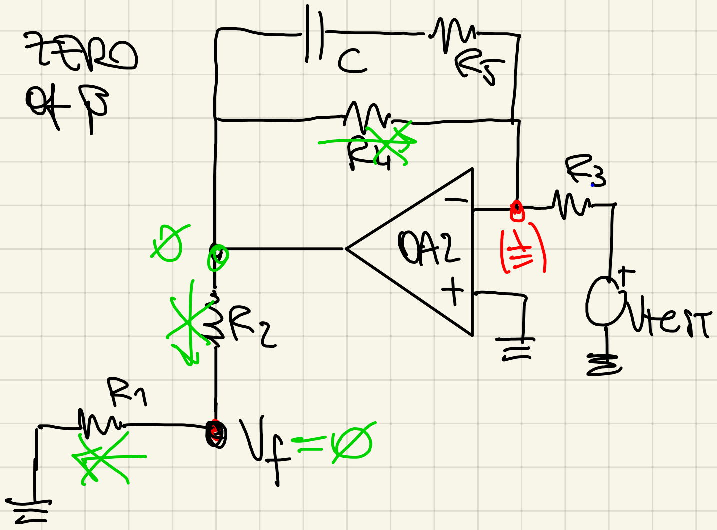
$$\beta(\infty) = \frac{R_4 \| R_5}{R_3} \cdot \frac{R_1}{R_1 + R_2} = 9.8\,m$$

$$\Rightarrow \frac{1}{\beta}(\infty) = 102$$

POLE of β



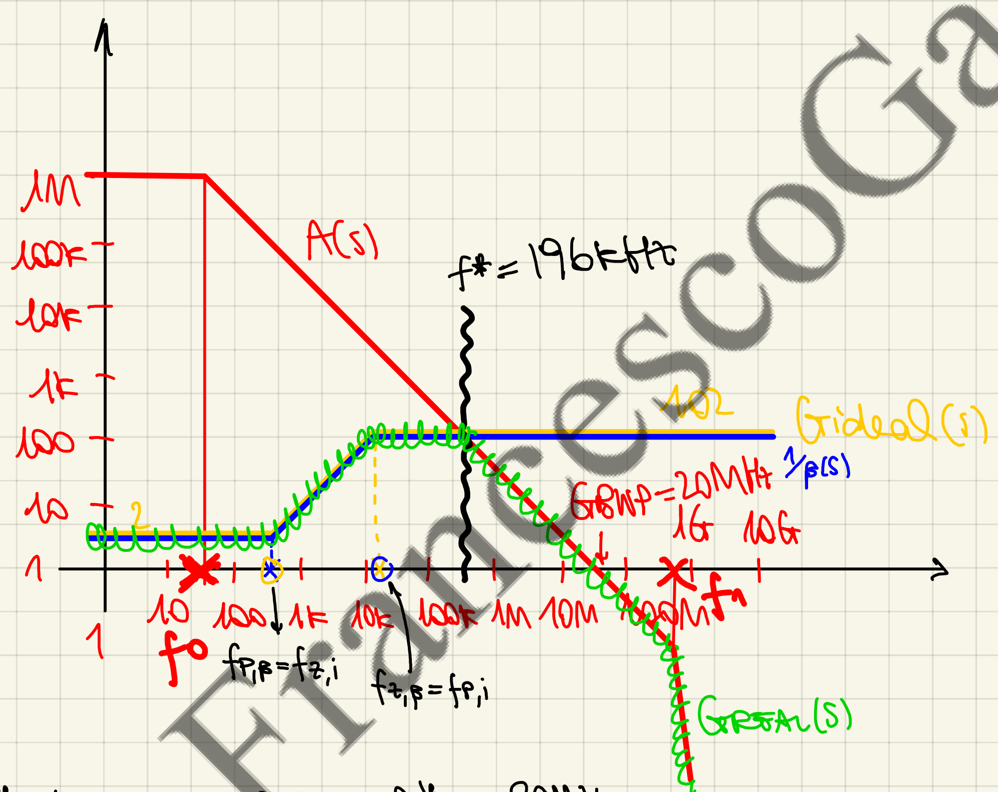
ZERO of β



$$f_{p,\beta} = \frac{1}{2\pi C (R_4+R_5)} = 312\,Hz$$

$$f_{z,\beta} = \frac{1}{2\pi C R_5} \simeq 16\,kHz$$

$$\Rightarrow \frac{1}{\beta}(s) = G_i(s)$$



$$f^* \cdot 102 = GBWP \rightarrow f^* = \frac{20MHz}{102} = 196\,kHz$$