Frequency Compensation

Introduction

What
Application of techniques to correct the pole-zero pattern of the system and obtain:
- MFM frequency response
- No overshoot step response
- Maximally flat group delay
- etc.

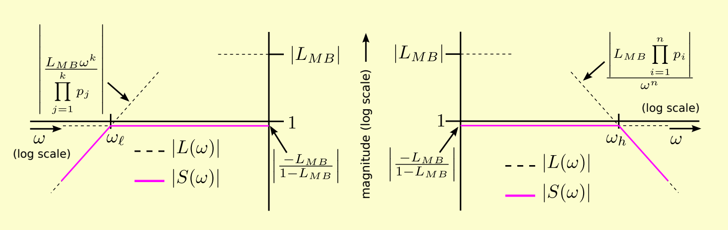
Why
After the design of the bandwidth the loop gain pole product has its desired value but the poles of the feedback system are not (yet) at the desired locations

How
Such that the bandwidth is maintained and other performance aspects are not adversely affected

Design approach

Wide-band
Separate design of low-frequency cut-off from high-frequency cut-off

$$A_f(s) = A_i(s)\frac{-L_{MB}}{1-L_{MB}}\frac{b_k s^k}{1+b_1s+b_2s^2+\cdots b_ks^k}\frac{1}{1+a_1s+a_2s^2+\cdots a_ns^n}$$



High-pass (low-frequency) cut-off
Low-frequency zeros and poles in the loop gain
- AC coupling in the loop and dynamic behavior of source and/or load.
  Loop signal path comprises:
  * Capacitors in series with the signal path
  * Inductors in parallel with the signal path

Design task
Adjust b_j (j=1...k-1) for desired filter response

Low-pass (high-frequency) cut-off
High-frequency poles in the loop gain
- Bandwidth limitation of transistors and dynamic behavior of source and/or load.
  Loop signal path comprises:
  * Capacitors in parallel with the signal path
  * Inductors in series with the signal path

Design task
Adjust a_i (i=1...n-1) for desired filter response

Design techniques
1. Phantom zeros
2. Pole splitting by changing interaction between poles
3. Pole-splitting by pole-zero canceling
4. Resistive broadbanding
5. Bandwidth reduction

Design strategies
1. Maintain servo bandwidth
2. Exchange bandwidth ideal transfer with servo bandwidth
   - Only possible if initial bandwidth servo function is more than required
3. Reduce bandwidth servo function
   - Only possible if initial bandwidth servo function is more than required

Phantom zero compensation

The concept
Insertion of a zero in the loop gain that coincides with a pole in the ideal transfer

$$A_f(s) = A_i(s)\frac{-L(s)}{1-L(s)}$$

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

zero in loop gain

pole in ideal transfer

Phantom zero does not appear as a zero in the gain, but changes the denominator of the servo function

$$A_f(s) = A_i(s)\frac{-L(s)}{1-L(s)(1-s/z_1)}$$

Compensation of second-order systems
Loop gain with two poles and one phantom zero

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

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

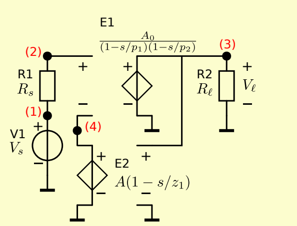
$$A_f = A_i(s)\frac{-L_{DC}}{1-L_{DC}}\frac{1}{1+s\left(\frac{L_{DC}}{z(1-L_{DC})}-\frac{p_1+p_2}{p_1p_2(1-L_{DC})}\right)+\frac{s^2}{p_1p_2(1-L_{DC})}}$$

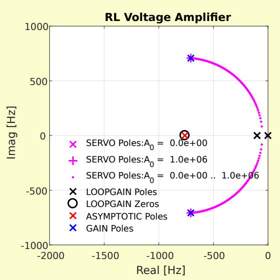
$$A_f \approx A_i(s)\frac{-L_{DC}}{1-L_{DC}}\frac{1}{1+s\left(-\frac{1}{z}-\frac{p_1+p_2}{p_1p_2(1-L_{DC})}\right)+\frac{s^2}{p_1p_2(1-L_{DC})}} \quad \left| \begin{array}{l} |L_{DC}| \gg 1 \\ \omega_h = \frac{1}{p_1p_2(1-L_{DC})} \end{array}\right.$$

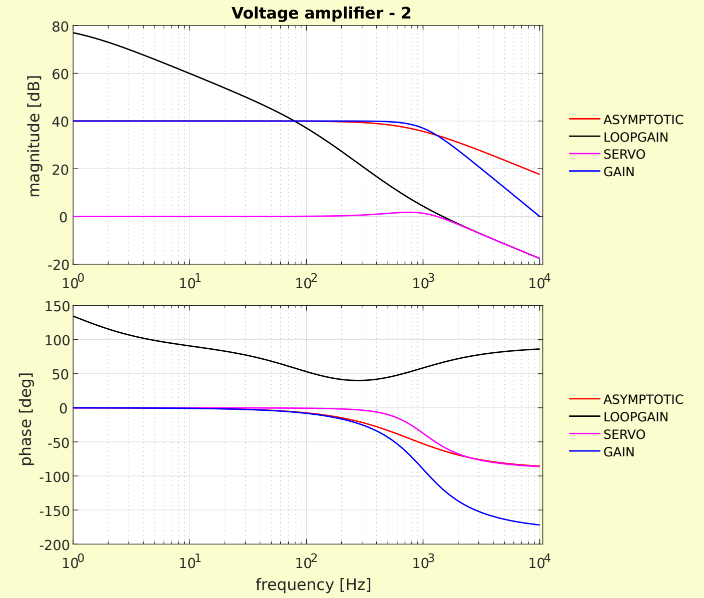
phantom zero changes the first order coefficient of s

second-order MFM if: $S'(s) = \frac{1}{1+s\frac{\sqrt{2}}{\omega_h}+\frac{s^2}{\omega_h^2}} \rightarrow z = -\frac{\omega_h^2}{\sqrt{2}\omega_h+p_1+p_2}$

Note: After compensation the servo function itself is not an MFM function because it has a zero. This zero however, is not visible in the gain. Hence, the high-frequency roll-off of the gain with respect to the ideal gain has an MFM characteristic.







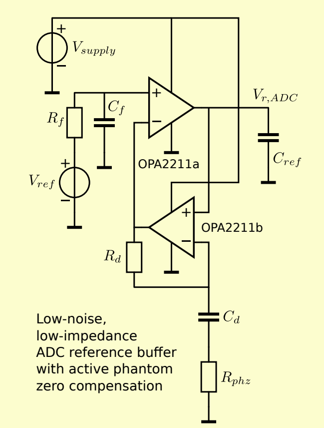
Second order phantom zero MFM compensation
- No compensation required if absolute value of the sum of the poles equals two times the bandwidth
- Passive negative zero can only increase the absolute value of the sum of the poles

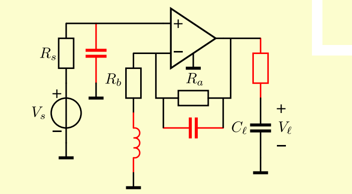
Third order phantom zero MFM compensation
- No compensation required if:
  * Absolute value of the sum of the poles equals the achievable bandwidth times the square root of two
  * Sum of the products of two poles equals two times the squared achievable bandwidth
- One phantom zero if:
  * Absolute value of the sum of the poles equals two times the achievable bandwidth
  * Sum of the products of two poles is less than two times the squared achievable bandwidth
- Two (real or complex conjugated) phantom zeros if:
  * Absolute value of the sum of the poles is less than two times the achievable bandwidth
  * Sum of the products of two poles is less than two times the squared achievable bandwidth

Implementation of phantom zeros

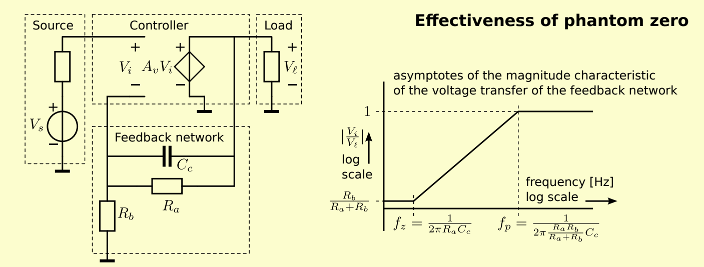
Passive phantom zeros
Reduction of an existing attenuation in the loop for frequencies above the frequency of the zero
1. Design pole in the ideal gain:
   - The ideal gain cannot be changed through modification of the controller!
   - A pole in the ideal gain can be established through insertion of a
     * pole in transfer from source to the input of the amplifier
     * pole in transfer from the output of the amplifier to the load
     * zero in transfer of the feedback network
2. Evaluate if this pole establishes an **effective** zero in the loop gain.
   This is the case if it increases the loop gain at frequencies above the frequency of the zero:
   - It should not introduce a new dominant pole
   - it should not significantly change the frequency of a dominant pole

Active phantom zeros
Direct implementation of the concept
- If a passive implementation is not possible
- Active differentiating network in the feedback path
- Poles of active circuit must not be dominant.



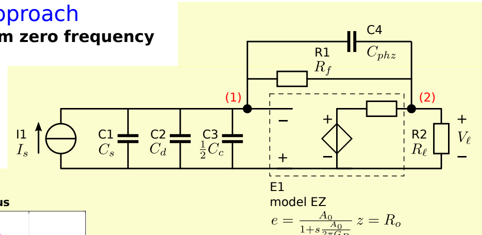


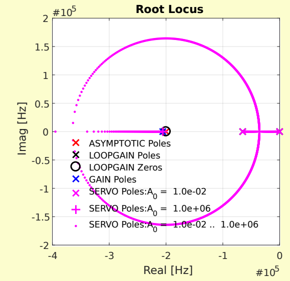
Possible phantom zero implementations in a voltage amplifier with resistive source capacitive load and resistive feedback



Bandwidth limitation with phantom zero

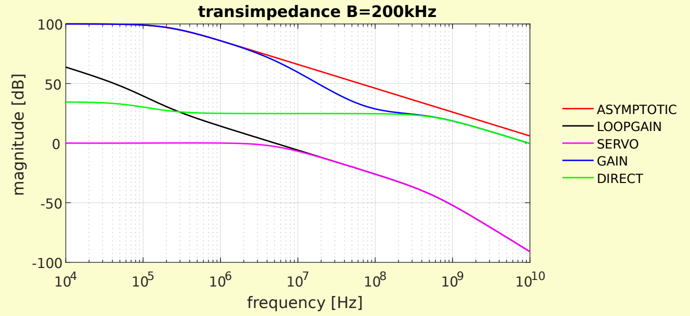
Active filter design approach
High loop gain at phantom zero frequency
- A pole of the loop gain tends to coincide with the phantom zero
- This pole appears in the transfer of the amplifier





If the loop gain at the frequency of the phantom zero is much larger than unity, the bandwidth of the ideal gain is fixed by the phantom zero. This is because one of the poles of the servo function then approximately coincides with the phantom zero (this follows from the root-locus). The phantom zero itself is not observable in the gain because it coincides with the pole in the ideal transfer.

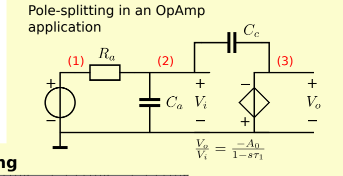
Note: The phantom zero capacitance increases the direct transfer.

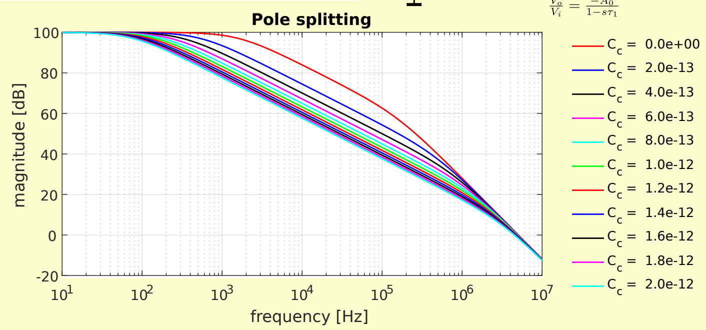


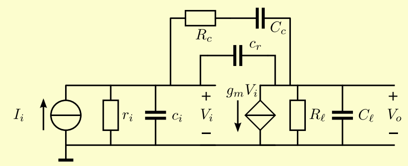
Pole splitting

Pole-splitting by changing the interaction between two poles
Uses local negative feedback and replaces over-all with local loop gain

1. Transistor-level implementation is known as Miller compensation (Miller effect)
2. Causes positive zero if local feedback capacitance contributes to direct transfer
   - Can be compensated for with impedance in series with feedback capacitor
     * Adds another pole



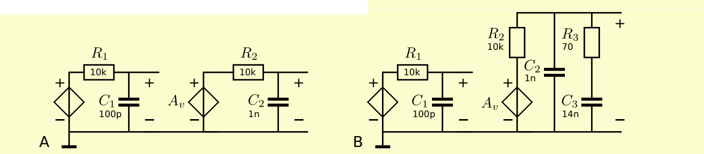




Pole-splitting or "Miller compensation" by increasing the reverse transfer capacitance c_r with C_c
R_c eliminates the influence of C_c on the direct transfer (positive zero)

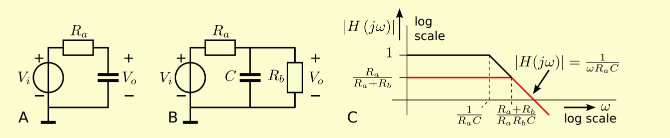
$R_c = \frac{1}{g_m}$

Pole splitting through pole-zero canceling
Reduction of loop gain in frequency range between the split poles
1. Brute-force technique
   - Dominant impedances in parallel with the signal path
2. Detrimental to almost all other performance aspects
   - At the input port: noise
   - At the output port: power efficiency
   - Reduction of loop gain: inaccuracy and distortion
   - Energy storage: overdrive recovery



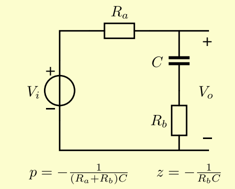
Resistive broadbanding

Exchanging gain for bandwidth
Brute-force technique: detrimental to almost all other performance aspects
- At the input port: noise
- At the output port: power efficiency
- Reduction of loop gain: inaccuracy and distortion



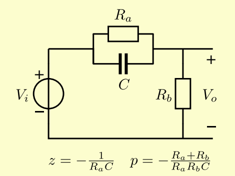
Lag and lead phase compensation

Compensation with focus on phase-margin improvement only
No clear filter characteristic as design objective; solely stability
- No unique relation between phase margin and magnitude/phase/delay characteristic
- No unique relation between phase margin and step response



$p = -\frac{1}{(R_a+R_b)C}$ $z = -\frac{1}{R_bC}$

Phase lag network:
Absolute frequency of the pole below that of the zero.
Looks like network for pole-zero canceling

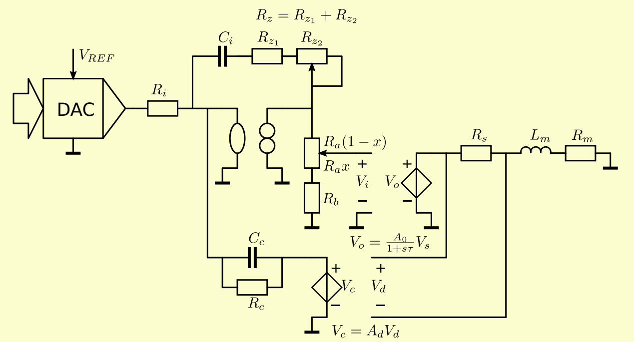


$z = -\frac{1}{R_aC}$ $p = -\frac{R_a+R_b}{R_aR_bC}$

Phase lead network:
Absolute frequency of the pole above that of the zero.
Looks like network for phantom zero implementation

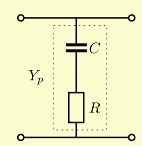
Nested control

Controllers for low-frequency power amplifiers and converters
Controller with negative feedback integrators, differentiators and amplifiers
- If the bandwidth of system to be controlled (plant) is much less than the bandwidth of the technology in which the controller is realized:
  * Dominant poles fixed by means of negative feedback
  * Analog PID controllers



Compensation for failure modes
If the source or the load is disconnected from a feedback amplifier, or if it is shorted:
- The loop gain may change significantly and the amplifier may become instable
- Oscillations should not result in excessive dissipation and damage the amplifier.

Failure condition: disconnected source or load
An amplifier is stable for all port termination admittances if the real part of the port admittance is positive at all frequencies

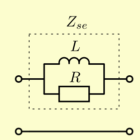


$\mathrm{Re}(Y_p) = \frac{1}{R}\frac{R^2C^2\omega^2}{1+R^2C^2\omega^2}$

Effective compensation for:

$\omega > \frac{1}{RC}$

Failure condition: shorted source or load
An amplifier is stable for all port termination impedances if the real part of the port impedance is positive at all frequencies



$\mathrm{Re}(Z_{sc}) = R\frac{\frac{L^2}{R^2}\omega^2}{1+\frac{L^2}{R^2}\omega^2}$

Effective compensation for:

$\omega > \frac{R}{L}$

Note: The sign of the real part of an impedance equals the sign of the real part of the equivalent admittance.