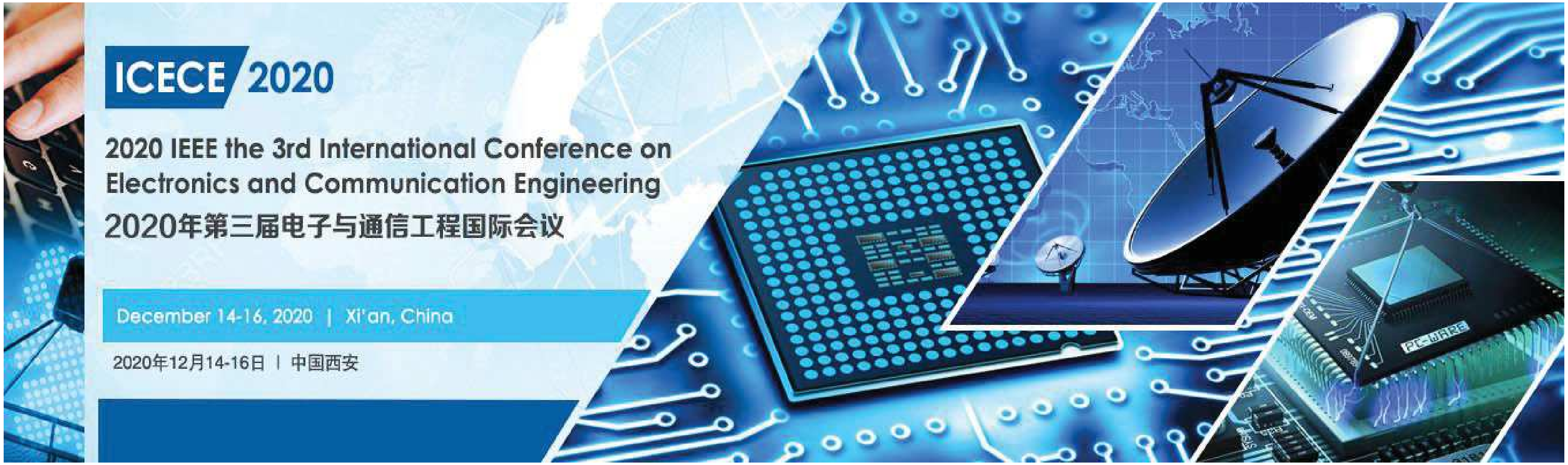

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Study of Behaviors of Electronic Amplifiers using Nichols Chart

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Outline

1. Research Background

- Motivation, objectives and achievements
- Self-loop function in a transfer function

2. Analysis of Behaviors of High-order Systems

- Operating regions of high-order systems

3. Ringing Test for Feedback Amplifiers

- Stability test for shunt-shunt feedback amplifiers
- Stability test for unity-gain and inverting amplifiers

4. Ringing Test for High-order Low-Pass Filters

- Stability test for passive and active RLC circuits
- Stability test for Deboo low-pass filters

5. Conclusions

1. Research Background

Noise in Electronic Systems

Performance of a system

Signal to Noise Ratio:

$$\mathrm{SNR} = \frac{\text{Signal power}}{\text{Noise power}}$$

Performance of a device

Figure of Merit:

$$\mathrm{F} = \frac{\text{Output SNR}}{\text{Input SNR}}$$

Common types of noise:

- Electronic noise, thermal noise, intermodulation noise, cross-talk, flicker noise, thermal noise...

Ringing does the following things:

- Causes EMI noise,
- Increases current flow,
- Decreases the performance, and
- Damages the devices.

Unstable system

↓

STABILITY TEST

1. Research Background

Objectives of Study

- Derivation of self-loop function based on the proposed comparison measurement
- Investigation of operating regions of linear negative feedback networks
- Observation of phase margin at unity gain on the Nichols chart

→ Over-damping (high delay in rising time)

→ Critical damping (max power propagation)

→ Under-damping (overshoot and ringing)

1. Research Background

Achievements of Study

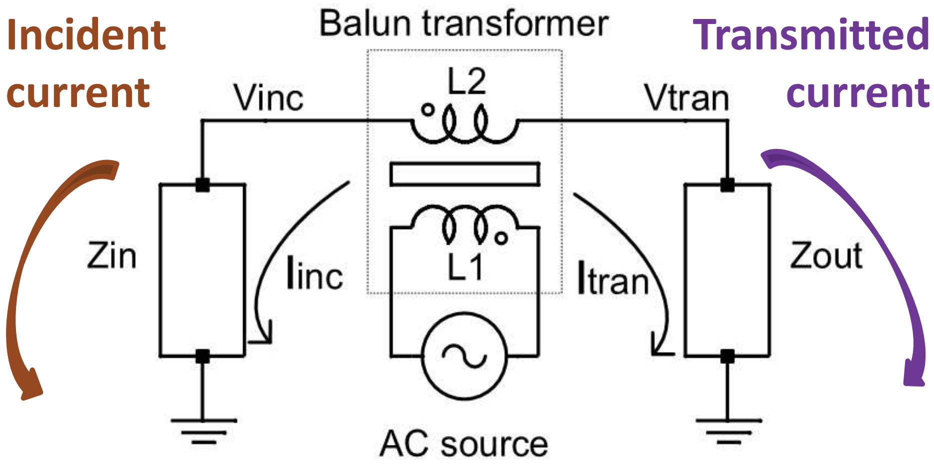
Comparison measurement

- **Feedback amplifiers**
- **High-order low-pass filters**

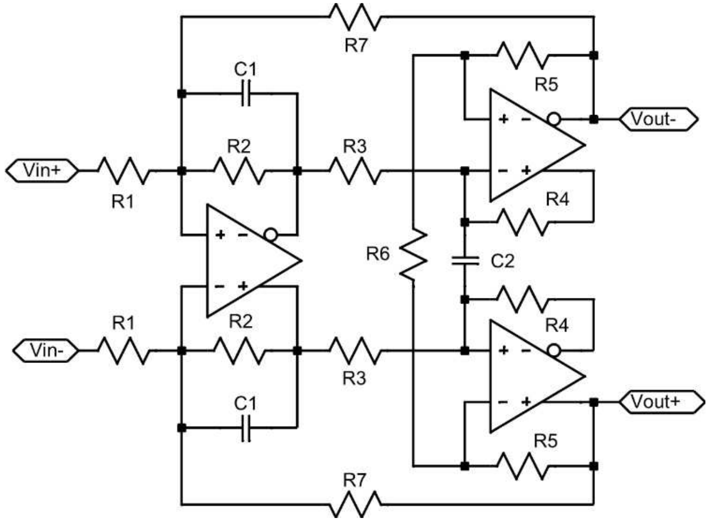
Self-loop function

$$L(\omega) = \frac{A(\omega)}{H(\omega)} - 1$$

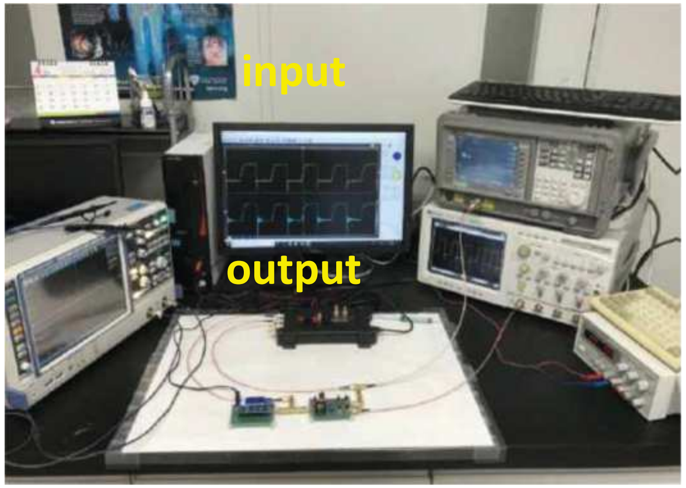
Alternating current conservation



2nd-order Deboo low-pass LPF



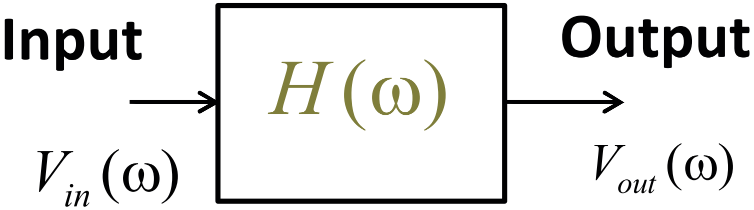
Implemented circuit



1. Research Background

Self-loop Function in A Transfer Function

Linear system



Model of a linear system

$$H(\omega) = \frac{b_0(j\omega)^n + \ldots + b_{n-1}(j\omega) + b_n}{a_0(j\omega)^n + \ldots + a_{n-1}(j\omega) + a_n}$$

Transfer function

$$H(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)} = \frac{A(\omega)}{1 + L(\omega)}$$

$A(\omega)$ **: Numerator function**

$H(\omega)$ **: Transfer function**

$L(\omega)$ **: Self-loop function**

Variable: angular frequency (ω)

- ○ **Polar chart → Nyquist chart**
- ○ **Magnitude-frequency plot**
- ○ **Angular-frequency plot**

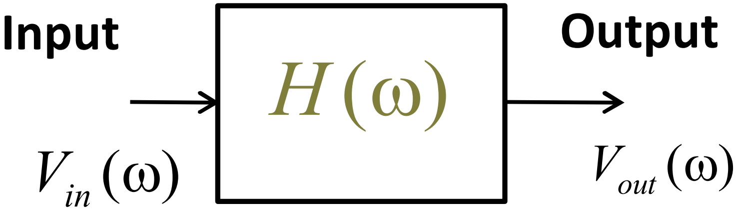
$\left.\begin{array}{l}\text{Magnitude-frequency plot}\\\text{Angular-frequency plot}\end{array}\right\}$ **Bode plots**

- ○ **Magnitude-angular diagram → Nichols diagram**

1. Research Background

Comparison Measurement

Linear system



Model of a linear system

$$H(\omega) = \frac{b_0(j\omega)^n + \ldots + b_{n-1}(j\omega) + b_n}{a_0(j\omega)^n + \ldots + a_{n-1}(j\omega) + a_n}$$

Transfer function

$$H(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)} = \frac{A(\omega)}{1 + L(\omega)}$$

Sequence of steps:

(i) Measurement of numerator function A(ω),

(ii) Measurement of transfer function H(ω), and

(iii) Derivation of self-loop function.

Self-loop function

$$\boxed{L(\omega) = \frac{A(\omega)}{H(\omega)} - 1}$$

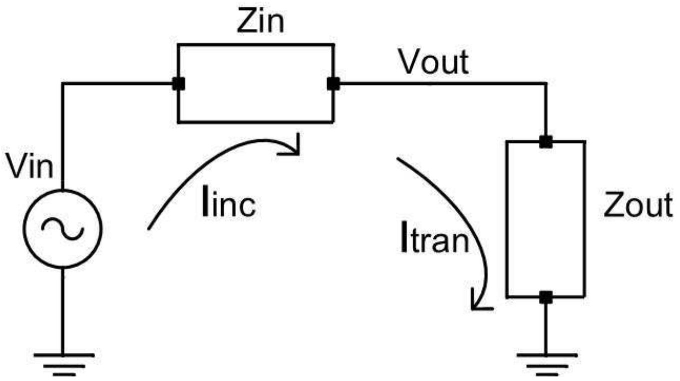
1. Research Background

Alternating Current Conservation

Transfer function

$$H(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)} = \frac{1}{1+\frac{Z_{in}}{Z_{out}}}$$

$$\Rightarrow \boxed{L(\omega) = \frac{Z_{in}}{Z_{out}};}$$



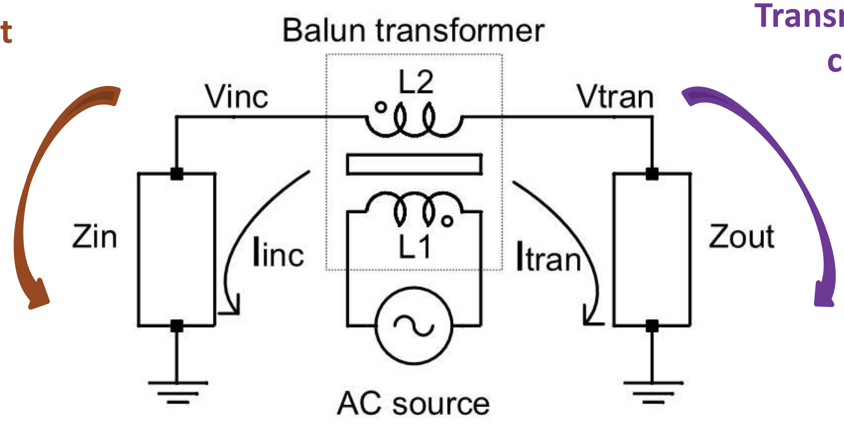
Simplified linear system

Self-loop function

$$\frac{V_{inc}}{Z_{in}} = -\frac{V_{trans}}{Z_{out}} \Rightarrow \boxed{L(\omega) = -\frac{V_{inc}}{V_{trans}} = \frac{Z_{in}}{Z_{out}}}$$

10 mH inductance

Incident current



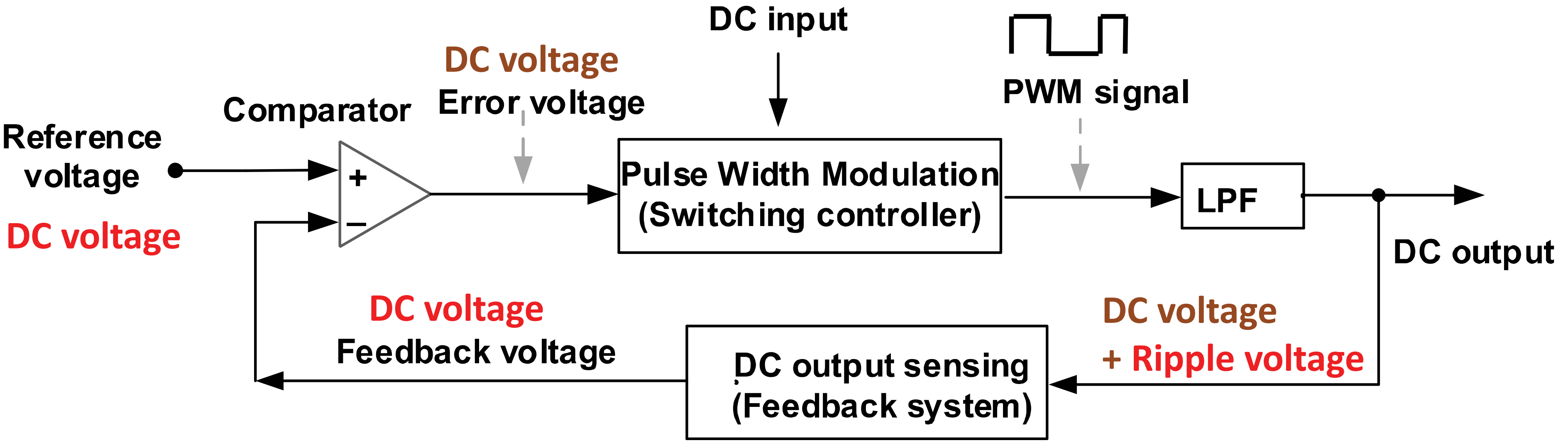
Transmitted current

Derivation of self-loop function

1. Research Background

Characteristics of Adaptive Feedback Network

Block diagram of a typical adaptive feedback system



Adaptive feedback is used to control the output source along with the decision source (DC-DC Buck converter).

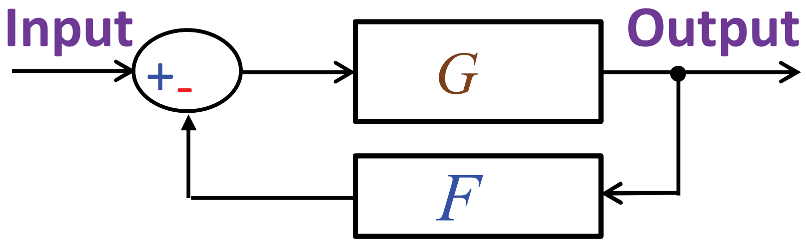
Transfer function of an adaptive feedback network is significantly different from transfer function of a linear negative feedback network.

→ Loop gain is independent of frequency variable (referent voltage, feedback voltage, and error voltage are DC voltages).

1. Research Background

Loop Gain in Feedback Systems

Adaptive feedback systems

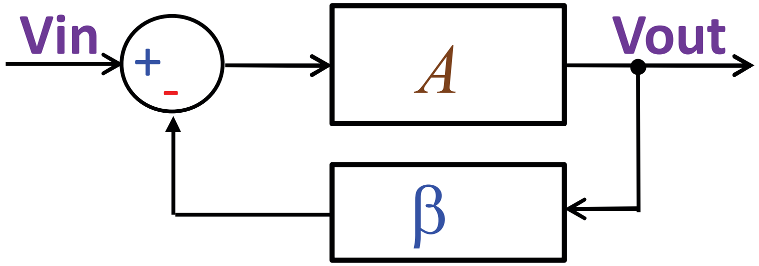


Transfer function

GF : loop gain

$$H = \frac{G}{1+GF} \approx 1$$

Inverting amplifier

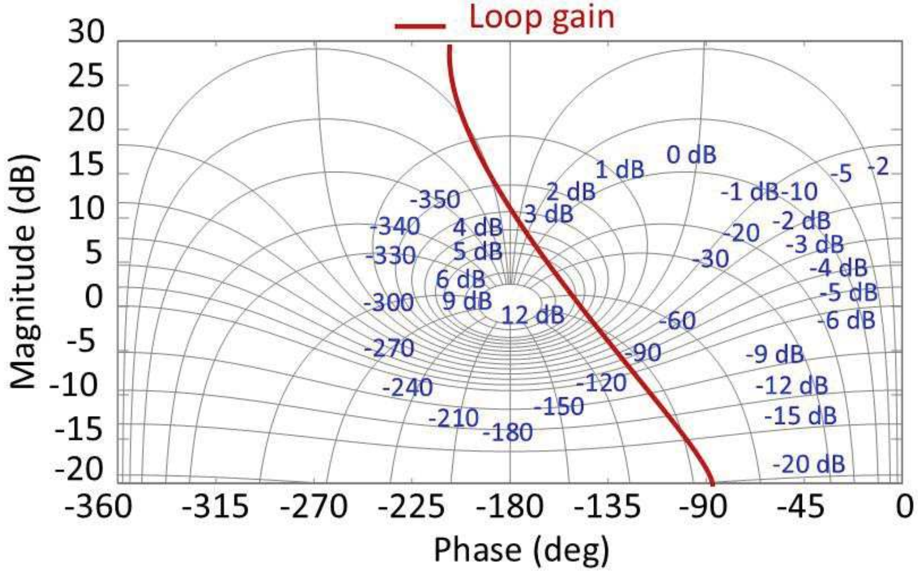


Transfer function

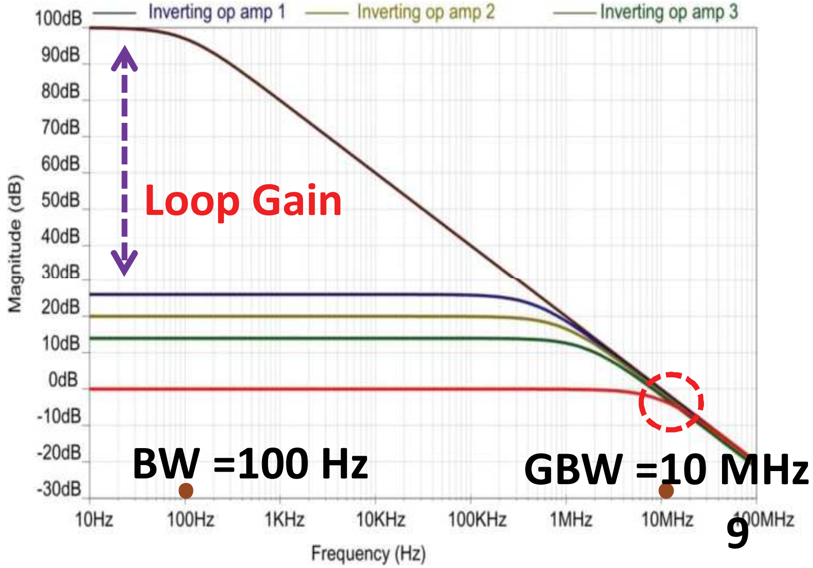
Aβ : loop gain

$$H = \frac{A}{1+A\beta} \approx \frac{1}{\beta}$$

Nichols plot of loop gain



Gain reduction



Outline

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2. **Analysis of Behaviors of High-order Systems**
   - **Operating regions of high-order systems**
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5. Conclusions

2. Analysis of Behaviors of High-order Systems

Characteristics of 2^{nd}-order Transfer Function

Second-order transfer function: $H(\omega) = \dfrac{1}{1 + a_0 (j\omega)^2 + a_1 j\omega}$

Case	Over-damping	Critical damping	Under-damping
Delta (Δ)	$\frac{1}{a_0} < \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^{\ 2} - 4a_0 > 0$	$\frac{1}{a_0} = \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^{\ 2} - 4a_0 = 0$	$\frac{1}{a_0} > \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^{\ 2} - 4a_0 < 0$
Module $\lvert H(\omega)\rvert$	$\dfrac{\frac{1}{a_0}}{\sqrt{\omega^2 + \left(\frac{a_1}{2a_0} - \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}\right)^2}\sqrt{\omega^2 + \left(\frac{a_1}{2a_0} + \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}\right)^2}}$	$\boxed{\frac{1}{a_0}\frac{1}{\left[\omega^2 + \left(\frac{a_1}{2a_0}\right)^2\right]} = \frac{1}{2} = -6dB}$	$\dfrac{\frac{1}{a_0}}{\sqrt{\left(\omega - \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}\right)^2 + \left(\frac{a_1}{2a_0}\right)^2}\sqrt{\left(\omega + \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}\right)^2 + \left(\frac{a_1}{2a_0}\right)^2}}$
Angular $\theta(\omega)$	$-\arctan\left(\dfrac{\omega}{\frac{a_1}{2a_0} - \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}}\right) - \arctan\left(\dfrac{\omega}{\frac{a_1}{2a_0} + \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}}\right)$	$-2\arctan\left(\dfrac{2a_0\omega}{a_1}\right)$	$-\arctan\left(\dfrac{\omega - \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}}{\frac{a_1}{2a_0}}\right) - \arctan\left(\dfrac{\omega + \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}}{\frac{a_1}{2a_0}}\right)$
$\omega_{cut} = \dfrac{a_1}{2a_0}$	$\lvert H(\omega_{cut})\rvert < \dfrac{2a_0}{a_1}$ $\theta(\omega_{cut}) > -\dfrac{\pi}{2}$	$\lvert H(\omega_{cut})\rvert = \dfrac{2a_0}{a_1}$ $\theta(\omega_{cut}) = -\dfrac{\pi}{2}$	$\lvert H(\omega_{cut})\rvert > \dfrac{2a_0}{a_1}$ $\theta(\omega_{cut}) < -\dfrac{\pi}{2}$

2. Analysis of Behaviors of High-order Systems

Characteristics of 2nd-order Self-loop Function

Second-order self-loop function: $L(\omega) = j\omega\left[a_0 j\omega + a_1\right]$

Case	Over-damping		Critical damping		Under-damping	
Delta (Δ)	$\Delta = a_1^2 - 4a_0 > 0$		$\Delta = a_1^2 - 4a_0 = 0$		$\Delta = a_1^2 - 4a_0 < 0$	
$\lvert L(\omega)\rvert$	$\omega\sqrt{(a_0\omega)^2 + a_1^2}$		$\omega\sqrt{(a_0\omega)^2 + a_1^2}$		$\omega\sqrt{(a_0\omega)^2 + a_1^2}$	
$\theta(\omega)$	$\frac{\pi}{2} + \arctan\frac{a_0\omega}{a_1}$		$\frac{\pi}{2} + \arctan\frac{a_0\omega}{a_1}$		$\frac{\pi}{2} + \arctan\frac{a_0\omega}{a_1}$	
$\omega_1 = \frac{a_1}{2a_0}\sqrt{\sqrt{5}-2}$	$\lvert L(\omega_1)\rvert > 1$	$\pi - \theta(\omega_1) > 76.3^o$	$\lvert L(\omega_1)\rvert = 1$	$\pi - \theta(\omega_1) = 76.3^o$	$\lvert L(\omega_1)\rvert < 1$	$\pi - \theta(\omega_1) < 76.3^o$
$\omega_2 = \frac{a_1}{2a_0}$	$\lvert L(\omega_2)\rvert > \sqrt{5}$	$\pi - \theta(\omega_2) > 63.4^o$	$\lvert L(\omega_2)\rvert = \sqrt{5}$	$\pi - \theta(\omega_2) = 63.4^o$	$\lvert L(\omega_2)\rvert < \sqrt{5}$	$\pi - \theta(\omega_2) < 63.4^o$
$\omega_3 = \frac{a_1}{a_0}$	$\lvert L(\omega_3)\rvert > 4\sqrt{2}$	$\pi - \theta(\omega_3) > 45^o$	$\lvert L(\omega_3)\rvert = 4\sqrt{2}$	$\pi - \theta(\omega_3) = 45^o$	$\lvert L(\omega_3)\rvert < 4\sqrt{2}$	$\pi - \theta(\omega_3) < 45^o$

2. Analysis of Behaviors of High-order Systems

Operating Regions of 2nd-Order System

- **Under-damping:**

$$L_1(\omega) = (j\omega)^2 + j\omega;$$

$$H_1(\omega) = \frac{1}{(j\omega)^2 + j\omega + 1};$$

- **Critical damping:**

$$H_2(\omega) = \frac{1}{(j\omega)^2 + 2j\omega + 1};$$

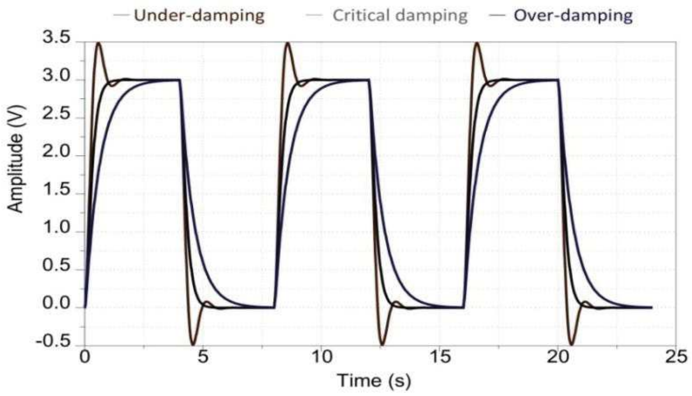
$$L_2(\omega) = (j\omega)^2 + 2j\omega;$$

- **Over-damping:**

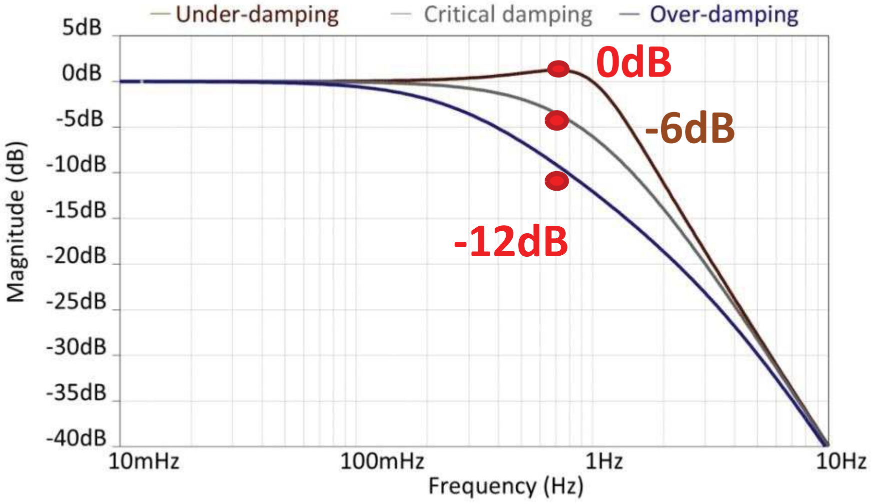
$$H_3(\omega) = \frac{1}{(j\omega)^2 + 3j\omega + 1};$$

$$L_3(\omega) = (j\omega)^2 + 3j\omega;$$

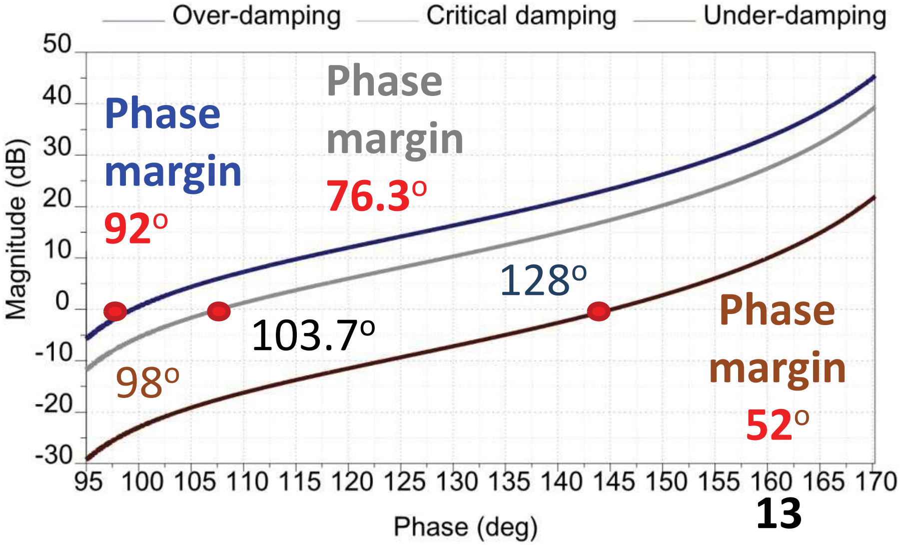
Transient response



Bode plot of transfer function



Nichols plot of self-loop function



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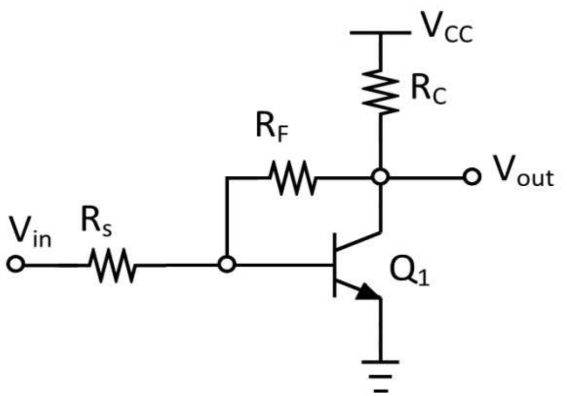
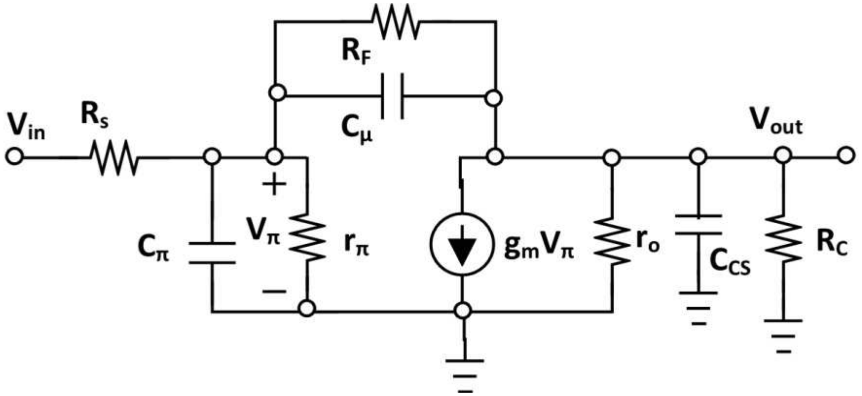
3.Ringing Test for Feedback Amplifiers

Analysis of Shunt-Shunt Feedback Amplifier

BJT shunt-shunt feedback amplifier



Small signal model



Apply superposition at the nodes V_π and V_{out}, we have

$$V_\pi\left(\frac{1}{R_s}+\frac{1}{r_\pi}+\frac{1}{Z_{C\pi}}+\frac{1}{R_F}+\frac{1}{Z_{C\mu}}\right)=\frac{V_{in}}{R_s}+\frac{V_{out}}{Z_{C\mu}};\quad V_{out}\left(\frac{1}{Z_{C\mu}}+\frac{1}{Z_{CCS}}+\frac{1}{R_C}+\frac{1}{r_o}\right)=V_\pi\left(\frac{1}{Z_{C\mu}}+\frac{1}{R_F}-g_m\right);$$

Transfer function and self-loop function

$$H(\omega)=\frac{V_{out}}{V_{in}}=\frac{b_0 j\omega+b_1}{a_0(j\omega)^2+a_1 j\omega+1};\quad L(\omega)=j\omega\left[a_0 j\omega+a_1\right]$$

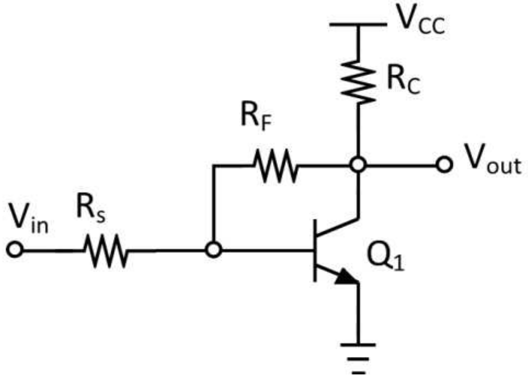
Where, $b_0=R_L C_{GD1};\ b_1=-R_L g_{m1};a_0=R_S R_L\left(C_{GD1}C_{GS1}+C_{GD1}C_{DB1}+C_{DB1}C_{GS1}\right);$

$a_1=R_L\left(C_{GD1}+C_{DB1}\right)+R_S\left(C_{GS1}+C_{GD1}\right)+R_S R_L g_{m1}C_{GD1};$

3.Ringing Test for Feedback Amplifiers

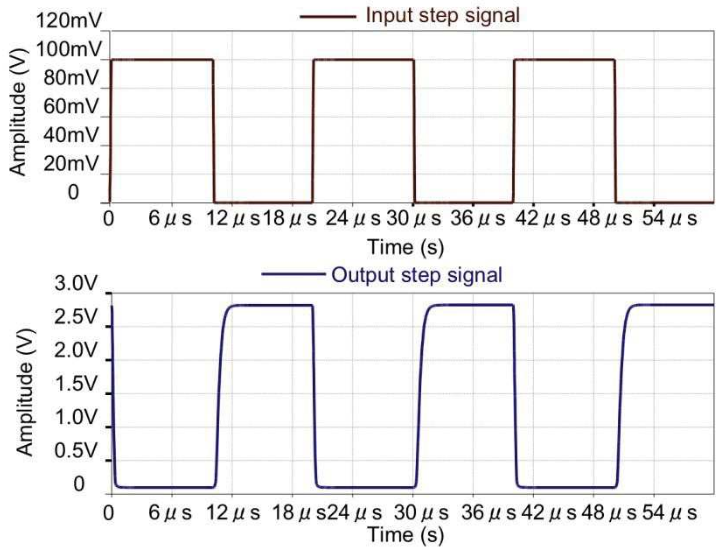
Characteristics of Shunt-Shunt Feedback Amplifier

BJT shunt-shunt feedback amplifier

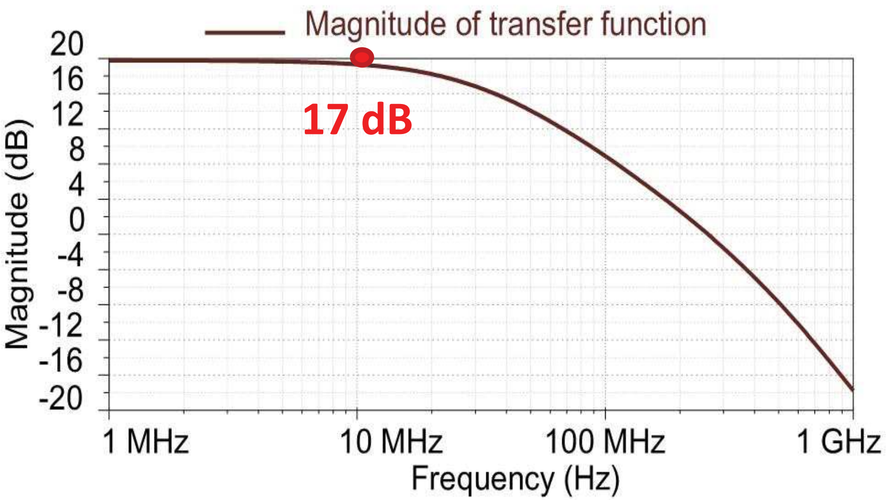


R_f = 1 kΩ, R_C = 10 kΩ, R_S = 950 Ω.

Transient response

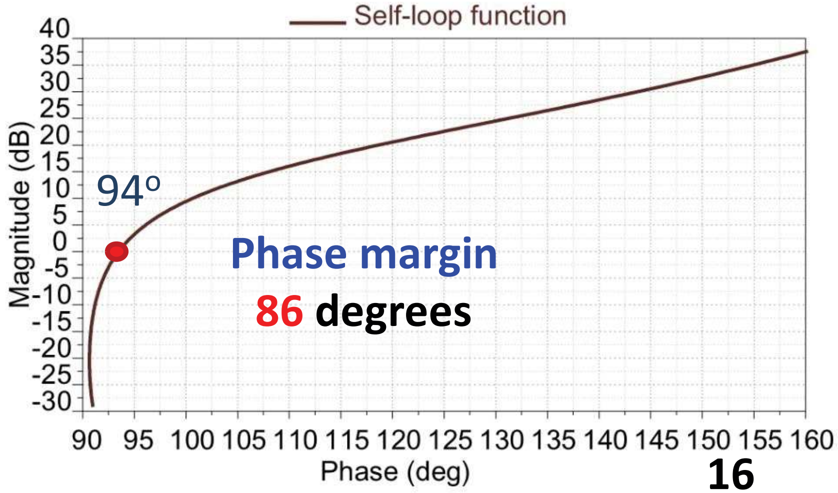


Bode plot of transfer function



17 dB

Nichols plot of self-loop function



94°

Phase margin

86 degrees

3.Ringing Test for Feedback Amplifiers

Analysis of Op Amp without Miller's Capacitor

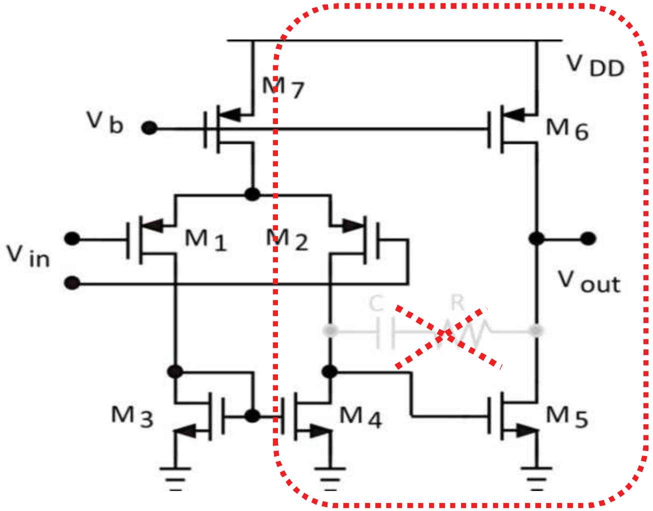
Open-loop function

$$A_{op}(\omega)=\frac{b_0(j\omega)^3+b_1(j\omega)^2+b_2 j\omega+b_3}{a_0(j\omega)^4+a_1(j\omega)^3+a_2(j\omega)^2+a_3 j\omega+1};$$

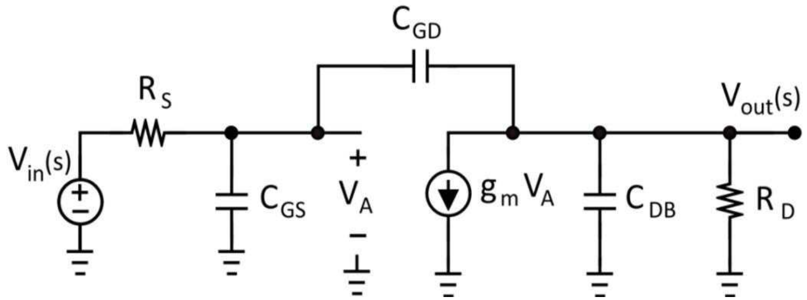
Self-loop function

$$L_{op}(\omega)=a_0(j\omega)^4+a_1(j\omega)^3+a_2(j\omega)^2+a_3 j\omega;$$

Without frequency compensation



Small signal model of 2nd-stage



Transfer function

$$H(\omega)=\frac{b_0 j\omega+b_1}{a_0(j\omega)^2+a_1 j\omega+1};$$

Self-loop function

$$L(\omega)=a_0(j\omega)^2+a_1 j\omega$$

Where, $a_0=R_D C_{GD};\ a_1=-R_D g_m;$

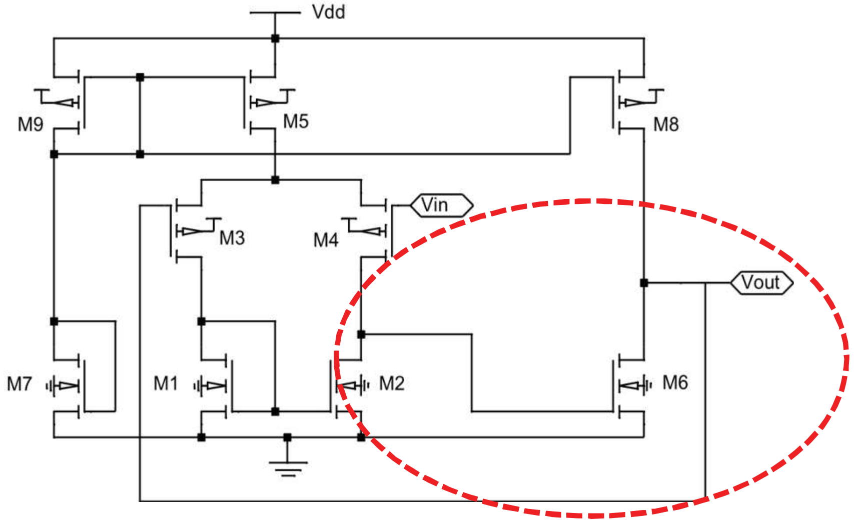
$$b_0=R_D R_S\left[(C_{GD}+C_{DB})(C_{GS}+C_{GD})-C_{GD}^2\right];$$

$$b_1=\left[R_D(C_{GD}+C_{DB})+R_S(C_{GS}+C_{GD})+R_D R_S g_m C_{GD}\right];$$

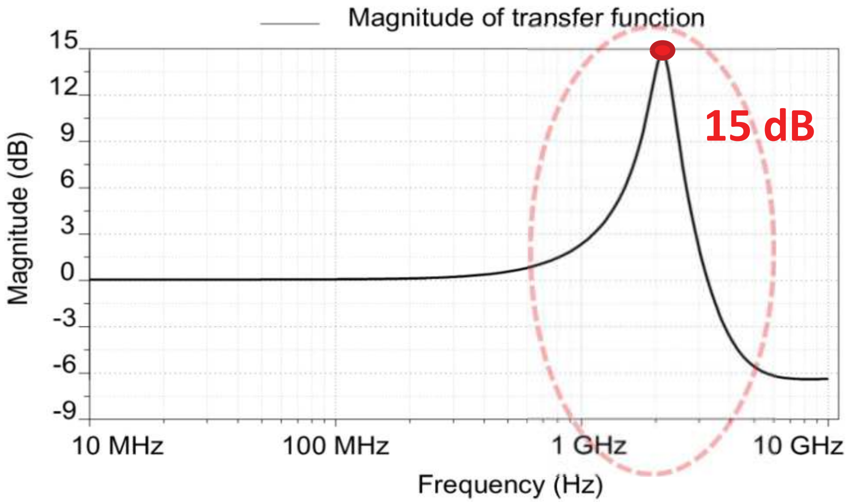
3.Ringing Test for Feedback Amplifiers

Unity-Gain Amplifier without Miller's Capacitor

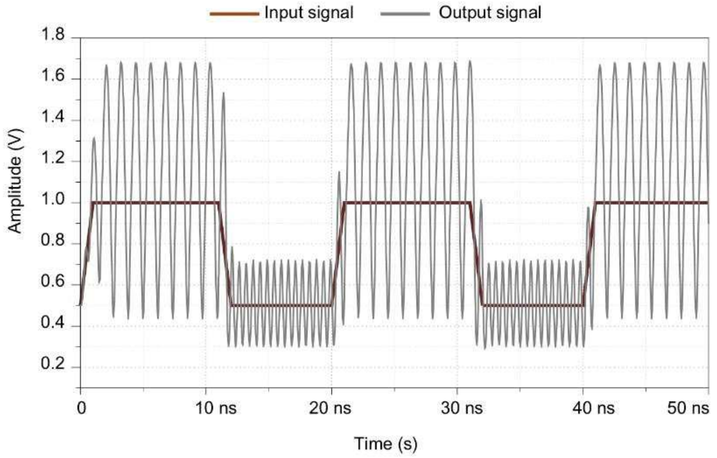
Unity-Gain Amplifier



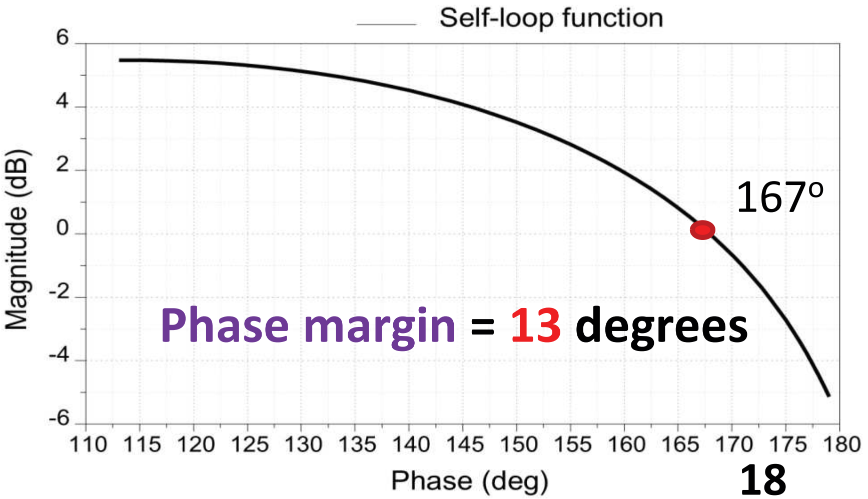
Bode plot of transfer function H(ω)



Transient response



Nichols plot of self-loop function L(ω)



Phase margin = 13 degrees

3.Ringing Test for Feedback Amplifiers

Two-stage Op Amp with Frequency Compensation

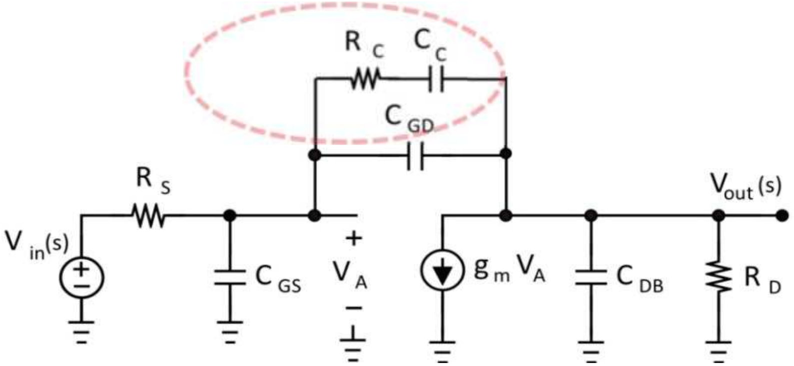
Open-loop function

$$A_{op}(\omega)=\frac{b_0(j\omega)^5+b_1(j\omega)^4+b_2(j\omega)^3+b_3(j\omega)^2+b_4 j\omega+b_5}{a_0(j\omega)^6+a_1(j\omega)^5+a_2(j\omega)^4+a_3(j\omega)^3+a_4(j\omega)^2+a_5 j\omega+1};$$

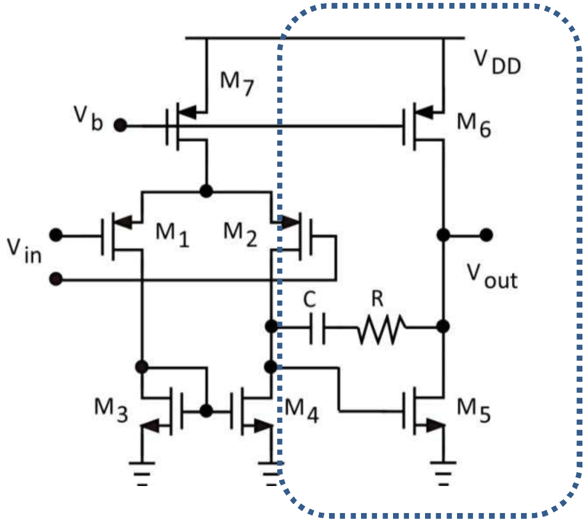
Self-loop function

$$L_{op}(\omega)=a_0(j\omega)^6+a_1(j\omega)^5+a_2(j\omega)^4+a_3(j\omega)^3+a_4(j\omega)^2+a_5 j\omega;$$

Small signal model of 2nd-stage



With Miller's capacitor and resistor



Transfer function

$$H(\omega)=\frac{b_0(j\omega)^3+b_1(j\omega)^2+b_2 j\omega+b_3}{a_0(j\omega)^4+a_1(j\omega)^3+a_2(j\omega)^2+a_3 j\omega+1};$$

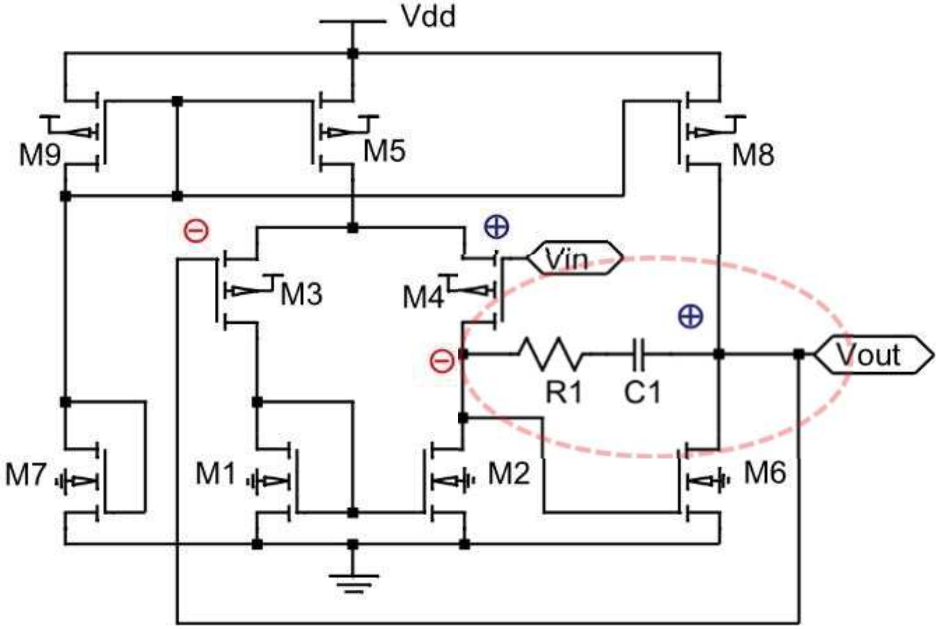
Self-loop function

$$L(\omega)=a_0(j\omega)^4+a_1(j\omega)^3+a_2(j\omega)^2+a_3 j\omega$$

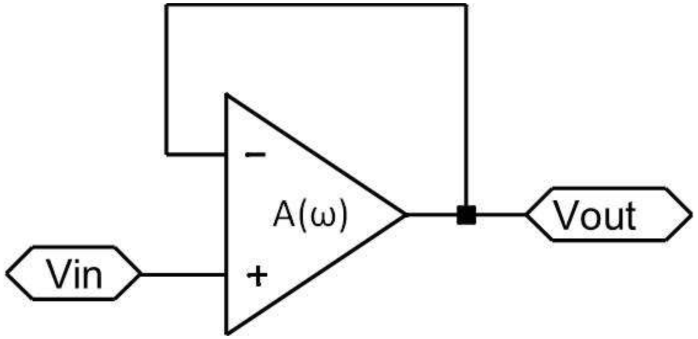
3.Ringing Test for Feedback Amplifiers

Unity-Gain Amplifier with Miller's Capacitor

Unity-gain amplifier with Miller's capacitor



Simplified model



Under-damping:

R1= 2 kΩ, C1 = 1 pF

Critical damping:

R1 = 3.5 kΩ, C1 = 0.2 pF

Over-damping:

R1 = 3.5 kΩ, C1 = 0.8 pF

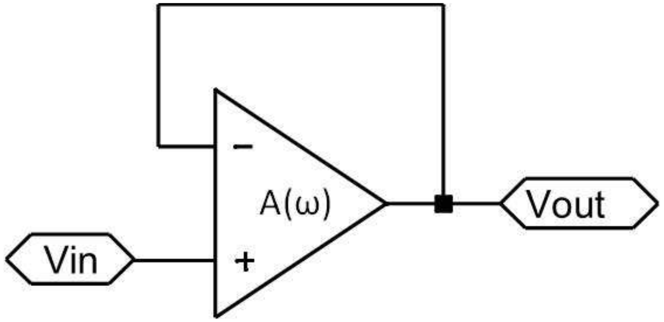
Transfer function and self-loop function

$$H(\omega) = \frac{1}{1+\frac{1}{A(\omega)}} \approx 1; \quad L(\omega) = \frac{1}{A(\omega)};$$

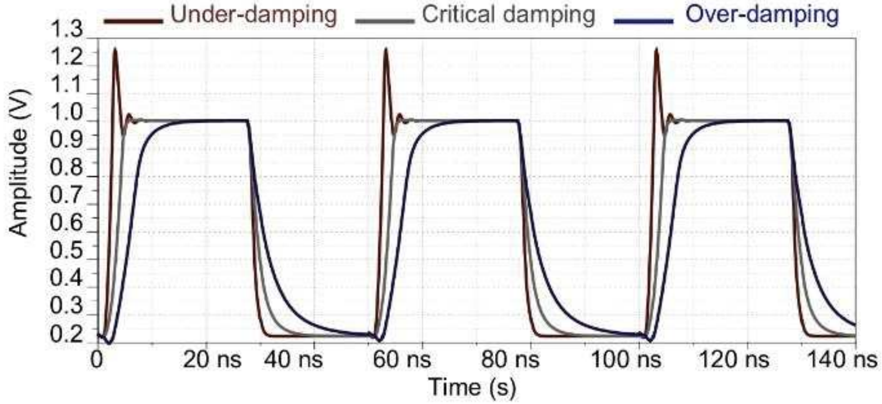
3.Ringing Test for Feedback Amplifiers

Behaviors of Unity-Gain Amplifier

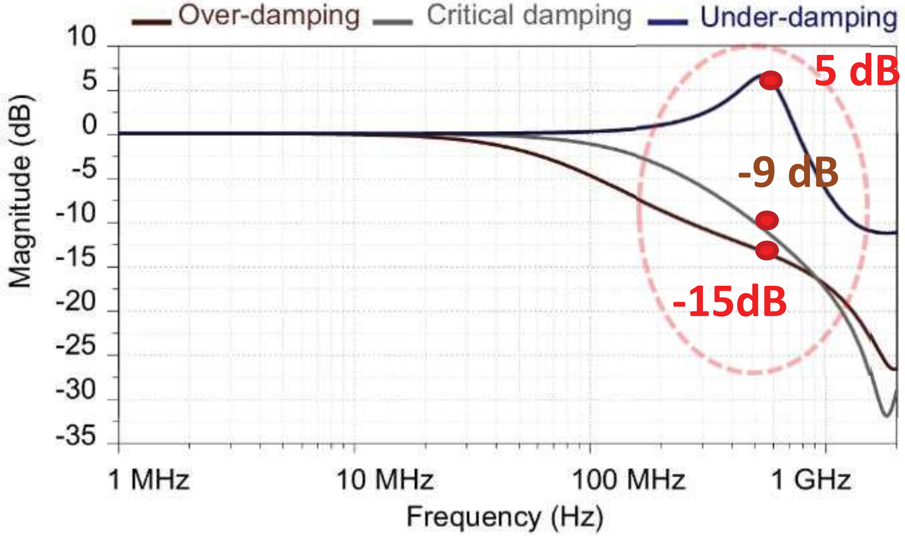
Simplified model of unity gain amplifier



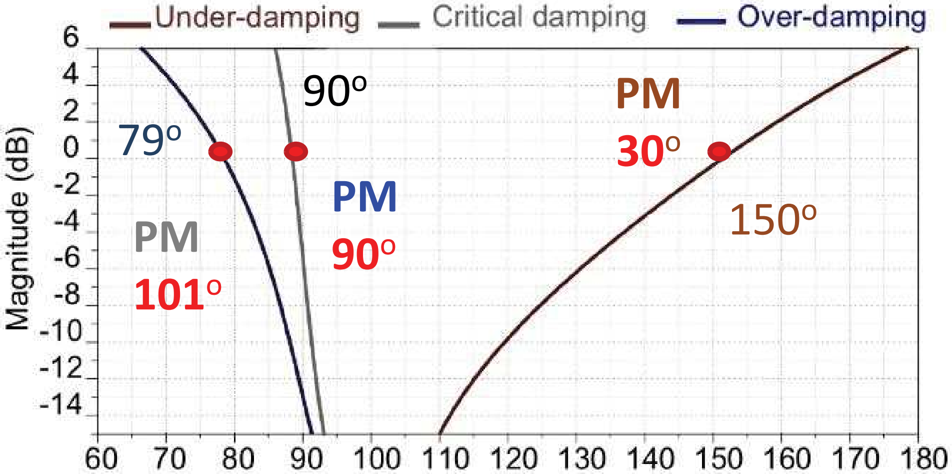
Simulated transient response



Bode plot of transfer function



Nichols plot of self-loop function

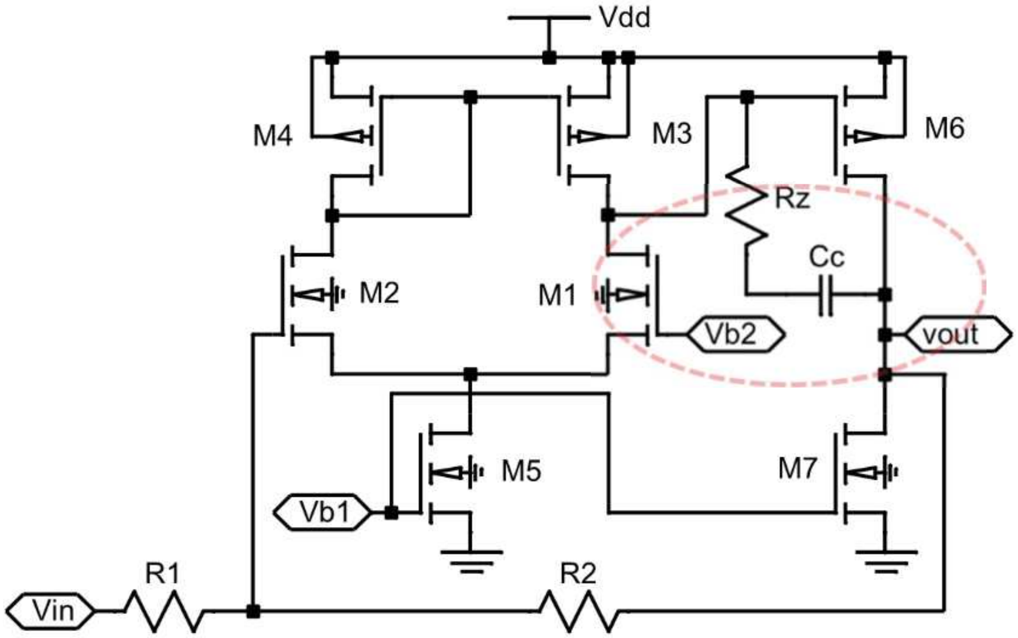


Phase (deg)

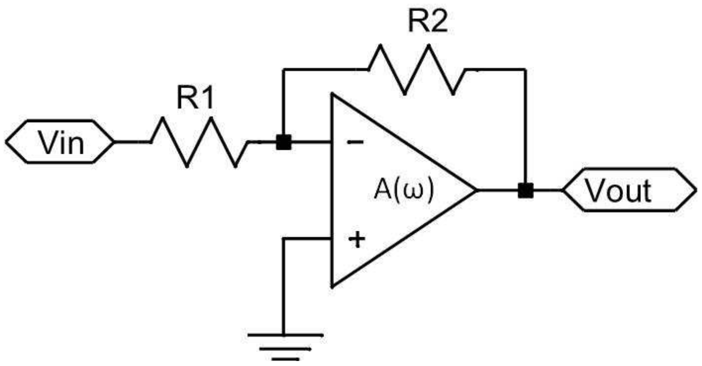
3.Ringing Test for Feedback Amplifiers

Inverting Amplifier with Miller's Capacitor

Inverting amplifier



Simplified model



Under-damping:

Rz= 0 kΩ, Cz = 0 pF

Critical damping:

Rz = 0.5 kΩ, Cz = 0.5 pF

Over-damping:

Rz = 4 kΩ, Cz = 0.5 pF

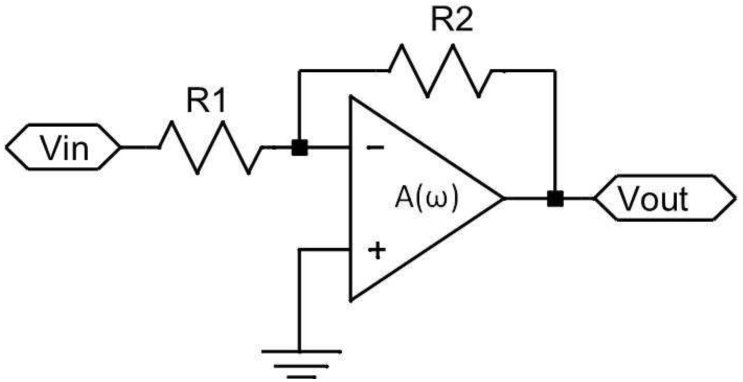
Transfer function and self-loop function

$$H(\omega) = \frac{-\frac{R_2}{R_1}}{1 + L(\omega)} \approx -\frac{R_2}{R_1}; L(\omega) = \frac{1}{A(\omega)}\left(1 + \frac{R_2}{R_1}\right);$$

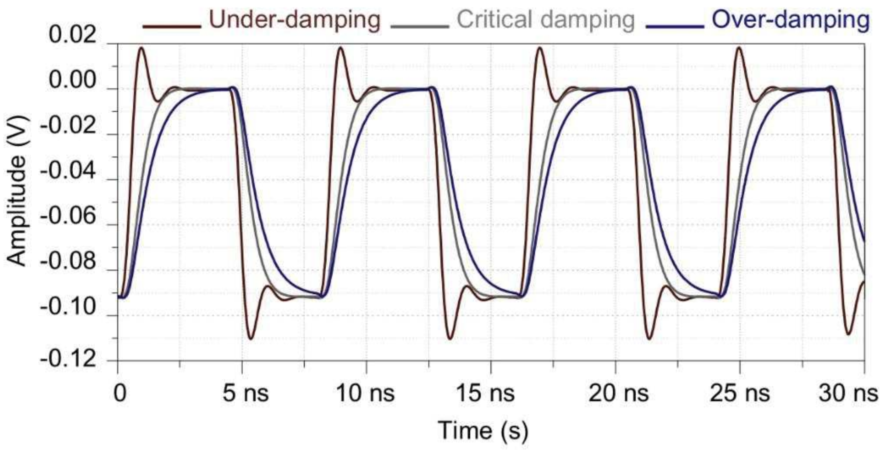
3.Ringing Test for Feedback Amplifiers

Behaviors of Inverting Amplifier

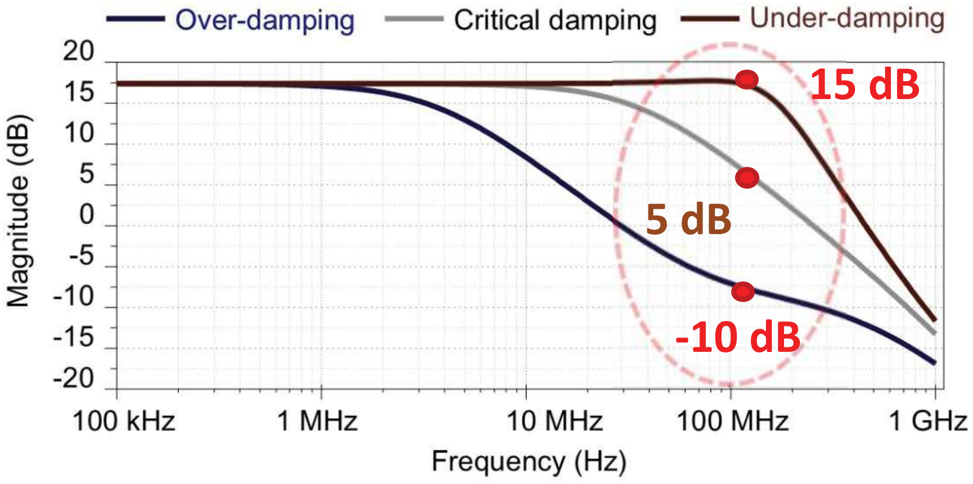
Simplified model of inverting amplifier



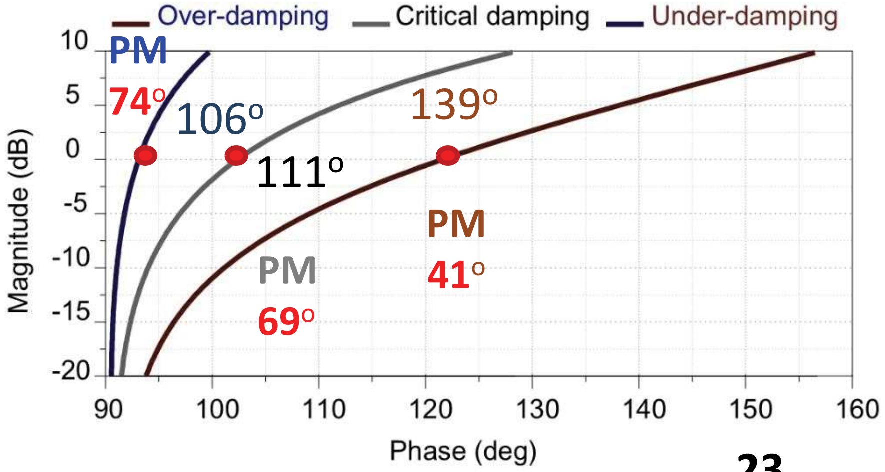
Simulated transient response



Bode plot of transfer function



Nichols plot of self-loop function



Outline

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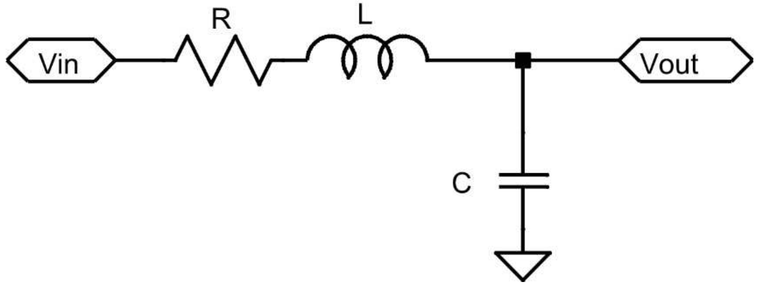
4. **Ringing Test for High-order Low-Pass Filters**
- **Stability test for passive and active RLC circuits**
- **Stability test for Deboo low-pass filters**

5. Conclusions

4. Ringing Test for High-order Low-Pass Filters

Analysis of 2nd-Order Passive RLC LPF

Passive RLC Low-pass Filter



Transfer function

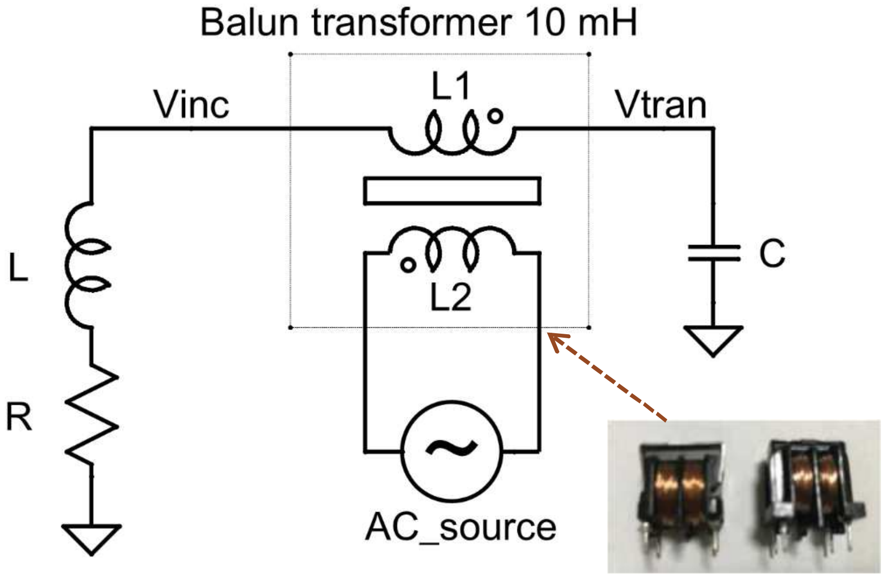
$$H(\omega)=\frac{V_{out}}{V_{in}}=\frac{1}{a_0(j\omega)^2+a_1 j\omega+1};$$

Self-loop function

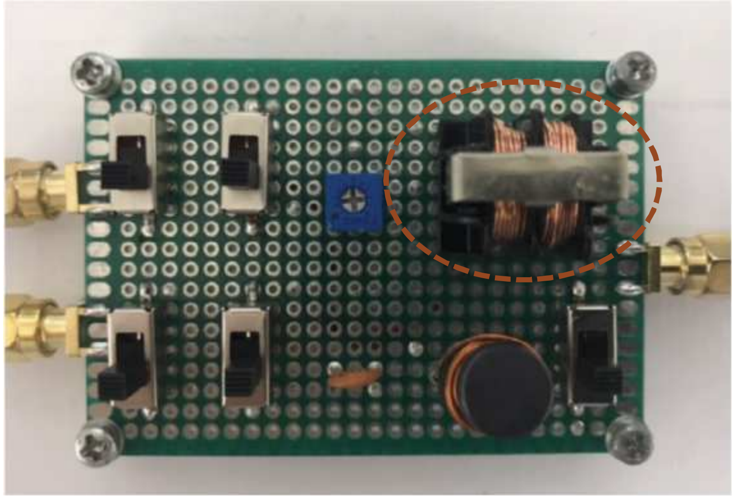
$$L(\omega)=a_0(j\omega)^2+a_1 j\omega;$$

where, $a_0=LC;a_1=RC;$

Derivation of self-loop function



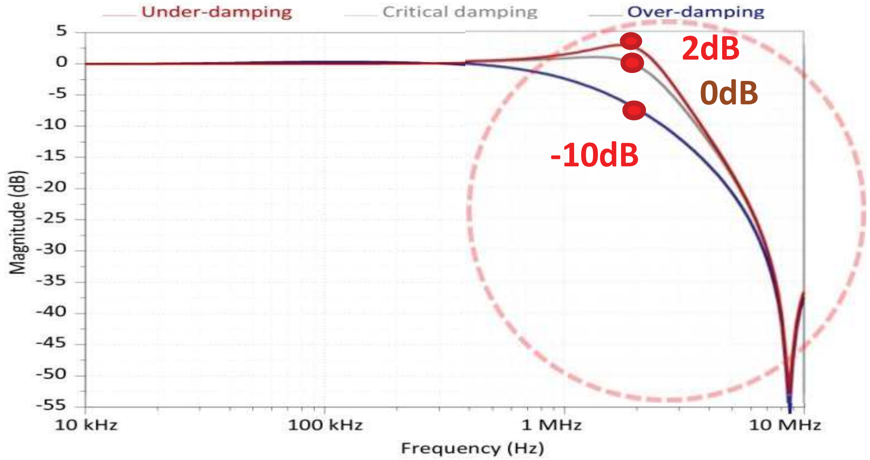
Implemented circuit



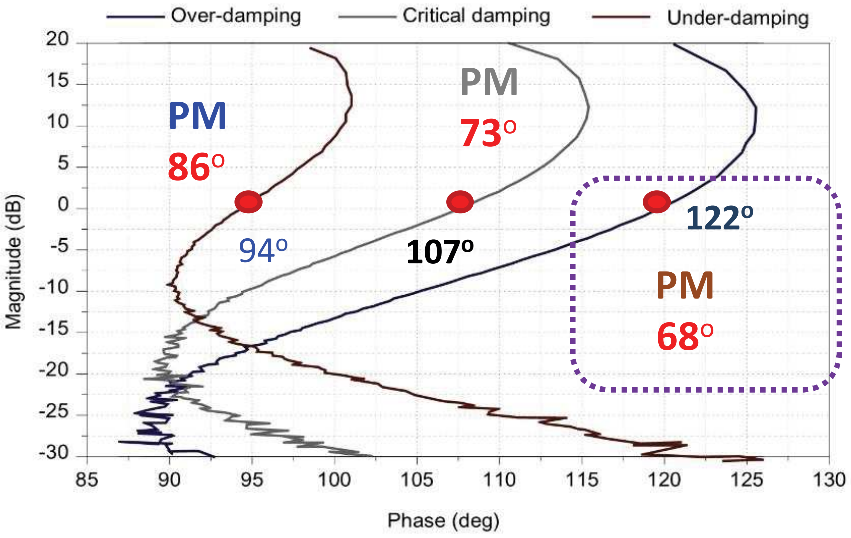
4. Ringing Test for High-order Low-Pass Filters

Measurement Results for 2nd-Order Passive RLC LPF

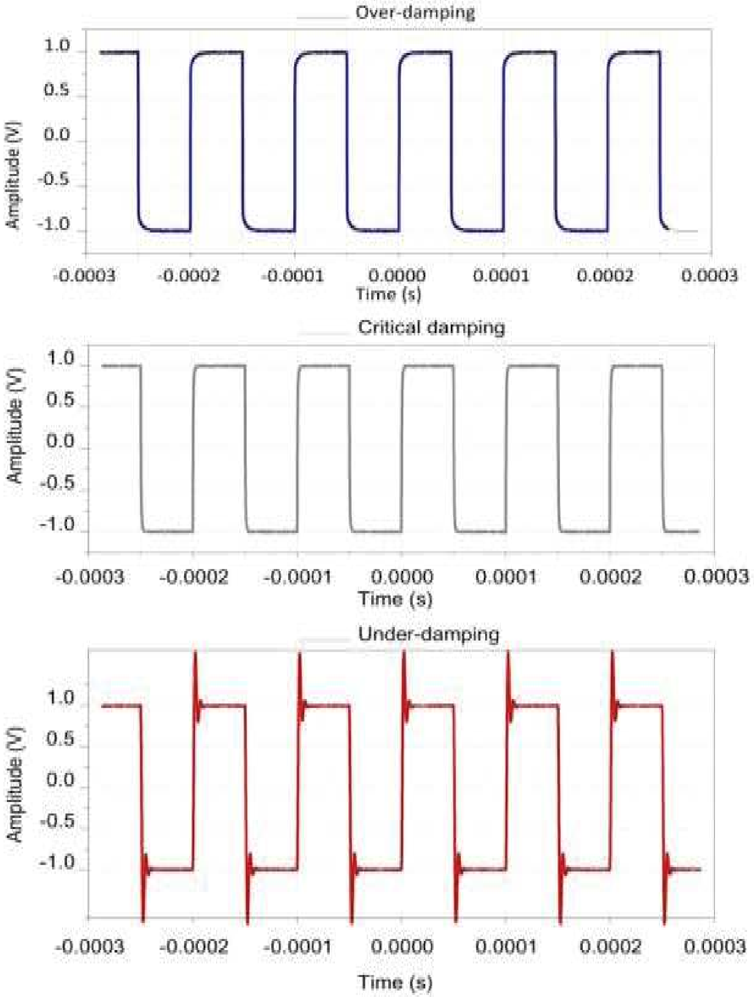
Bode plot of transfer function



Nichols plot of self-loop function



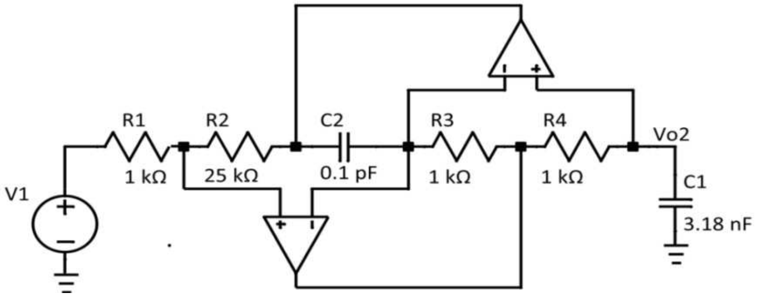
Transient responses



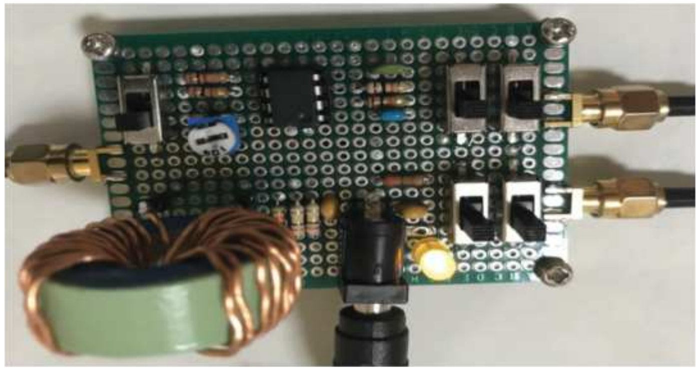
4. Ringing Test for High-order Low-Pass Filters

Stability Test for 2nd-Order Active Ladder LPF

Active ladder low-pass filter



Implemented circuit



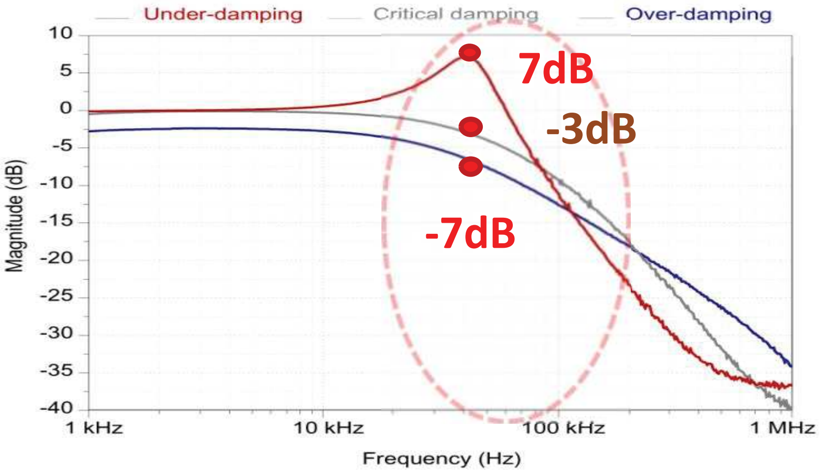
Transfer function

$$H(\omega)=\frac{V_{out}}{V_{in}}=\frac{1}{a_0\left(j\omega\right)^2+a_1 j\omega+1};$$

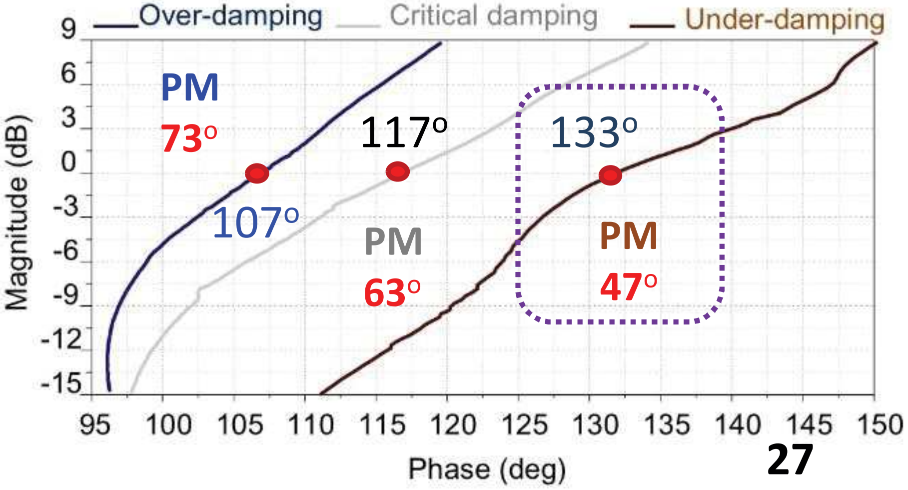
Self-loop function

$$L(\omega)=a_0\left(j\omega\right)^2+a_1 j\omega;$$

Bode plot of transfer function



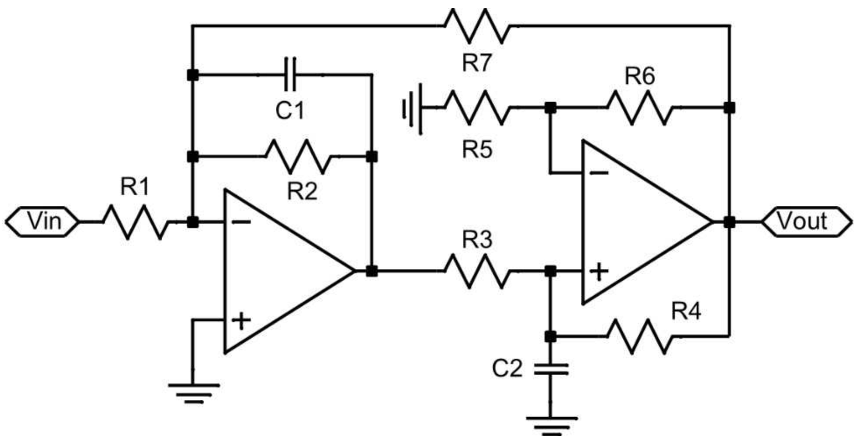
Nichols plot of self-loop function



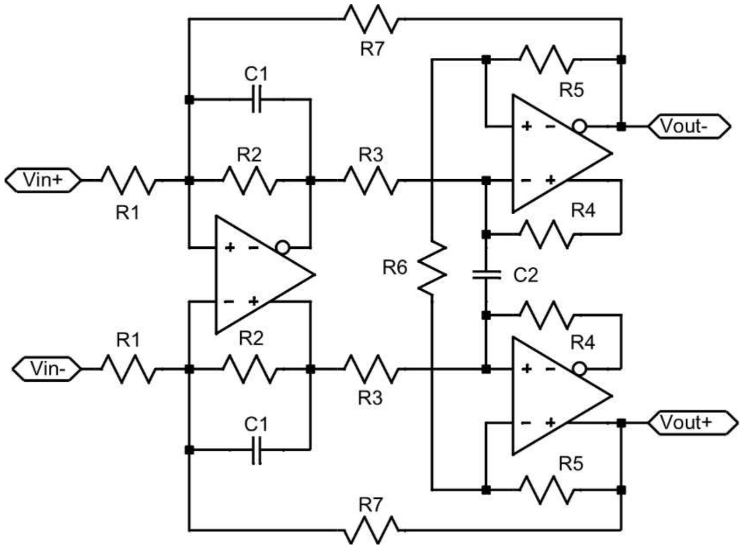
4. Ringing Test for High-order Low-Pass Filters

Analysis of 2nd-Order Deboo low-pass LPF

Single ended Deboo low-pass LPF



Fully differential Deboo low-pass LPF



Transfer function & self-loop function

$$H(\omega) = -\frac{b_0}{a_0 (j\omega)^2 + a_1 j\omega + 1};$$

$$L(\omega) = a_0 (j\omega)^2 + a_1 j\omega;$$

where,

$$b_0 = \frac{R_2 R_4 R_7 (R_5 + R_6)}{R_1 \left[R_2 R_4 (R_5 + R_6) + R_7 (R_4 R_5 - R_3 R_6) \right]};$$

$$a_0 = \frac{R_2 R_3 R_4 R_5 R_7 C_1 C_2}{R_2 R_4 (R_5 + R_6) + R_7 (R_4 R_5 - R_3 R_6)};$$

$$a_1 = \frac{R_2 R_7 C_1 (R_4 R_5 - R_3 R_6) + R_3 R_4 R_5 R_7 C_2}{R_2 R_4 (R_5 + R_6) + R_7 (R_4 R_5 - R_3 R_6)};$$

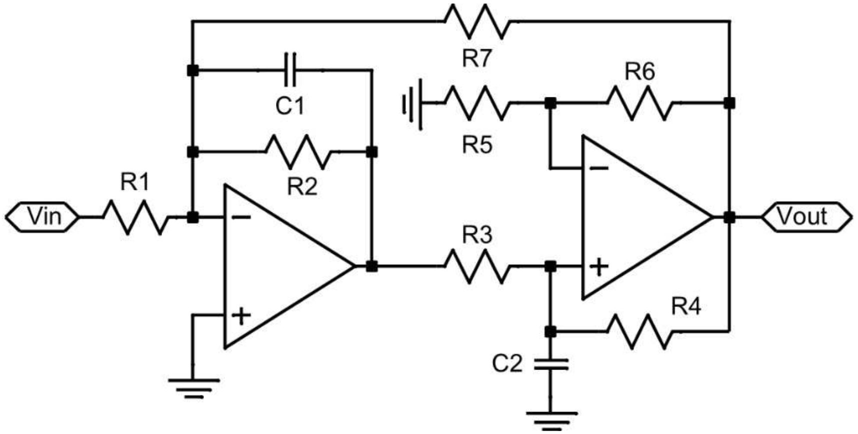
R_1 = R_3 = R_5 = 1 kΩ, R_2 = 10 kΩ, R_6 = R_7 = 5 kΩ, C_1 = 1 nF, C_2 = 0.5 nF at f_0 = 10 kHz.

- **Over-damping (R4 = 3 kΩ),**
- **Critical damping (R4 = 6 kΩ), and**
- **Under-damping (R4 = 10 kΩ).**

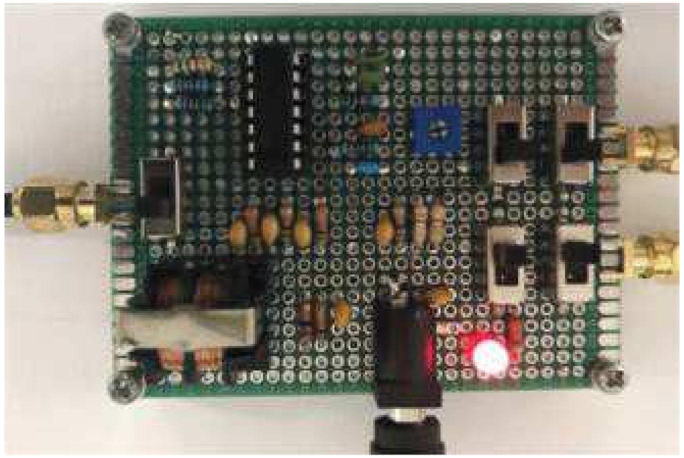
4. Ringing Test for High-order Low-Pass Filters

Implemented Circuit of Deboo low-pass LPF

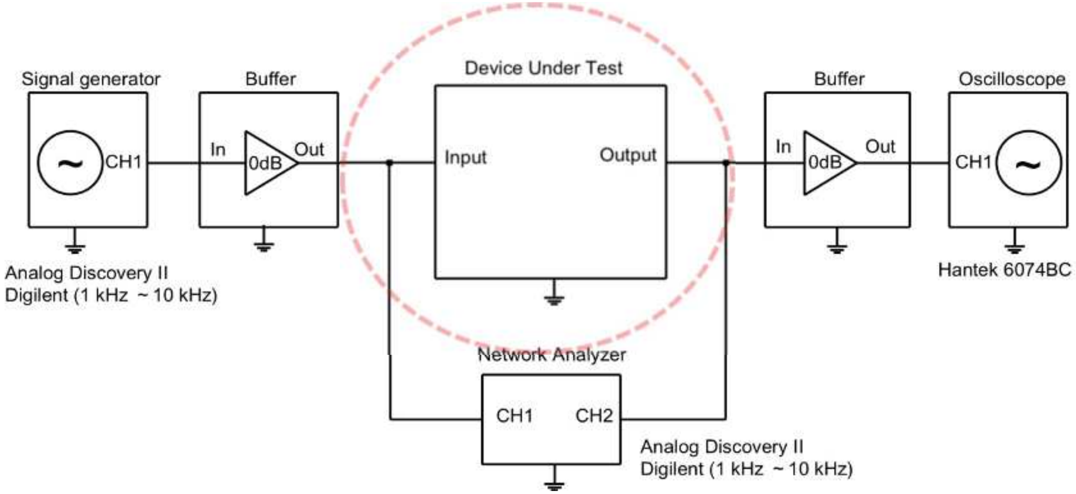
Schematic of Deboo low-pass LPF



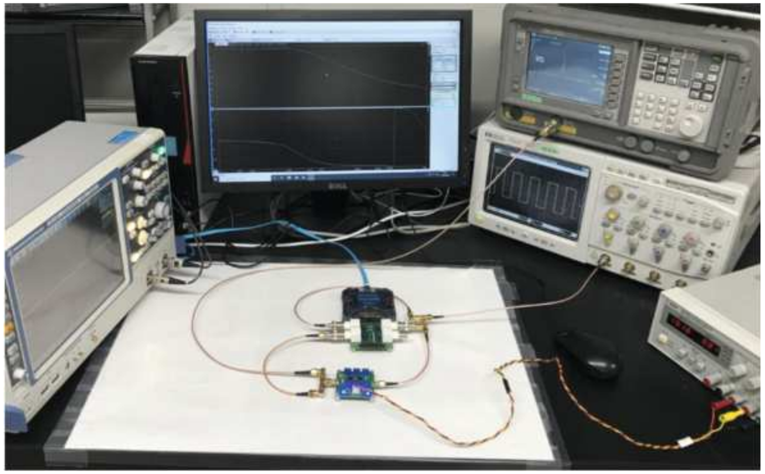
Implemented Circuit



System Under Test



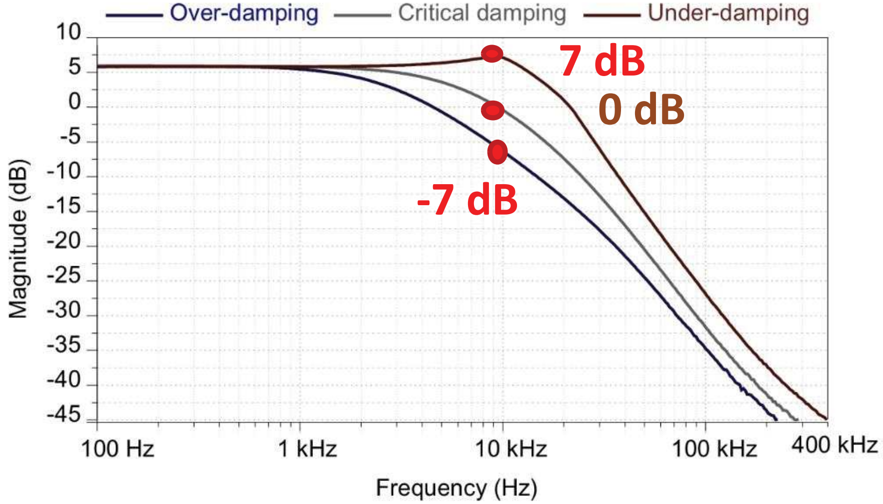
Measurement set up



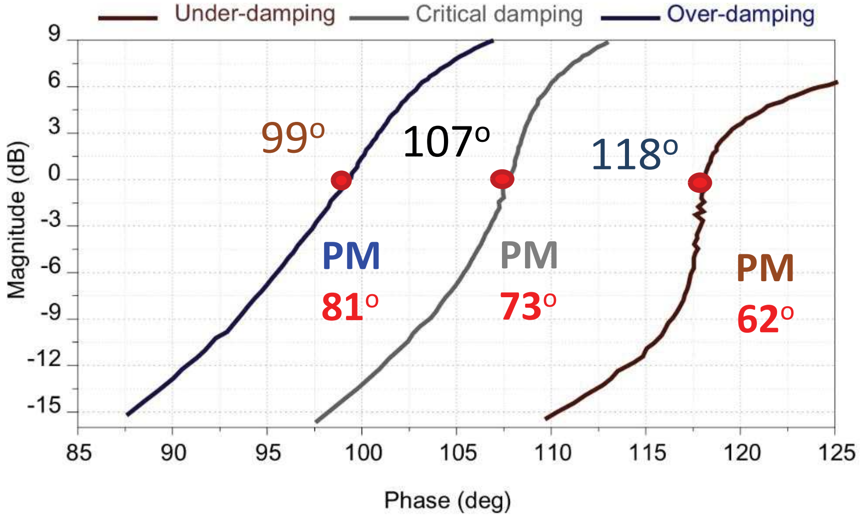
4. Ringing Test for High-order Low-Pass Filters

Measurement Results of Deboo low-pass LPF

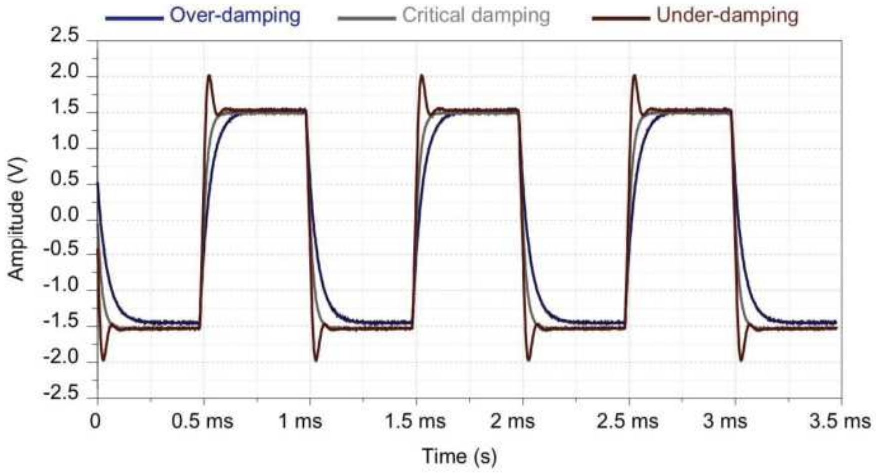
Bode plot of transfer function



Nichols plot of self-loop function



Transient response



Over-damping:

→**Phase margin is 81 degrees.**

Critical damping:

→**Phase margin is 73 degrees.**

Under-damping:

→**Phase margin is 62 degrees.**

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5. **Conclusions**

5. Limitations of Conventional Methods

- **Middlebrook's measurement of loop gain**

→Applying only in feedback systems (**DC-DC converters**).

- **Replica measurement of loop gain**

→Using two identical networks (**not real measurement**).

- **Nyquist's stability condition**

→ Theoretical analysis for feedback systems (**Lab tool**).

- **Nichols chart of loop gain**

→ Only used in feedback control theory (**Lab tool**).

5. Comparison

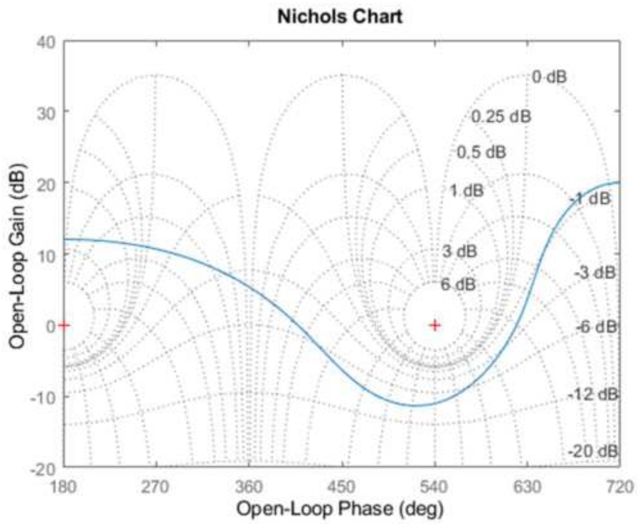
Features	Comparison measurement	Alternating current conservation	Replica measurement	Middlebrook's method
Main objective	Self-loop function	Self-loop function	Loop gain	Loop gain
Transfer function accuracy	Yes	Yes	No	No
Breaking feedback loop	No	Yes	Yes	Yes
Operating region accuracy	Yes	Yes	No	No
Phase margin accuracy	Yes	Yes	No	No
Passive networks	Yes	Yes	No	No

5. Discussions

- **Loop gain is independent of frequency variable.**

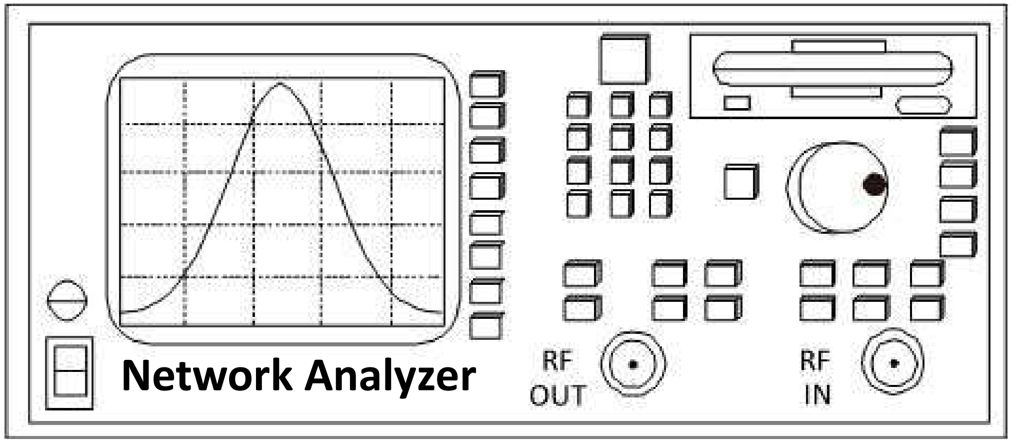
→Loop gain in adaptive feedback network is significantly different from self-loop function in linear negative feedback network.

Nichols chart is only used in MATLAB simulation.



https://www.mathworks.com/help/control/ref/nichols.html

Nichols chart isn't used widely in practical measurements (only used in control theory).



➡ **(Technology limitations)**

5. Conclusions

This work:

- **Proposal of comparison measurement for deriving self-loop function in a transfer function**

  → Observation of self-loop function can help us optimize the behavior of a high-order system.

- **Implementation of circuit and measurements of self-loop functions for high-order feedback amplifiers.**

  →Theoretical concepts of stability test are verified by laboratory simulations and practical experiments.

Future of work:

- **Stability test for parasitic components in transmission lines, printed circuit boards, physical layout layers**

References

[1] L. Fan, Z. Miao, "*Admittance-Based Stability Analysis: Bode Plots, Nyquist Diagrams or Eigenvalue Analysis*", IEEE Trans. on Power Systems, vol. 35, no. 4, July 2020.

[2] M. Liu, I. Dassios, G. Tzounas, F. Milano, “*Stability Analysis of Power Systems with Inclusion of Realistic-Modeling of WAMS Delays*”, IEEE Trans. on Power Sys., vol.34, no.1, pp. 627-636, 2019.

[3] S. Zhong, Y. Huang, “*Comparison of the Phase Margins of Different ADRC Designs,*” IEEE Chinese Control Conf., China, July 2019.

[4] H. Abdollahi, A. Khodamoradi, E. Santi, P. Mattavelli, "*Online Bus Impedance Estimation and Stabilization of DC Power Distribution Systems: A Method Based on Source Converter Loop-Gain Measurement*", IEEE Applied Power Electronics Conference and Exposition, LA, USA, June 2020.

[5] L. Fan, Z. Miao, “*Admittance-Based Stability Analysis: Bode Plots, Nyquist Diagrams or Eigenvalue Analysis?,*” IEEE Trans. on Power Systems, vol. 35, no. 4, pp. 3312 – 3315, July 2020.

[6] Y. Ren, X. Wang, L. Chen, Y. Min, G. Li, L. Wang, Y. Zhang, “*A Strictly Sufficient Stability Criterion for Grid-Connected Converters Based on Impedance Models and Gershgorin's Theorem,*” IEEE Trans. on Power Delivery, vol. 35, no. 3, pp. 1606 – 1609, June 2020.

[7] V. Salis, A. Costabeber, S. Cox, F. Tardelli, P. Zanchetta, “*Experimental Validation of Harmonic Impedance Measurement and LTP Nyquist Criterion for Stability Analysis in Power Converter Networks,*” IEEE Trans. on Power Electronics, vol. 34, no. 8, pp. 7972 – 7982, Aug. 2019.

[8] S. Wang, B. Li, Z. Xu, X. Zhao, D. Xu, “*A Precise Stability Criterion for Power Hardware-in-the-Loop Simulation System,*” 10th Int. Conf. on Power Electronics and ECCE Asia, Busan, Korea, May 2019.

[9] S. Plesnick, J. Berardino, R. Irwin, “*The Generalized Nyquist Criterion Applied to Complex DC Power System Networks,*” IEEE Electric Ship Technologies Symposium, DC, USA, Aug. 2019.

References

[10] J. Ardila, E. Roa, “*A Novel Loop Gain Adaptation Method for Digital CDRs Based on the Cross-Correlation Function,*” IEEE Int. Symp. on Circuits and Systems, Sapporo, Japan, May 2019.

[11] A. Ochoa, D. Patterson, M. McGuckin, “*Driving Point Loop Gain and Return Ratio,*” IEEE 62nd Int. Midwest Symposium on Circuits and Systems, TX, USA, Aug. 2019.

[12] M. Tran, A. Kuwana, H. Kobayashi, "*Derivation of Loop Gain and Stability Test for Low Pass Tow-Thomas Biquad Filter*", 10th Int. Conf. on Computer Science, Engineering and Applications, London, UK, July 2020.

[13] M. Tran, A. Kuwana, H. Kobayashi, "*Ringing Test for Third-Order Ladder Low-Pass Filters*", 11th IEEE Annual Ubiquitous Computing, Electronics & Mobile Communication Conference, USA, 2020.

[14] N. Sayyaf, M. Tavazoei, “Frequency Data-Based Procedure to Adjust Gain and Phase Margins and Guarantee the Uniqueness of Crossover Frequencies,” IEEE Trans. on Industrial Electronics, vol. 67, no. 3, pp. 2176 – 2185, March 2020.

[15] M. Tran, A. Kuwana, H. Kobayashi, “Derivation of Loop Gain and Stability Test for Multiple Feedback Low Pass Filter Using Deboo Integrator”, The 8th IIAE Int. Conf. on Industrial Application Engineering, Shimane Japan, March, 2020.

[16] M. Liu, I. Dassios, F. Milano “*On the Stability Analysis of Systems of Neutral Delay Differential Equations*”, Circuits, Systems, and Signal Processing, vol. 38, no. 4, pp. 1639-1653, 2019.

[17] M. Tran, A. Kuwana, H. Kobayashi, “*Design of Active Inductor and Stability Test for Ladder RLC Low Pass Filter Based on Widened Superposition and Voltage Injection*”, The 8th IIAE Int. Conf. on Industrial Application Engineering, Shimane Japan, March 2020.

Thank you very much!

谢 谢

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GUNMA UNIVERSITY

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Laboratory