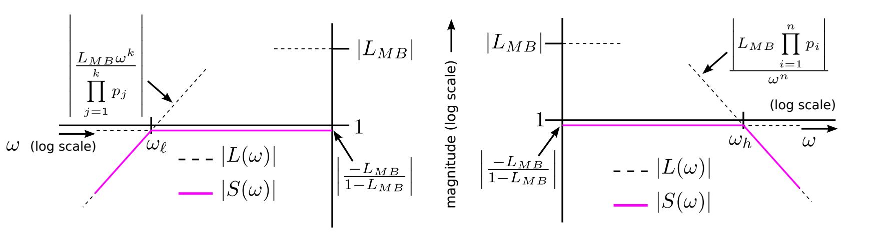
Frequency compensation techniques

Bandwidth definition of a feedback amplifier

ω_ℓ MFM high-pass cut-off frequency

ω_h MFM low-pass cut-off frequency



After the design of the bandwidth the poles of the transfer are generally not in MFM positions.

Use the root-locus technique to find the poles of the servo function from the poles, the zeros and the mid-band frequency value of the loop gain.

$$A_f(s) = A_i(s)\ \frac{-L_{MB}}{1-L_{MB}}\ \frac{b_k s^k}{1+b_1 s+b_2 s^2+\cdots b_k s^k}\ \frac{1}{1+a_1 s+a_2 s^2+\cdots a_n s^n}$$

Frequency compensation

Application of techniques to obtain the desired frequency response.

Orthogonal design

No or negligible interaction with other performance aspects, such as:

- Noise
- Power dissipation
- Drive capability
- Energy storage
- Weak nonlinearity
- Bandwidth

Phantom zero compensation

Zeros can be inserted in to loop gain to modify the root locus.

Loop gain zeros in the transmission band also appear in the servo function.

A low-pass MFM response is an all-pole response.

Servo function may have zeros but transfer must have an all-pole response.

$$A_f(s) = A_{f\infty}(s)\frac{-L(s)}{1-L(s)} \leftarrow$$

A zero in the loop gain also appears in the servo function

A phantom zero is a zero in the loop gain which is not observable in the gain: it is canceled by a pole in the asymptotic gain.

$$A_f(s) = \frac{A_{f\infty}(s)}{\cancel{(1-s/z_1)}}\frac{-L(s)\cancel{(1-s/z_1)}}{1-L(s)(1-s/z_1)}$$

Second order

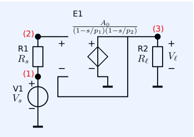
Second order MFM transfer $\quad F_2(s) = \frac{1}{1+s\sqrt{2}/\omega_h+s^2/\omega_h^2}$

Case: no compensation required

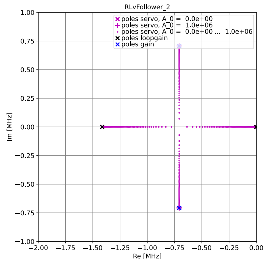
Loop gain with two poles:

$$L(s) = \frac{L_{MB}}{(1-s/p_1)(1-s/p_2)}$$

SLiCAP test bench



SLiCAP root locus plot



Servo function:

$$S_2(s) = \frac{-L_{MB}}{1-L_{MB}}\frac{1}{1-s\frac{p_1+p_2}{(1-L_{MB})p_1p_2}+s^2\frac{1}{(1-L_{MB})p_1p_2}}$$

Low-pass MFM cut-off frequency:

$$\omega_h^2 = (1-L_{MB})\,p_1p_2$$

No compensation required if the magnitude of the sum of the poles of the loop gain equals sqrt(2) times the low-pass cut-off frequency:

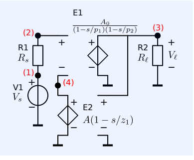
$$p_1+p_2 = -\sqrt{2}\omega_h$$

Case: compensation with one phantom zero

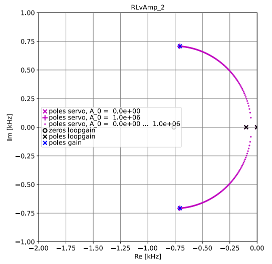
Loop gain with two poles and one zero:

$$L(s) = L_{MB}\frac{1-s/z}{(1-s/p_1)(1-s/p_2)}$$

SLiCAP test bench



SLiCAP root locus plot



Low-pass MFM cut-off frequency:

$$\omega_h^2 = (1-L_{MB})\,p_1p_2$$

Sum of the poles of the servo function:

$$p_a+p_b = p_1+p_2-\frac{p_1p_2}{z}L_{MB}$$

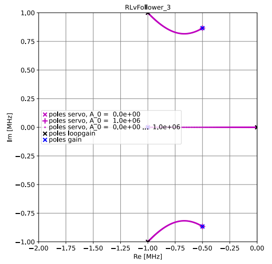
Conditions for MFM compensation:

$$-p_1-p_2 < \sqrt{2}\omega_h$$

Phantom zero frequency:

$$z = -\frac{\omega_h^2}{\sqrt{2}\omega_h+p_1+p_2}$$

SLiCAP root locus plot

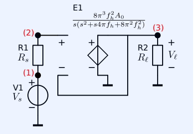


Third order

Third order MFM transfer:

$$F_3(s) = \frac{1}{1+2s/\omega_h+2s^2/\omega_h^2+s^3/\omega_h^3}$$

SLiCAP test bench



No compensation required

Loop gain with three poles:

$$L(s) = L_{MB}\frac{1}{(1-s/p_1)(1-s/p_2)(1-s/p_3)}$$

Servo function:

$$S_3(s) = \frac{-L_{MB}}{1-L_{MB}}\frac{1}{1-s\frac{p_1p_2+p_1p_3+p_2p_3}{(1-L_{MB})p_1p_2p_3}+s^2\frac{p_1+p_2+p_3}{(1-L_{MB})p_1p_2p_3}-s^3\frac{1}{(1-L_{MB})p_1p_2p_3}}$$

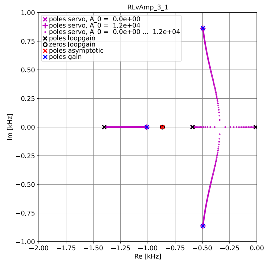
Low-pass MFM cut-off frequency:

$$\omega_h = \sqrt[3]{|(1-L_{MB})\,p_1p_2p_3|}$$

No compensation required if:

$$p_1p_2+p_1p_3+p_2p_3 = 2\omega_h^2$$
$$p_1+p_2+p_3 = -2\omega_h$$

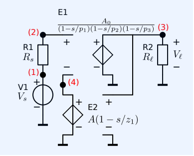
SLiCAP root locus plot



Compensation with one phantom zero

Loop gain with three poles and one zero:

$$L(s) = L_{MB}\frac{1-s/z_1}{(1-s/p_1)(1-s/p_2)(1-s/p_3)}$$



SLiCAP test bench

Low-pass MFM cut-off frequency:

$$\omega_h = \sqrt[3]{|(1-L_{MB})\,p_1p_2p_3|}$$

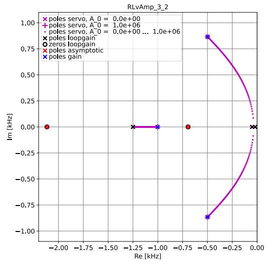
Conditions for MFM compensation:

$$p_1p_2+p_1p_3+p_2p_3 < 2\omega_h^2$$
$$p_1+p_2+p_3 = -2\omega_h$$

Phantom zero frequency:

$$z_1 = \frac{\omega_h^3}{p_1p_2+p_1p_3+p_2p_3-2\omega_h^2}$$

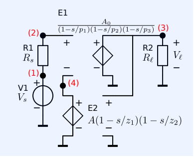
SLiCAP root locus plot



Compensation with two phantom zeros

Loop gain with three poles and two zeros:

$$L(s) = L_{MB}\frac{(1-s/z_1)(1-s/z_2)}{(1-s/p_1)(1-s/p_2)(1-s/p_3)}$$



SLiCAP test bench

Low-pass MFM cut-off frequency:

$$\omega_h = \sqrt[3]{|(1-L_{MB})\,p_1p_2p_3|}$$

Conditions for MFM compensation:

$$p_1+p_2+p_3-\frac{p_1p_2p_3L_{MB}}{z_1z_2} = -2\omega_h$$
$$p_1p_2+p_1p_3+p_2p_3-L_{MB}p_1p_2p_3\left(\frac{1}{z_1}+\frac{1}{z_2}\right) = 2\omega_h^2$$

Phantom zero frequencies:

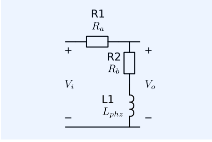
$$z_1z_2 = \frac{\omega_h^3}{p_1+p_2+p_3+2\omega_h}$$
$$z_1+z_2 = \frac{p_1p_2+p_1p_3+p_2p_3-2\omega_h^2}{p_1+p_2+p_3+2\omega_h}$$

Implementation of phantom zeros

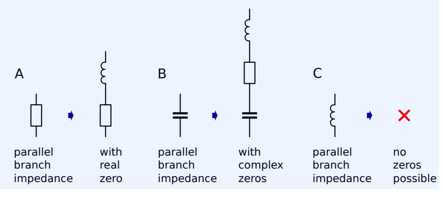
Phantom zero coincides with pole in the ideal gain: cannot be implemented in the cotroller.

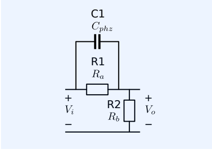
Passive phantom zeros in feedback network

If the feedback network causes an attenuation in the loop gain, at the frequency that corresponds with that of the phantom zero, this attenuation can be reduced for higher frequencies.

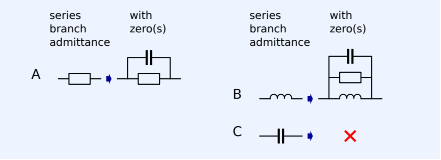


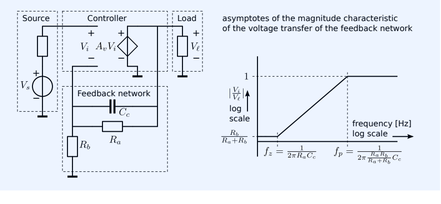
Resistive divider: add L in series with parallel branch.





Resistive divider: add C in parallel with series branch.



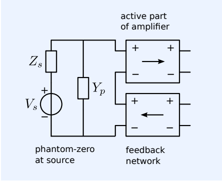


Effectiveness phantom zeros

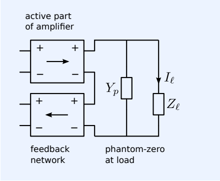
- Insertion of C or L may introduce a new pole
- Insertion of C or L may change pole frequencies
- Not effective if:
  - new pole is dominant
  - one pole moved out of dominant group

Passive phantom zeros at the source **Passive phantom zeros at the load**

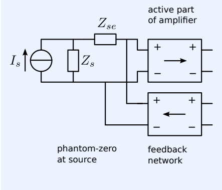
If the source/load impedance causes an attenuation in the loop gain, at the frequency that corresponds with that of the phantom zero, this attenuation can be reduced for higher frequencies.



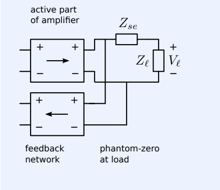
Phantom zero with input series feedback



Phantom zero with output series feedback

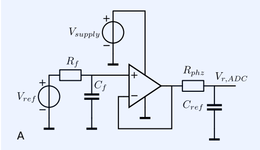


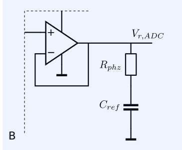
Phantom zero with input shunt feedback



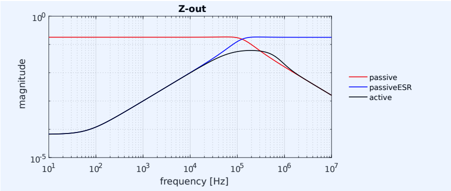
Phantom zero with output shunt feedback

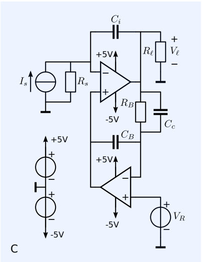
Active phantom zeros



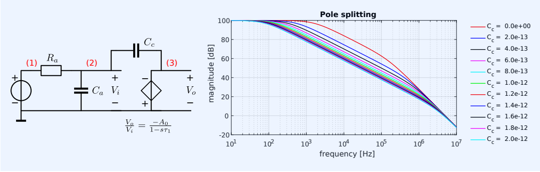


Examples frequency compensation of low-noise, low-impedance ADC reference,

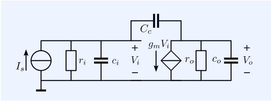




Pole-splitting by changing the interaction between poles



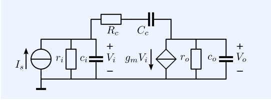
Pole-splitting in an OpAmp circuit



Pole-splitting 'Miller compensation' in a transistor stage

The compensation capacitor does not introduce a new pole:

- It dos not introduce a new free capacitor voltage because it creates a loop of capacitors or a loop of capacitors and voltage sources
- It changes the interaction between the existing poles
- Negative feedback amplifies this effect (see poster transistor stages)

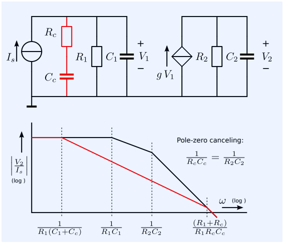


The compensation capacitor also introduces a right hal-plane zero

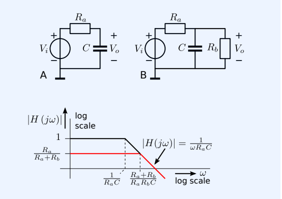
This zero can be replaced with a left half-plane pole at at higher frequency by placing a resistor in series with the compensation capacitor:

$$R_c = \frac{1}{g_m}$$

Pole-splitting through pole-zero canceling



Resistive broadbanding



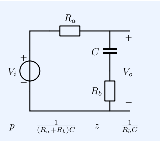
Bandwidth reduction

Reduce the loop gain-poles product:

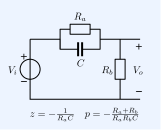
- Reduction of the mid-band loop gain (without increasing the frequency of a dominant pole)
- Reduction of the frequency of a dominant pole:
  - without pole splitting
  - with excessive pole-splitting: a pole is moved out of the dominant group

Phase margin design

- Phase margin is a property of the loop gain
- Only meaningful if the loop gain has a clear relation with the gain
- Only in an all-pole 2nd order system there is a clear relation between phase margin and the filter characteristics of the servo function



Phase lag network



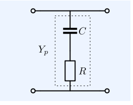
Phase lead network

Zeros in the loop gain in the frequency range of interest result in tilt in the step response and ripple in the frequency response.

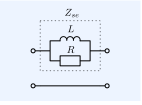
Compensation of disconnected or shorted source / load

In case of shunt or series feedback the port impedance is affected by feedback.

- If shorded, a negative real part of the port impedance at some frequency may cause instability.
- If left open, a negative real part of the port admittance at some frequency may cause instability

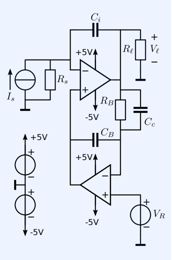


Compensation of a high-frequency, negative port admittance

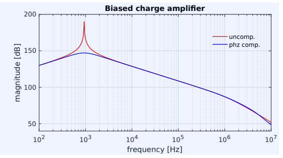


Compensation of a high-frequency, negative port impedance

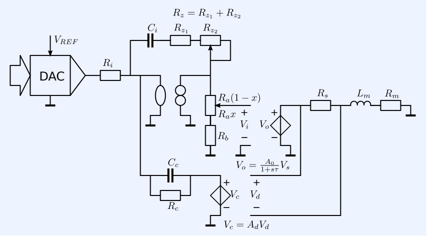
Frequency compensation of circuits with feedback biasing



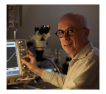
Integrating transimpedance amplifier with feedback biasing and phantom zero compensation



Analog PID controllers



Concept of a motor current driver with PI controller and phantom zero compensation



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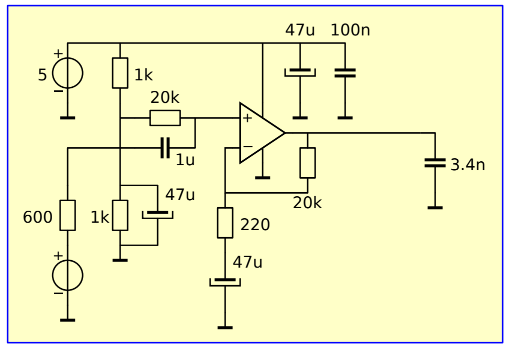
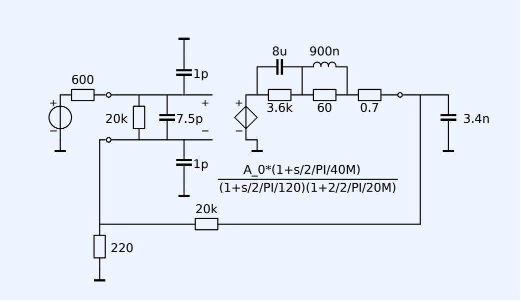
anton@montagne.nl
https://www.analog-electronics.eu

Example frequency compensation voltage amplifier for capacitive load

Uncompensated



Schematic diagram of the uncompensated amplifier



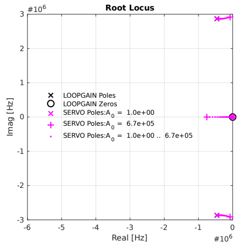
Small-signal equivalent circuit of the uncompensated amplifier

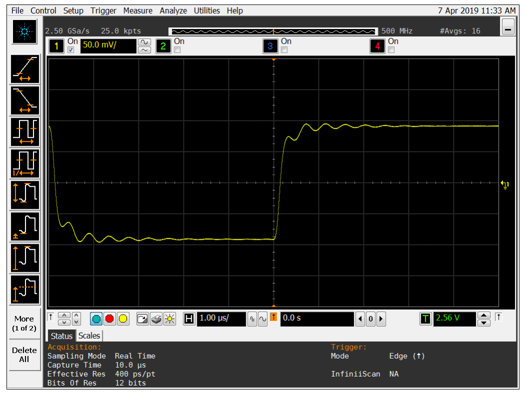
PZ analysis for: LOOPGAIN

DC value = -5918.0

Poles	Re [Hz]	Im [Hz]	Mag [Hz]	Q [-]
p_1	-6.508	0.0	6.508	
p_2	-120.0	0.0	120.0	
p_3	-4.598e5	-2.868e6	2.904e6	3.158
p_4	-4.598e5	2.868e6	2.904e6	3.158
p_5	-2.0e7	0.0	2.0e7	
p_6	-2.352e7	0.0	2.352e7	
p_7	-5.051e8	0.0	5.051e8	

Zeros	Re [Hz]	Im [Hz]	Mag [Hz]	Q [-]
z_1	-5.526	0.0	5.526	
z_2	-1.061e7	0.0	1.061e7	
z_3	-4.0e7	0.0	4.0e7	
z_4	-2.653e8	0.0	2.653e8	





7 Apr 2019 11:33 AM

2.50 GSa/s 25.0 kpts 500 MHz #Avgs: 16

1 On 50.0 mV/ 2 On 3 On 4 On

1.00 µs/ 0.0 s

Acquisition:
Sampling Mode Real Time
Capture Time 10.0 µs
Effective Res 400 ps/pt
Bits Of Res 12 bits

Trigger:
Mode Edge (↑)
InfiniiScan NA

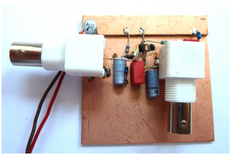
Measured step response of the uncompensated amplifier

PZ analysis for: GAIN

DC value = 91.89

Poles	Re [Hz]	Im [Hz]	Mag [Hz]	Q [-]
p_1	-40300.0	2.926e6	2.926e6	36.3
p_2	-40300.0	-2.926e6	2.926e6	36.3
p_3	-8.232e5	0.0	8.232e5	
p_4	-2.005e7	0.0	2.005e7	
p_5	-2.348e7	0.0	2.348e7	
p_6	-5.051e8	0.0	5.051e8	

Zeros	Re [Hz]	Im [Hz]	Mag [Hz]	Q [-]
z_1	-1.061e7	0.0	1.061e7	
z_2	-3.996e7	0.0	3.996e7	
z_3	-8.094e8	-7.427e8	1.098e9	0.6786
z_4	-8.094e8	7.427e8	1.098e9	0.6786



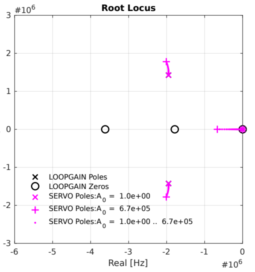
Compensation with two phantom zeros

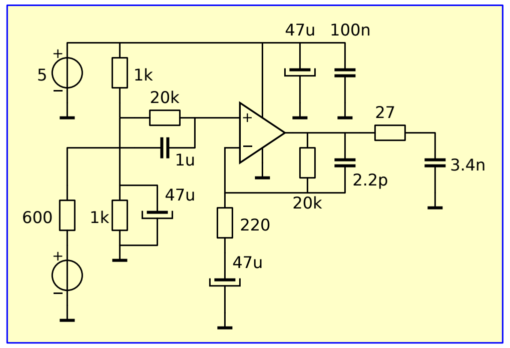
PZ analysis for: LOOPGAIN

DC value = -5918.0

Poles	Re [Hz]	Im [Hz]	Mag [Hz]	Q [-]
p_1	-6.508	0.0	6.508	
p_2	-120.0	0.0	120.0	
p_3	-1.95e6	1.426e6	2.416e6	0.6194
p_4	-1.95e6	-1.426e6	2.416e6	0.6194
p_5	-2.0e7	0.0	2.0e7	
p_6	-2.311e7	0.0	2.311e7	
p_7	-2.3e8	0.0	2.3e8	
p_8	-8.653e9	0.0	8.653e9	

Zeros	Re [Hz]	Im [Hz]	Mag [Hz]	Q [-]
z_1	-5.526	0.0	5.526	
z_2	-1.786e6	0.0	1.786e6	
z_3	-3.617e6	0.0	3.617e6	
z_4	-1.061e7	0.0	1.061e7	
z_5	-4.0e7	0.0	4.0e7	
z_6	-2.653e8	0.0	2.653e8	





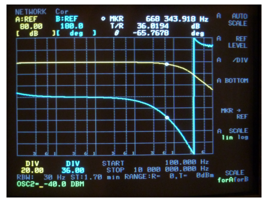
Schematic diagram of the compensated amplifier

PZ analysis for: GAIN

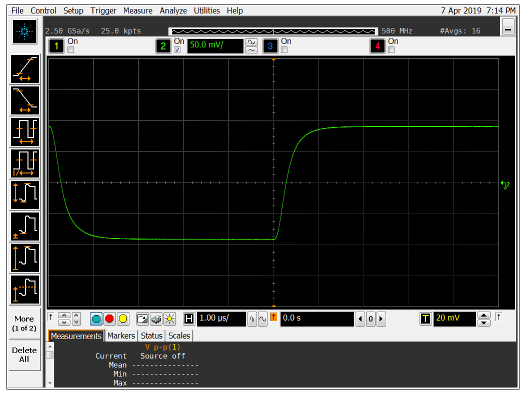
DC value = 91.89

Poles	Re [Hz]	Im [Hz]	Mag [Hz]	Q [-]
p_1	-6.662e5	0.0	6.662e5	
p_2	-2.009e6	-1.78e6	2.684e6	0.6681
p_3	-2.009e6	1.78e6	2.684e6	0.6681
p_4	-2.157e7	2.221e6	2.169e7	0.5026
p_5	-2.157e7	-2.221e6	2.169e7	0.5026
p_6	-2.299e8	0.0	2.299e8	
p_7	-8.652e9	0.0	8.652e9	

Zeros	Re [Hz]	Im [Hz]	Mag [Hz]	Q [-]
z_1	7.165e7	-1.781e8	1.92e8	1.34
z_2	7.165e7	1.781e8	1.92e8	1.34
z_3	-1.061e7	0.0	1.061e7	
z_4	-4.045e7	0.0	4.045e7	
z_5	-1.17e8	0.0	1.17e8	



Frequency response of the compensated amplifier



7 Apr 2019 7:14 PM

2.50 GSa/s 25.0 kpts 500 MHz #Avgs: 16

1 On 2 On 50.0 mV/ 3 On 4 On

1.00 µs/ 0.0 s 20 mV

V p-p(1)
Current Source off
Mean ---------------
Min ---------------
Max ---------------

Measured step response of the compensated amplifier