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Ringing Test for Negative Feedback Amplifiers

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Outline

1. **Research Background**
- Motivation, objectives and achievements
- Self-loop function in a transfer function

2. **Ringing Test for Feedback Amplifiers**
- Stability test for shunt-shunt feedback amplifiers

3. **Ringing Test for Op Amps with Feedback Loops**
- Stability test for unity-gain and inverting amplifiers

4. **Ringing Test for High-Order Low-Pass Filters**
- Stability test for 2nd-order Åkerberg-Mossberg filters

5. **Conclusions**

1. Research Background

Noise in Electronic Systems

Performance of a system

Signal to Noise Ratio:

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

Performance of a device

Figure of Merit:

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

Common types of noise:

- Electronic noise
- Thermal noise,
- Intermodulation noise,
- Cross-talk,
- Impulse noise,
- Shot noise, and
- Transit-time noise.

Device noise:

- Flicker noise,
- Thermal noise,
- White noise.

Linear networks

- Overshoot,
- Ringing
- Oscillation noise

1. Research Background

Effects of Ringing on Electronic Systems

Ringing represents a distortion of a signal.

Ringing is overshoot/undershoot voltage or current when it's seen on time domain.

Ringing does the following things:

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

Unstable system

↓

STABILITY TEST

1. Research Background

Objectives of Study

- Derivation of transfer function in electronic systems using superposition theorem
  - ○ Investigation of operating regions of linear negative feedback networks

→ Over-damping (high delay in rising time)

→ Critical damping (max power propagation)

→ Under-damping (overshoot and ringing)

- Ringing test for linear negative feedback amplifiers based on comparison measurement

1. Research Background

Achievements of Study

Superposition formula for multi-source networks

$$V_O(t)\sum_{i=1}^{n}\frac{1}{Z_i}+V_O(t)\sum_{i=1}^{n}\frac{1}{Z_{si}+\cfrac{1}{\sum_{k=1}^{n}\cfrac{1}{Z_{pik}}}}=\sum_{i=1}^{n}\left(\frac{V_i(t)}{Z_i}+I_{ai}(t)-I_{gi}(t)\right)$$

Transfer function

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

Self-loop function

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

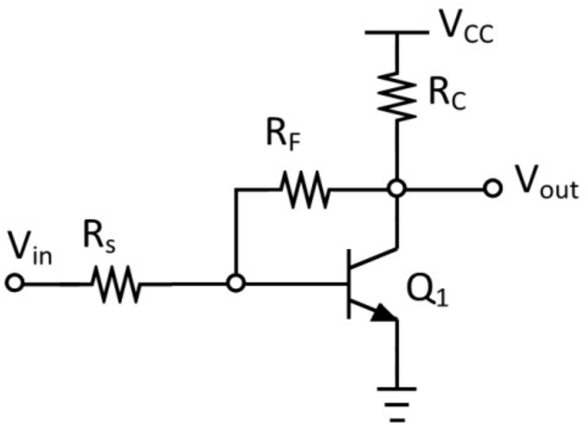
Derivation of self-loop function using comparison measurement

- **Shunt-shunt feedback amplifiers**
- **Inverting amplifiers**
- **Unity-gain amplifiers**
- **2nd-order low-pass filters**

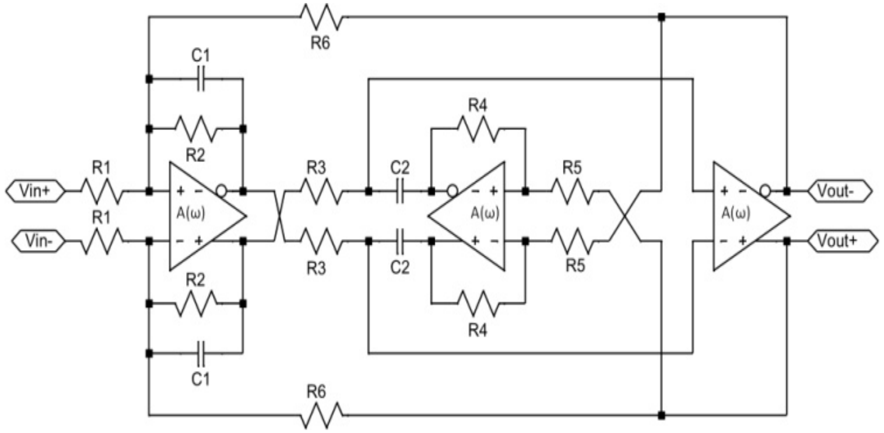
1. Research Background

Approaching Methods

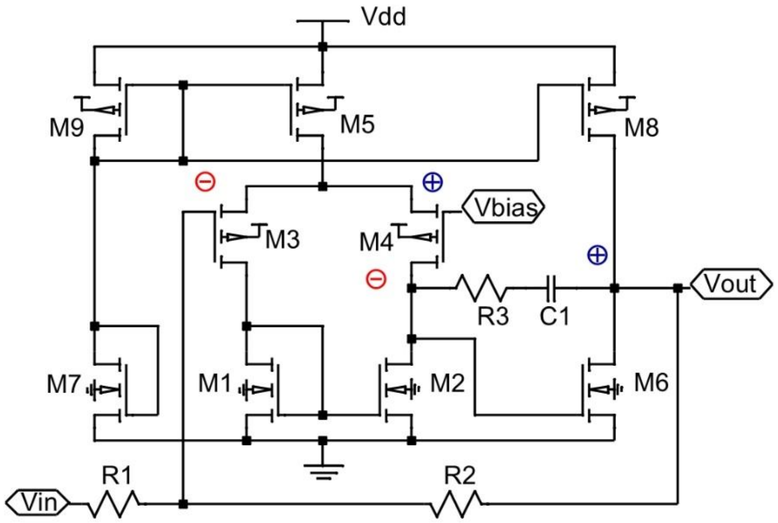
Shunt-shunt feedback amplifier



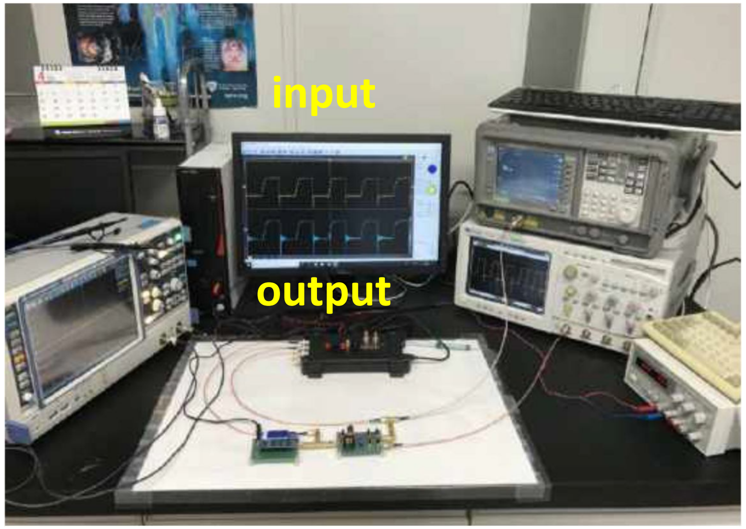
2nd-order Åkerberg-Mossberg LPF



Inverting amplifier



Implemented circuit



1. Research Background

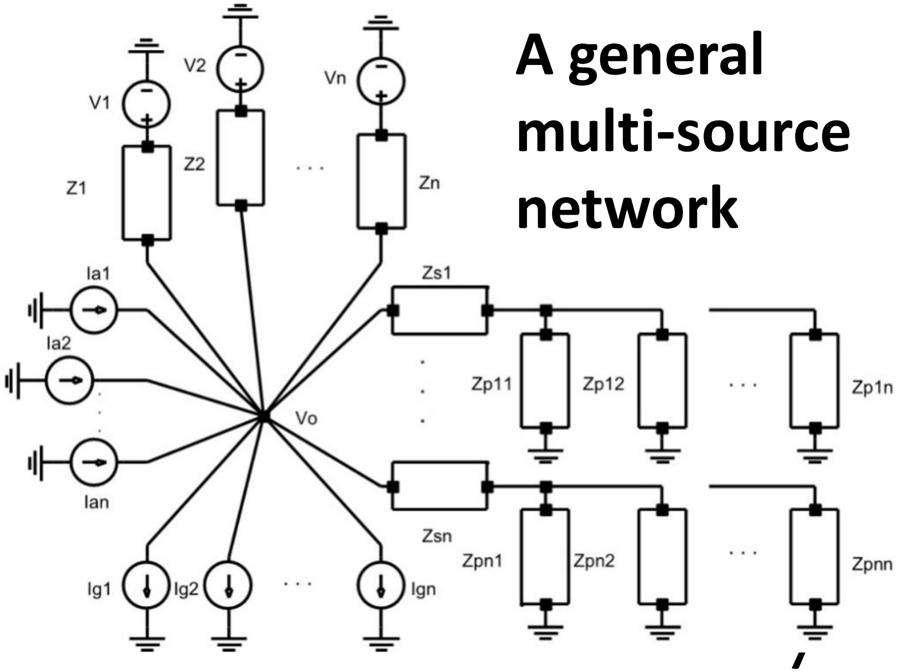
Superposition Theorem for Multi-Source Systems

Superposition formula:

$$V_O(t)\sum_{i=1}^{n}\frac{1}{Z_i}+V_O(t)\sum_{i=1}^{n}\frac{1}{Z_{si}+\frac{1}{\sum_{k=1}^{n}\frac{1}{Z_{pik}}}}=\sum_{i=1}^{n}\left(\frac{V_i(t)}{Z_i}+I_{ai}(t)-I_{gi}(t)\right)$$

$V_O(t)$: *Voltage at one node*
$V_i(t)$: *Input voltage sources*
$I_{ai}(t)$: *Ahead-toward current sources*
$I_{gi}(t)$: *Ground-toward current sources*
$Z_{i,\ si,\ pi,}(t)$: Impedances at each branch

○ Multi-source systems, feedback networks (op amps, amplifiers), polyphase filters, complex filters…

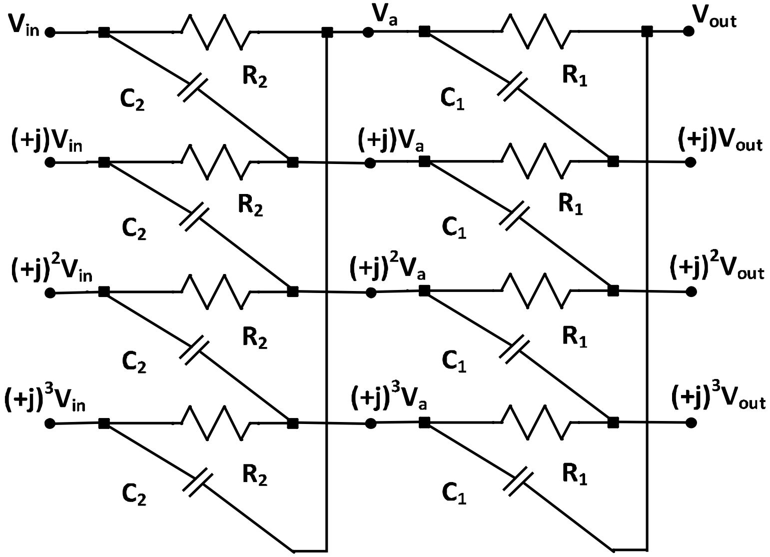


A general multi-source network

1. Research Background

Analysis of 2nd–Order Polyphase Filter

2nd-order RC polyphase filter



Apply superposition at each node

$$V_{out}\left(\frac{1}{Z_{C1}}+\frac{1}{R_1}\right)=\frac{V_a}{R_1}+\frac{(+j)^3V_a}{Z_{C1}};$$

$$V_a\left(\frac{1}{Z_{C2}}+\frac{1}{R_2}+\frac{2}{R_1+Z_{C1}}\right)=\frac{V_{in}}{R_2}+\frac{(+j)^3V_{in}}{Z_{C2}};$$

Transfer function for positive polyphase signal

$$H_P(\omega)=\frac{V_{out}}{V_{in}}=\frac{\left[1+(+j)^3b_1j\omega\right]\left[1+(+j)^3b_2j\omega\right]}{a_0(j\omega)^2+a_1j\omega+1};$$

Transfer function for negative polyphase signal

$$H_N(\omega)=\frac{V_{out}}{V_{in}}=\frac{\left[1+(-j)^3b_1j\omega\right]\left[1+(-j)^3b_2j\omega\right]}{a_0(j\omega)^2+a_1j\omega+1};$$

Here: $b_0=R_1C_1;b_1=R_2C_2;\ a_0=b_0b_1;\ a_1=b_0+b_1+2R_2C_1;$

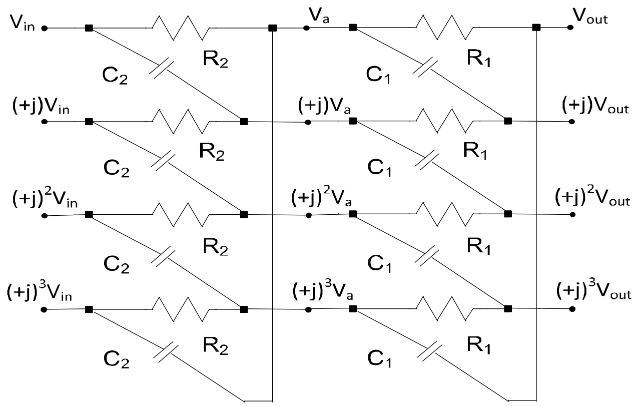
Image rejection ratio (IRR)

$$IRR(\omega)=\frac{|H_P(\omega)|}{|H_N(\omega)|}=\frac{|(1+b_1\omega)(1+b_2\omega)|}{|(1-b_1\omega)(1-b_2\omega)|};$$

1. Research Background

Behaviors of 2nd–Order Polyphase Filter

2-order RC polyphase filter

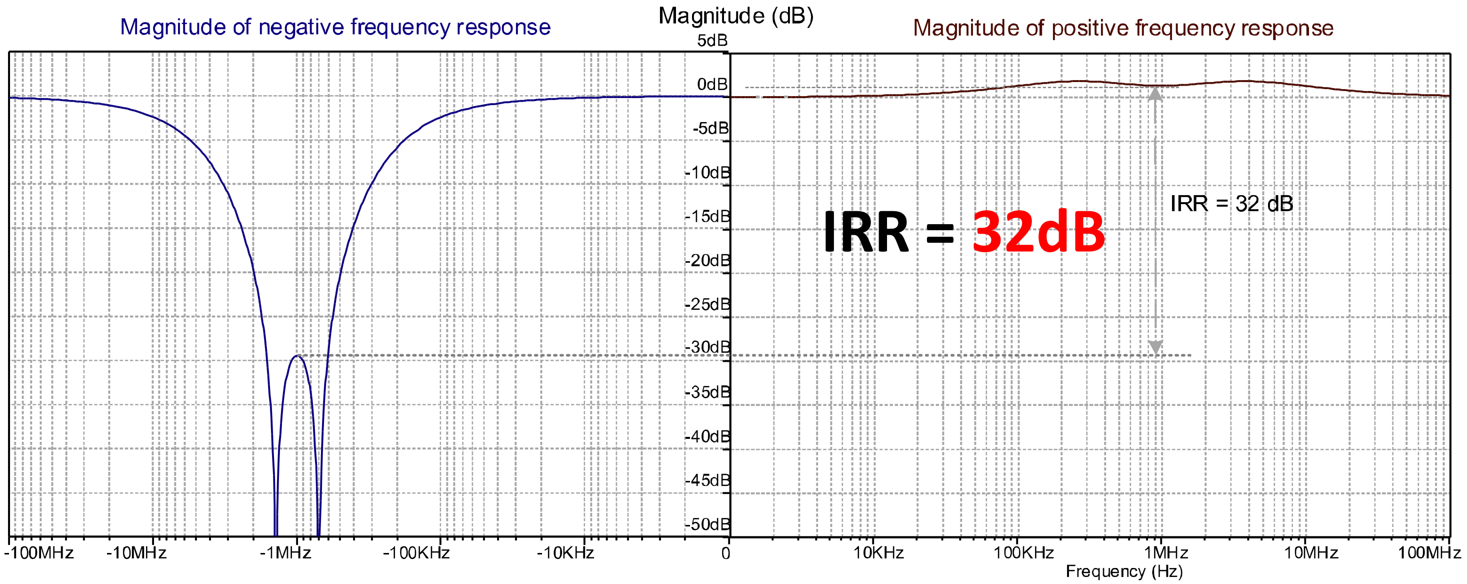


Transfer function in all frequency domain

$$\left|H(\omega)\right| = \frac{(1+b_1\omega)(1+b_2\omega)}{\sqrt{\left(1-a_0\omega^2\right)^2+\left(a_1\omega\right)^2}};\omega \in R$$

Here, R1 = 1 kΩ, C1 = 227 pF, R2 = 1 kΩ, C2 = 114 pF, at f_1 = 700 kHz, f_2 = 1.4 MHz,

Bode plot of transfer function in all frequency domain



IRR = 32dB

1. Research Background

Behavior of 4th-order Complex Filter

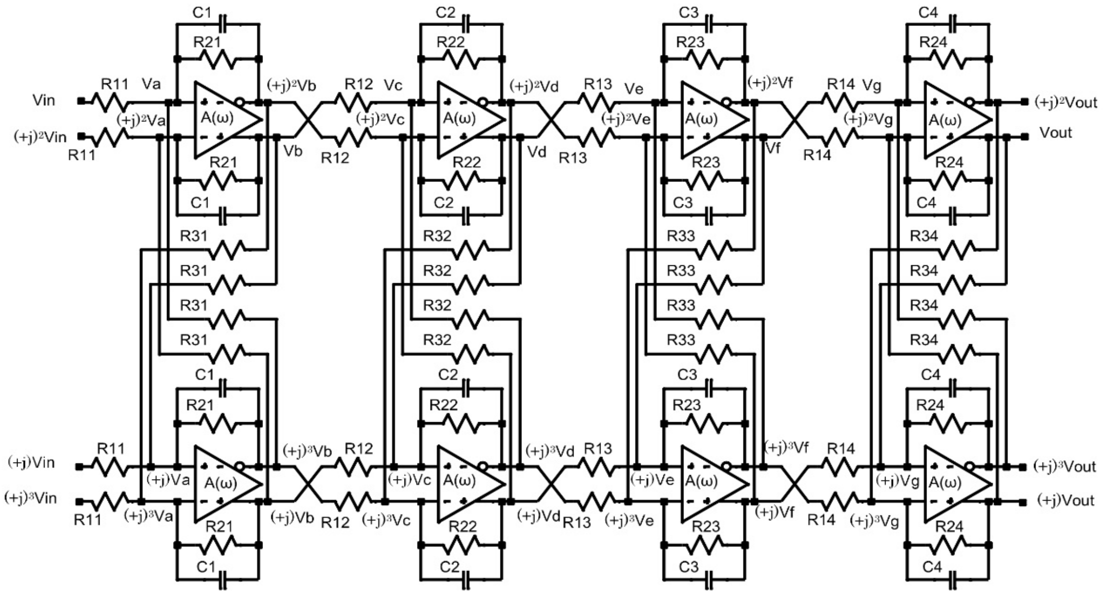
Transfer function
for positive
polyphase signals

$$H_P(\omega)=\frac{\frac{R_{21}}{R_{11}}}{\left[1+j\left(\frac{\omega}{\omega_{cut1}}+\frac{R_{21}}{R_{31}}\right)\right]}\frac{\frac{R_{22}}{R_{12}}}{\left[1+j\left(\frac{\omega}{\omega_{cut2}}+\frac{R_{22}}{R_{32}}\right)\right]}\frac{\frac{R_{23}}{R_{13}}}{\left[1+j\left(\frac{\omega}{\omega_{cut3}}+\frac{R_{23}}{R_{33}}\right)\right]}\frac{\frac{R_{24}}{R_{14}}}{\left[1+j\left(\frac{\omega}{\omega_{cut4}}+\frac{R_{24}}{R_{34}}\right)\right]};$$

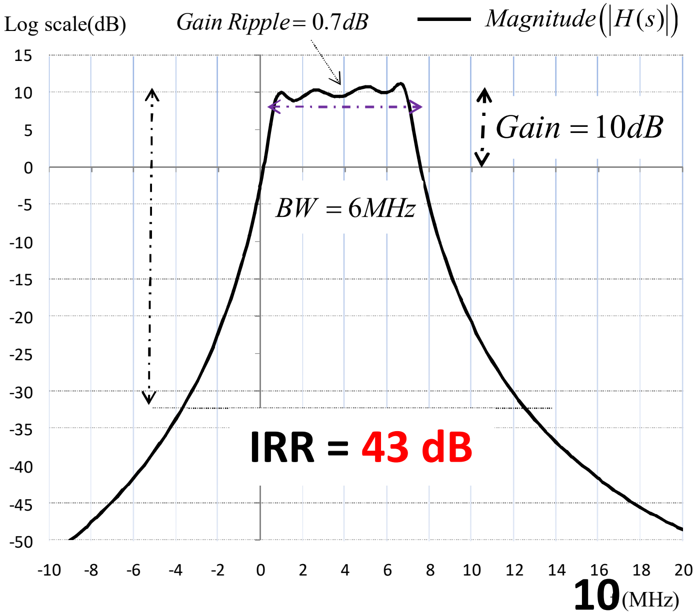
Transfer function
for negative
polyphase signals

$$H_N(\omega)=\frac{\frac{R_{21}}{R_{11}}}{\left[1+j\left(\frac{\omega}{\omega_{cut1}}-\frac{R_{21}}{R_{31}}\right)\right]}\frac{\frac{R_{22}}{R_{12}}}{\left[1+j\left(\frac{\omega}{\omega_{cut2}}-\frac{R_{22}}{R_{32}}\right)\right]}\frac{\frac{R_{23}}{R_{13}}}{\left[1+j\left(\frac{\omega}{\omega_{cut3}}-\frac{R_{23}}{R_{33}}\right)\right]}\frac{\frac{R_{24}}{R_{14}}}{\left[1+j\left(\frac{\omega}{\omega_{cut4}}-\frac{R_{24}}{R_{34}}\right)\right]};$$

4th-order complex filter



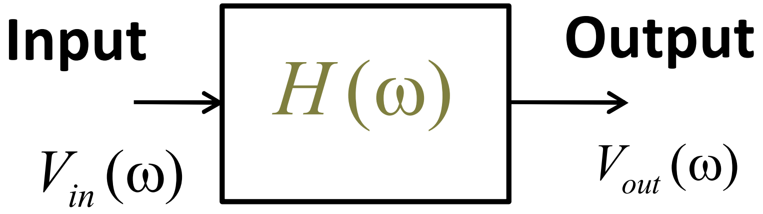
Bode plot of transfer function



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

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

$A(\omega)$ **: Open loop function**

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

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

Variable: angular frequency (ω)

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

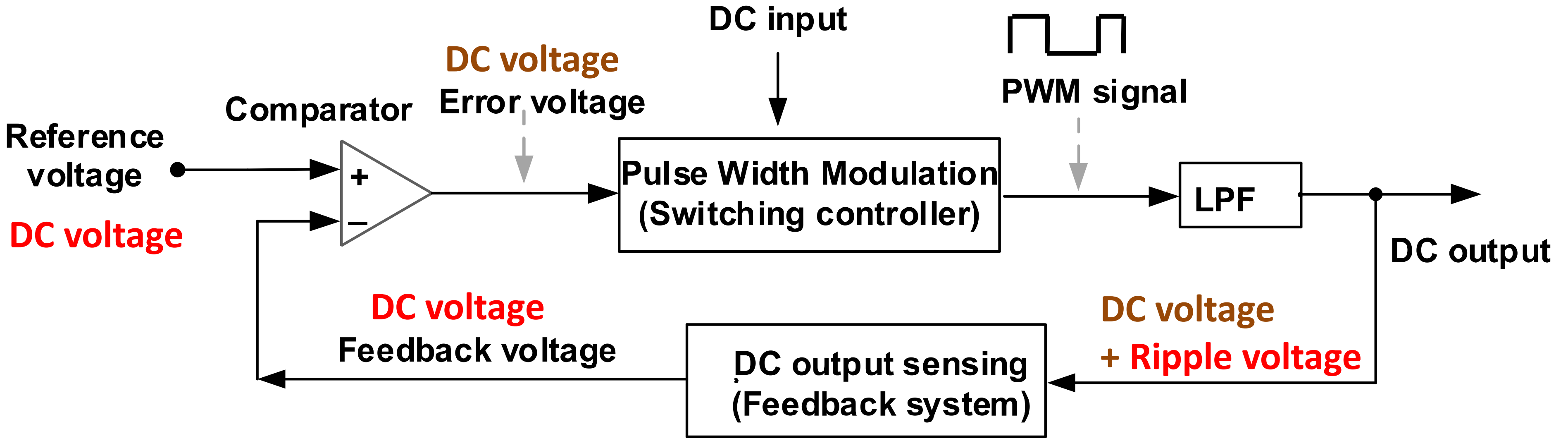
Bode plots

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

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).

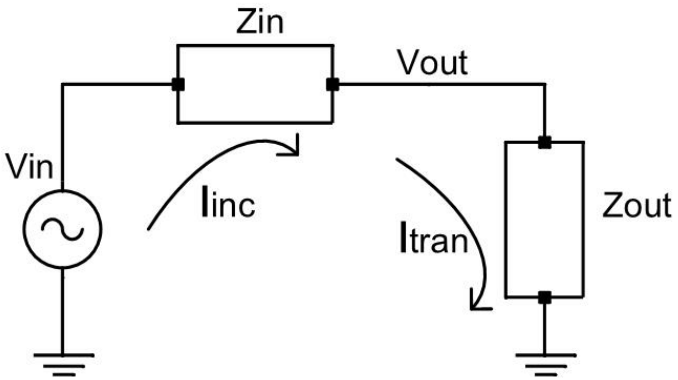
1. Research Background

Comparison Measurement

Transfer function

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

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



Simplified linear system

Sequence of steps:

(i) Measurement of open loop 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

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).**

- **Conventional superposition**

→**Solving for every source (several times).**

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5. Conclusions

2. Ringing Test for Feedback Amplifiers

Characteristics of 2nd-order Transfer Function

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

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 $\lvert H(\omega)\rvert$	$\frac{\frac{1}{a_0}}{\sqrt{\omega^2+\left(\frac{a_1}{2a_0}-\sqrt{\left(\frac{a_1}{2a_0}\right)^2-\frac{1}{a_0}}\right)^2}\sqrt{\omega^2+\left(\frac{a_1}{2a_0}+\sqrt{\left(\frac{a_1}{2a_0}\right)^2-\frac{1}{a_0}}\right)^2}}$		$\frac{\frac{1}{a_0}}{\left[\omega^2+\left(\frac{a_1}{2a_0}\right)^2\right]}=\frac{1}{2}=-6dB$		$\frac{\frac{1}{a_0}}{\sqrt{\left(\omega-\sqrt{\frac{1}{a_0}-\left(\frac{a_1}{2a_0}\right)^2}\right)^2+\left(\frac{a_1}{2a_0}\right)^2}\sqrt{\left(\omega+\sqrt{\frac{1}{a_0}-\left(\frac{a_1}{2a_0}\right)^2}\right)^2+\left(\frac{a_1}{2a_0}\right)^2}}$	
Angular $\theta(\omega)$	$-\arctan\left(\frac{\omega}{\frac{a_1}{2a_0}-\sqrt{\left(\frac{a_1}{2a_0}\right)^2-\frac{1}{a_0}}}\right)-\arctan\left(\frac{\omega}{\frac{a_1}{2a_0}+\sqrt{\left(\frac{a_1}{2a_0}\right)^2-\frac{1}{a_0}}}\right)$		$-2\arctan\left(\frac{2a_0\omega}{a_1}\right)$		$-\arctan\left(\frac{\omega-\sqrt{\frac{1}{a_0}-\left(\frac{a_1}{2a_0}\right)^2}}{\frac{a_1}{2a_0}}\right)-\arctan\left(\frac{\omega+\sqrt{\frac{1}{a_0}-\left(\frac{a_1}{2a_0}\right)^2}}{\frac{a_1}{2a_0}}\right)$	
$\omega_{cut}=\frac{a_1}{2a_0}$	$\lvert H(\omega_{cut})\rvert<\frac{2a_0}{a_1}$	$\theta(\omega_{cut})>-\frac{\pi}{2}$	$\lvert H(\omega_{cut})\rvert=\frac{2a_0}{a_1}$	$\theta(\omega_{cut})=-\frac{\pi}{2}$	$\lvert H(\omega_{cut})\rvert>\frac{2a_0}{a_1}$	$\theta(\omega_{cut})<-\frac{\pi}{2}$

2. Ringing Test for Feedback Amplifiers

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. Ringing Test for Feedback Amplifiers

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:**

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

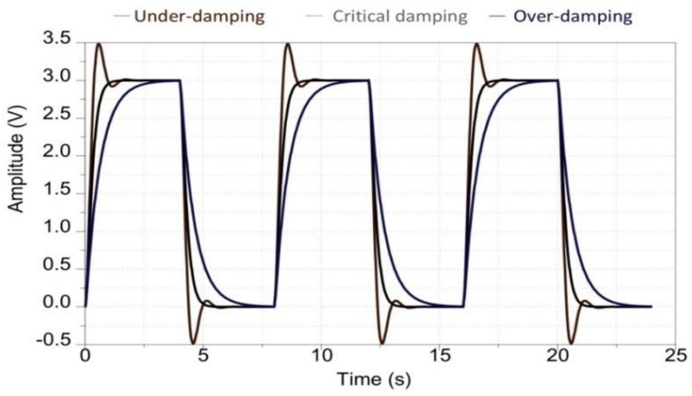
$$H_2(\omega) = \frac{1}{(j\omega)^2 + 2j\omega + 1};$$

- **Over-damping:**

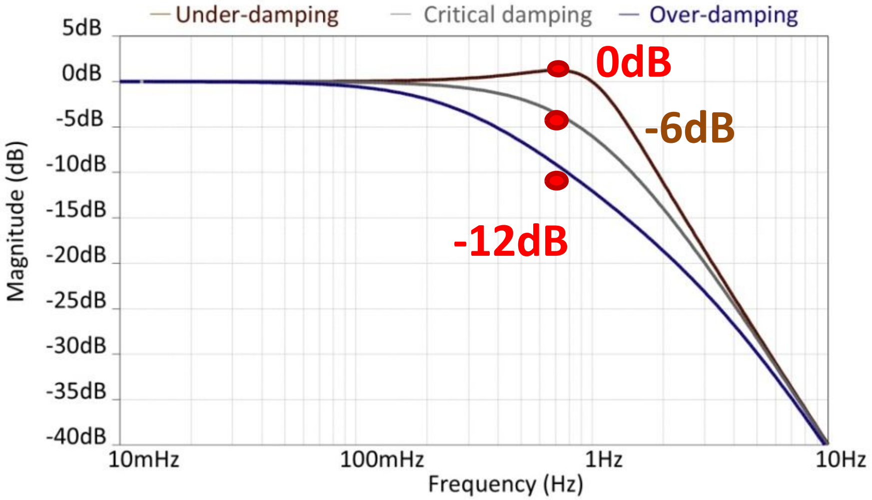
$$L_3(\omega) = (j\omega)^2 + 3j\omega;$$

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

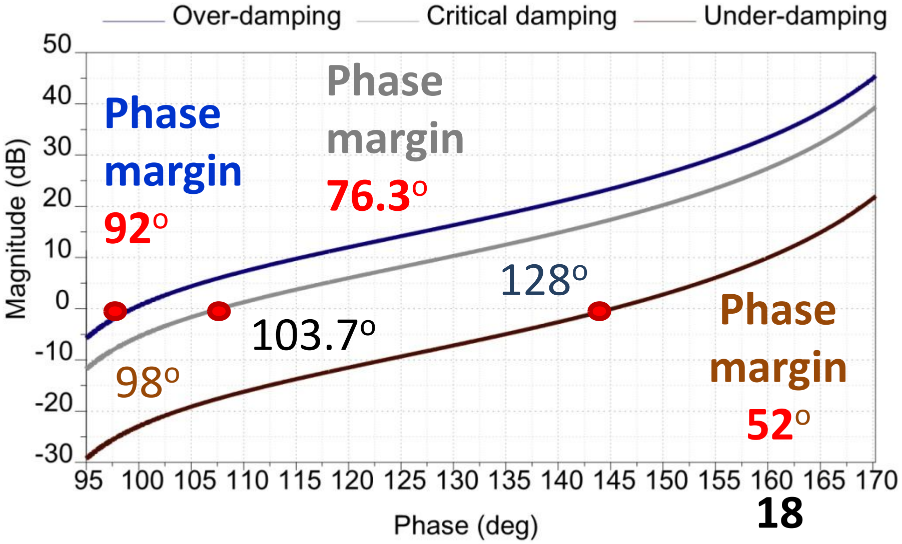
Transient response



Bode plot of transfer function



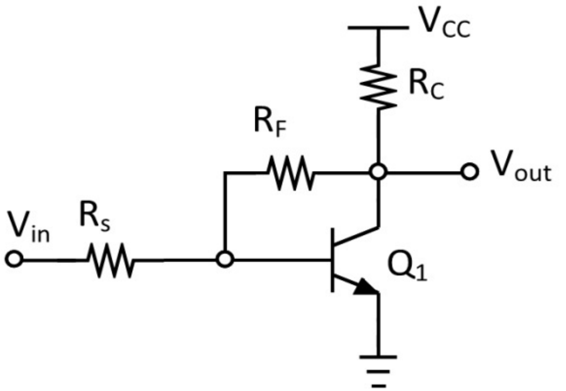
Nichols plot of self-loop function



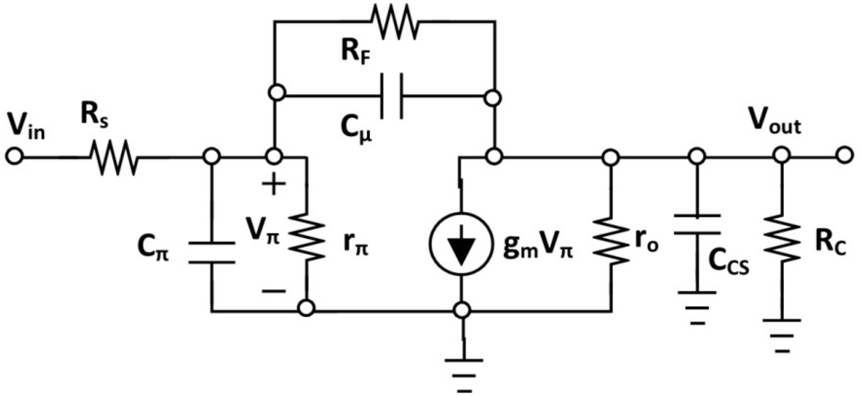
2. Ringing Test for Feedback Amplifiers

Analysis of Shunt-Shunt Feedback Amplifier

BJT shunt-shunt feedback amplifier



Small signal model



Apply superposition at the nodes V$_\pi$ 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 H(ω) and self-loop function L(ω)

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

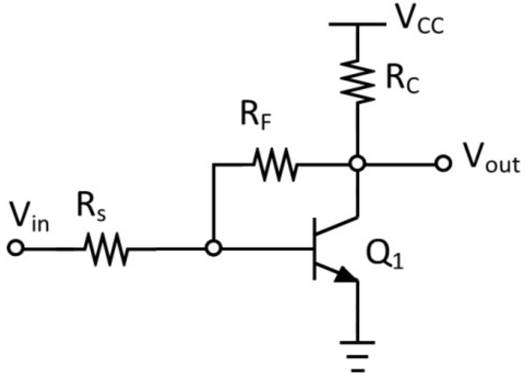
Where, $b_0=R_L C_{GD1};\ b_1=-R_L g_{m1};\ a_0=R_S R_L\left(C_{GD1}C_{GS1}+C_{GD1}C_{DB1}+C_{DB1}C_{GS1}\right);$

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

2. Ringing Test for Feedback Amplifiers

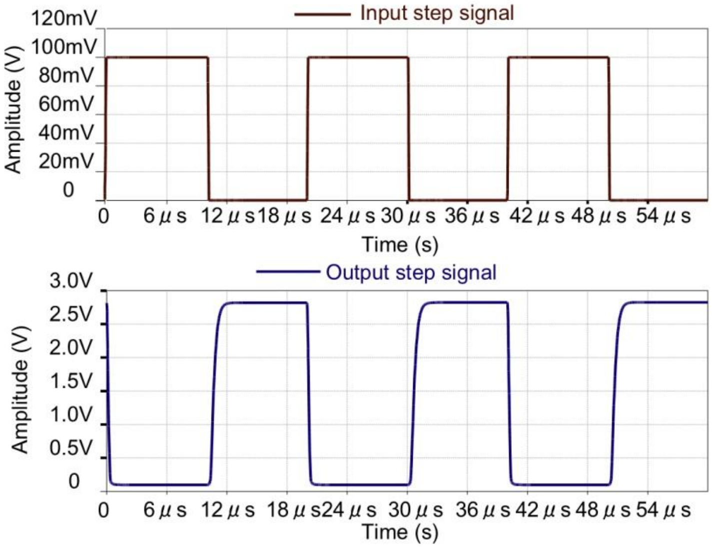
Characteristics of Shunt-Shunt Feedback Amplifier

BJT shunt-shunt feedback amplifier

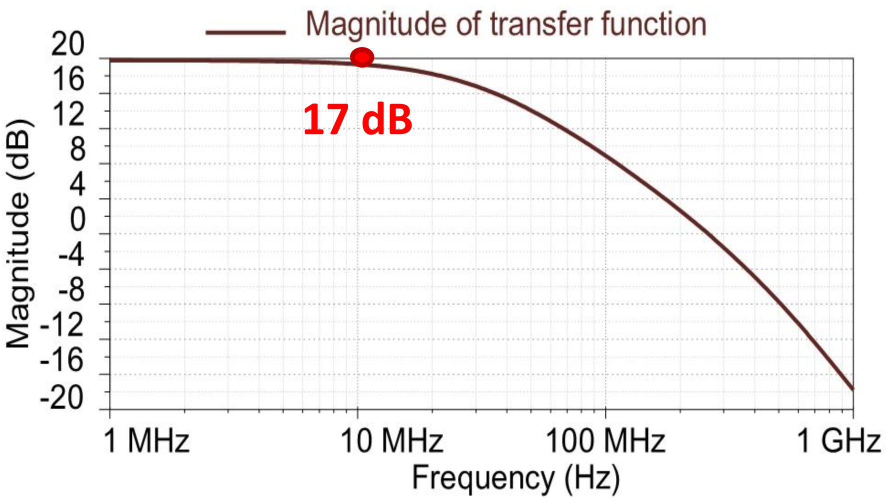


Rf = 1 kΩ, RC = 10 kΩ, RS = 950 Ω.

Transient response

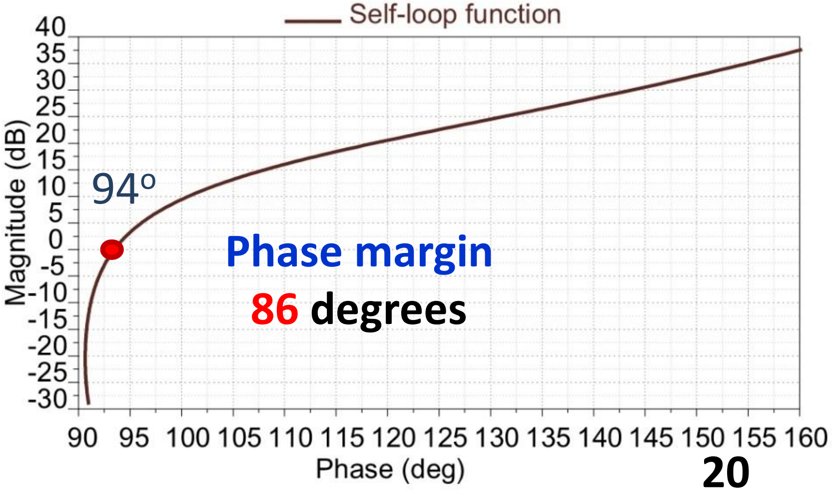


Bode plot of transfer function



17 dB

Nichols plot of self-loop function



94º

Phase margin

86 degrees

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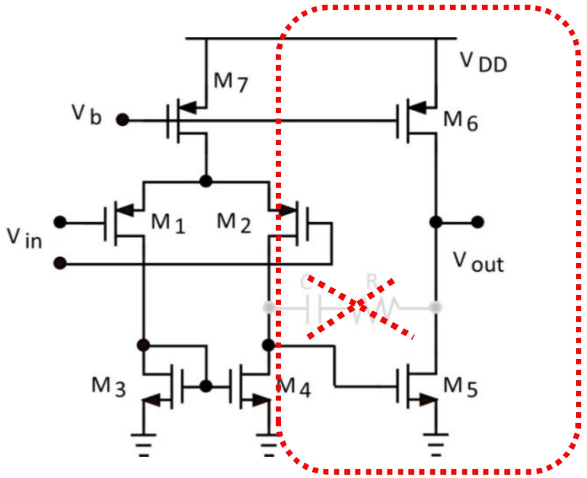
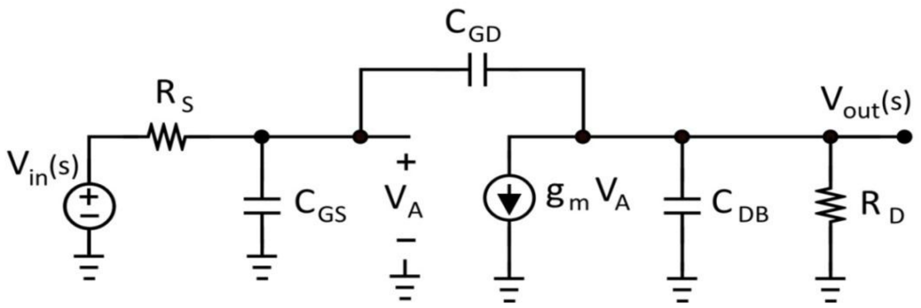
3.Ringing Test for Op Amps with Feedback Loops

Analysis of Op Amp without Miller’s Capacitor

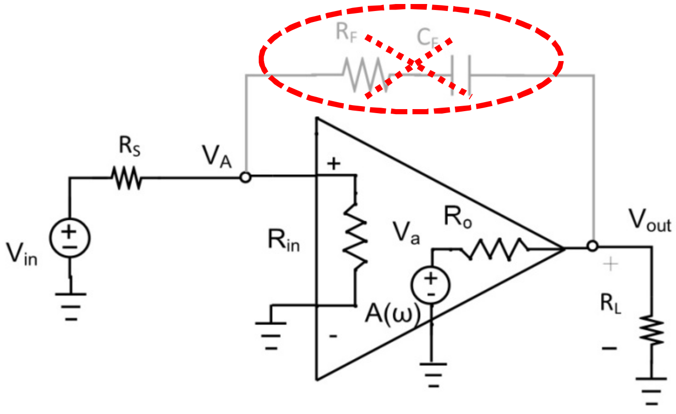
Without frequency compensation



Small signal model



Simplified model



Transfer function H(ω) and self-loop function L(ω)

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

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

Where,

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

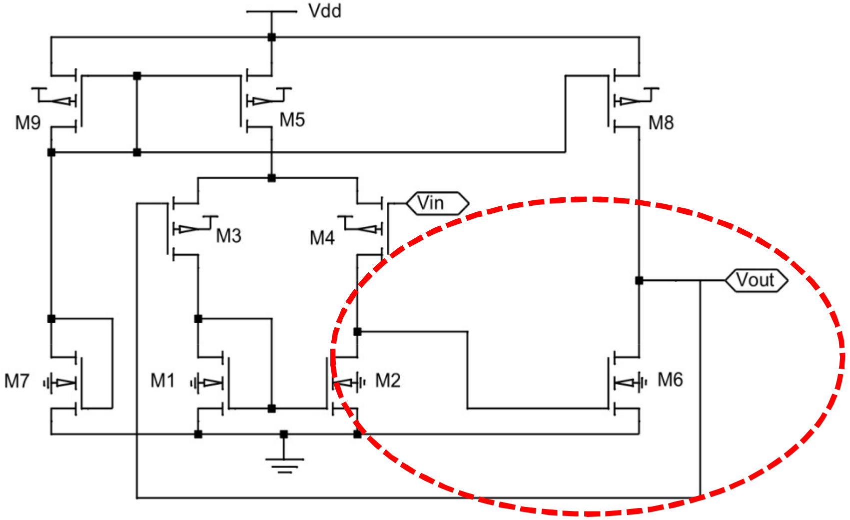
$$b_1 = \left[R_D (C_{GD} + C_{DB}) + R_S (C_{GS} + C_{GD}) + R_D R_S g_m C_{GD} \right]$$

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

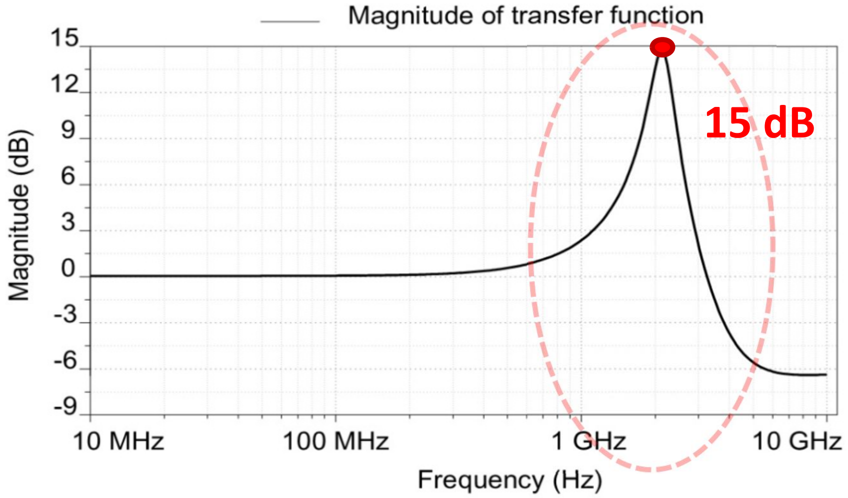
3.Ringing Test for Op Amps with Feedback Loops

Unity-Gain Amplifier without Miller's Capacitor

Unity-Gain Amplifier

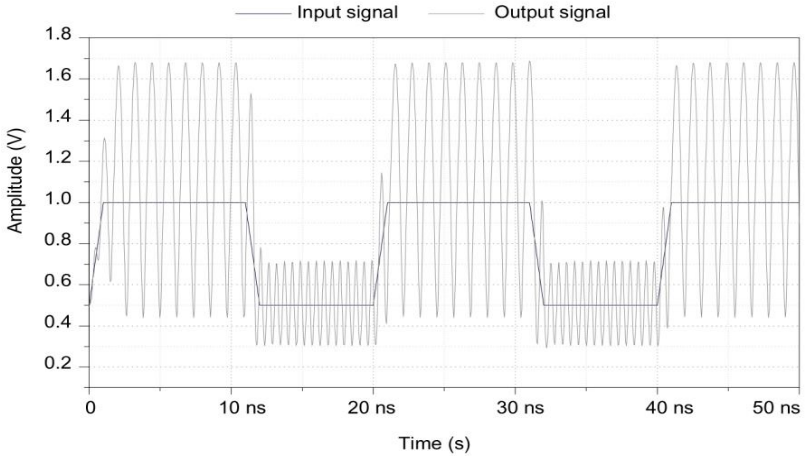


Bode plot of transfer function H(ω)

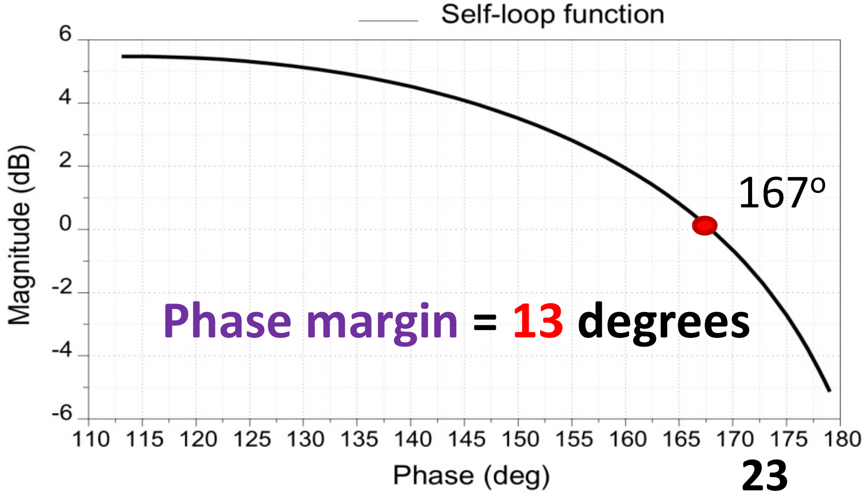


15 dB

Transient response



Nichols plot of self-loop function L(ω)



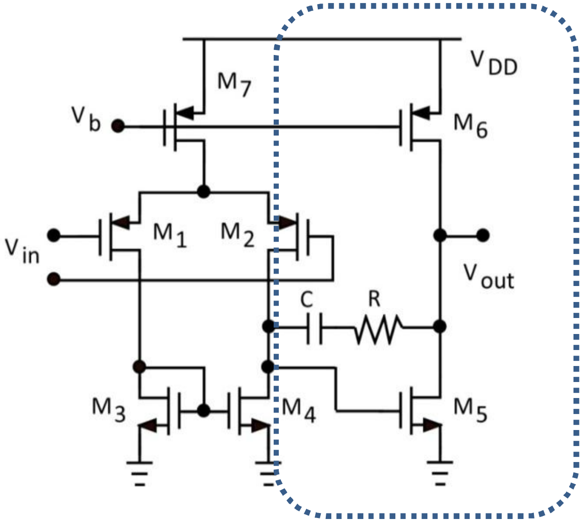
167^o

Phase margin = 13 degrees

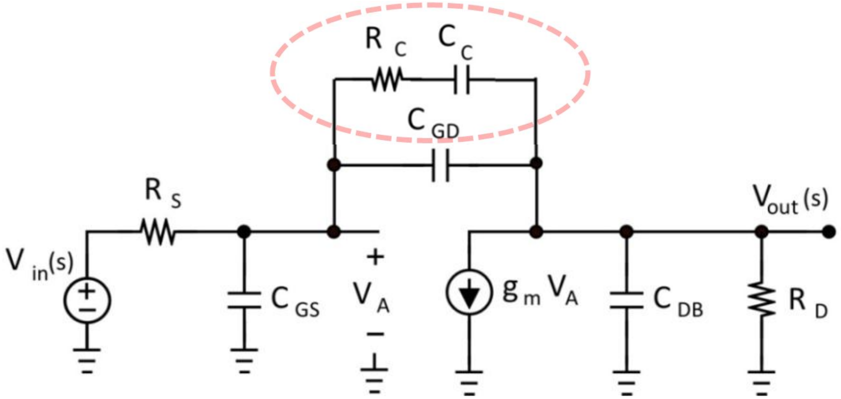
3.Ringing Test for Op Amps with Feedback Loops

Two-stage Op Amp with Frequency Compensation

With Miller's capacitor and resistor



Small signal model



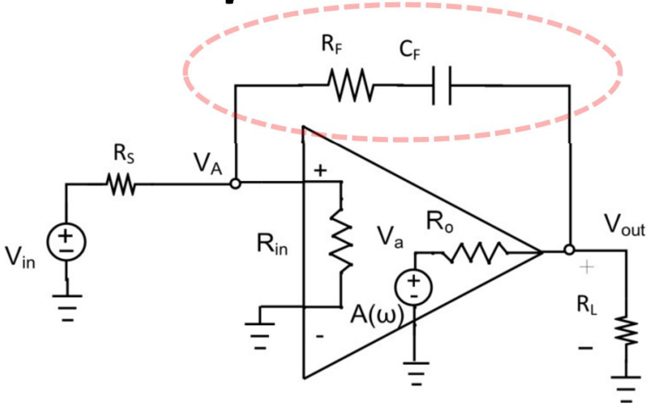
Transfer function H(ω)

$$H(\omega)=\frac{b_0(j\omega)^3+b_1(j\omega)^2+b_2j\omega+b_3}{a_0(j\omega)^4+a_1(j\omega)^3+a_2(j\omega)^2+a_3j\omega+1};$$

Self-loop function L(ω)

$$L(\omega)=a_0(j\omega)^4+a_1(j\omega)^3+a_2(j\omega)^2+a_3j\omega$$

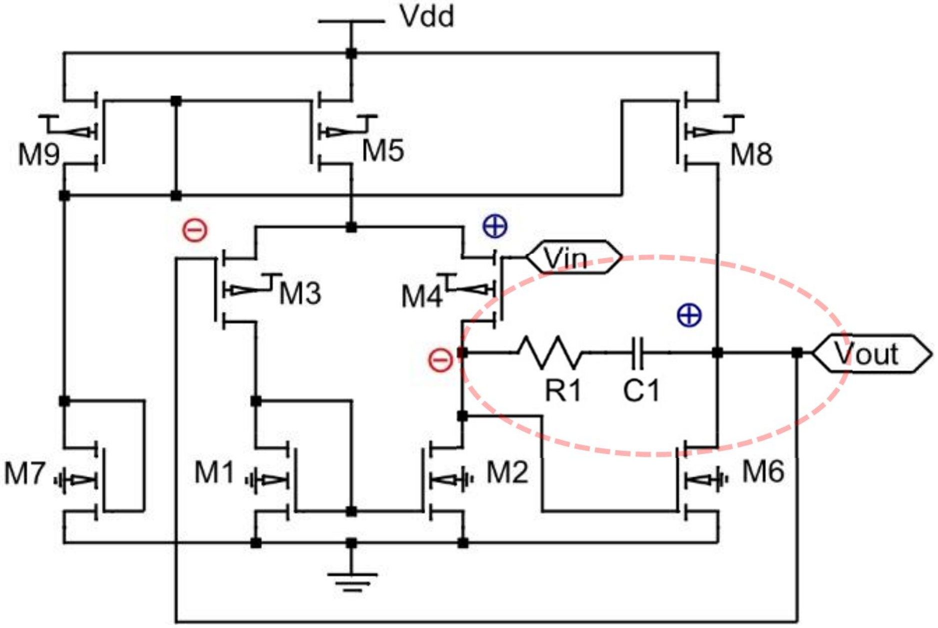
Simplified model



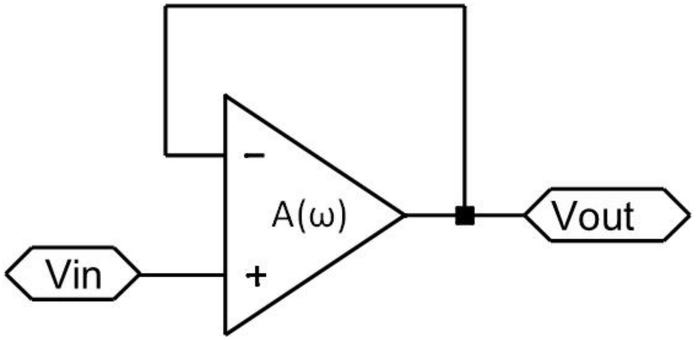
3.Ringing Test for Op Amps with Feedback Loops

Unity-Gain Amplifier with Miller's Capacitor

Unity-gain amplifier with Miller's capacitor



Simplified model of unity gain amplifier



Transfer function and self-loop function

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

Under-damping:

R1= 2 kΩ, C1 = 1 pF

Critical damping:

R1 = 3.5 kΩ, C1 = 0.2 pF

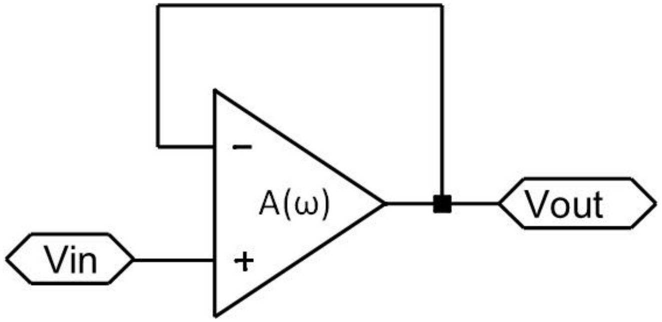
Over-damping:

R1 = 3.5 kΩ, C1 = 0.8 pF

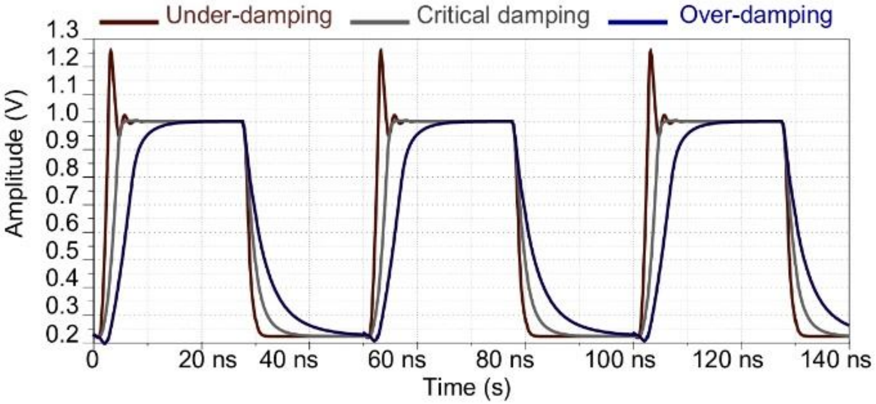
3.Ringing Test for Op Amps with Feedback Loops

Behaviors of Unity-Gain Amplifier

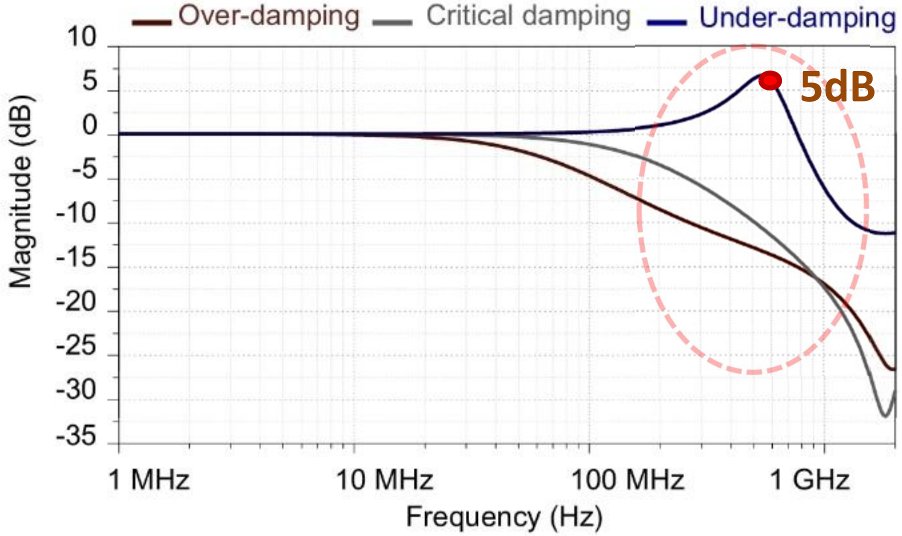
Simplified model of unity gain amplifier



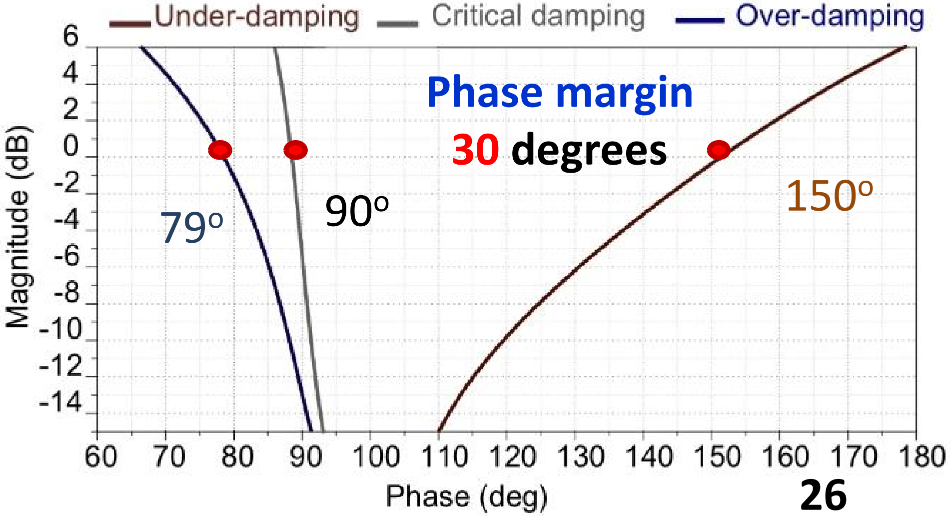
Simulated transient response



Bode plot of transfer function



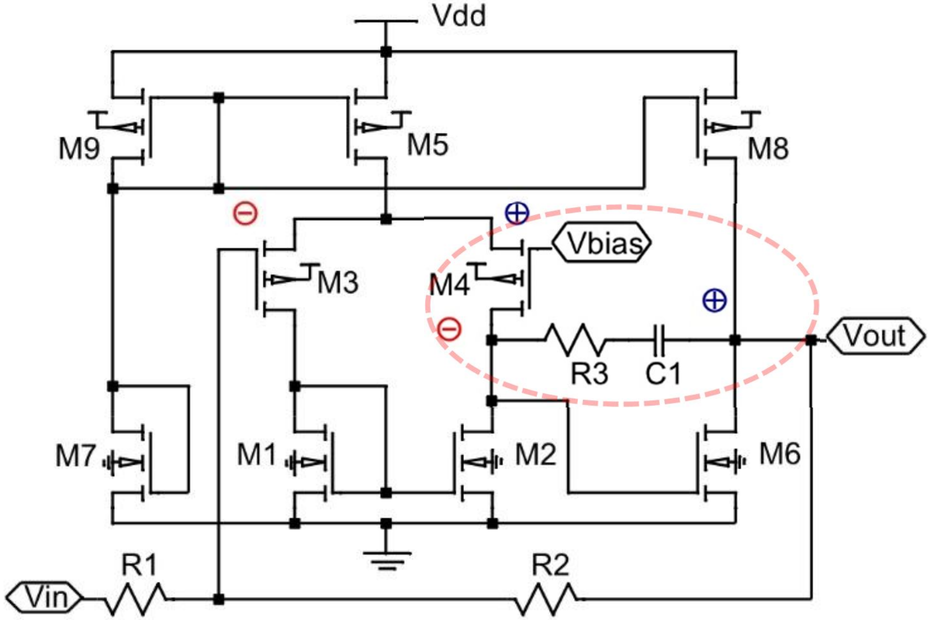
Nichols plot of self-loop function



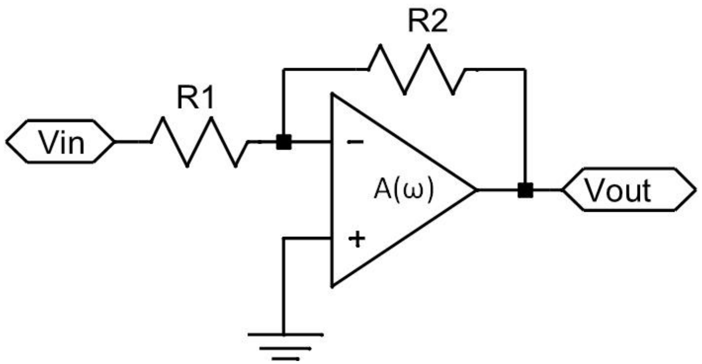
3.Ringing Test for Op Amps with Feedback Loops

Inverting Amplifier with Miller’s Capacitor

Inverting amplifier with frequency compensation



Simplified model of inverting amplifier



Transfer function and self-loop function

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

Under-damping:

R3= 2 kΩ, C1 = 1 pF

Critical damping:

R3 = 3.5 kΩ, C1 = 0.2 pF

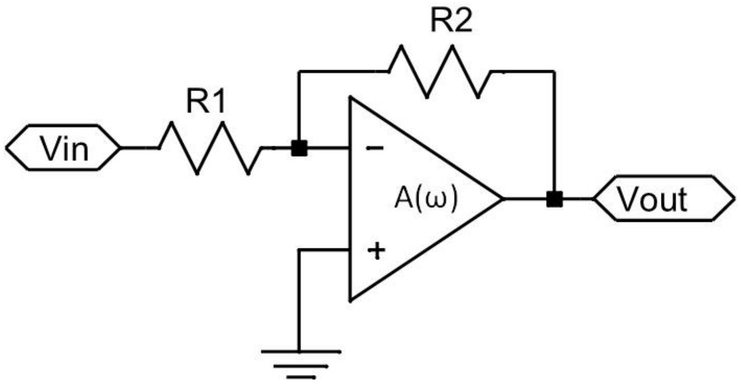
Over-damping:

R3 = 3.5 kΩ, C1 = 0.8 pF

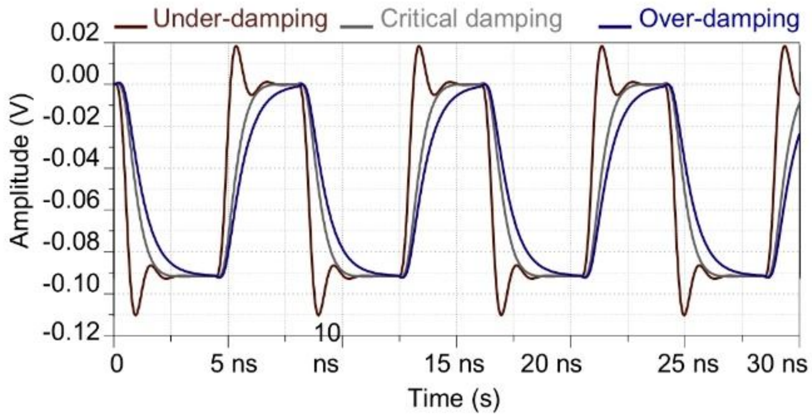
3.Ringing Test for Op Amps with Feedback Loops

Behaviors of Inverting Amplifier

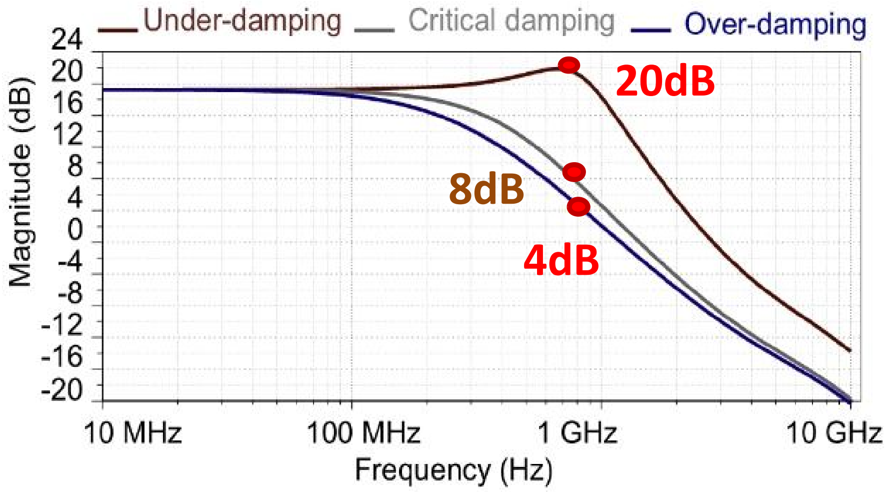
Simplified model of inverting amplifier



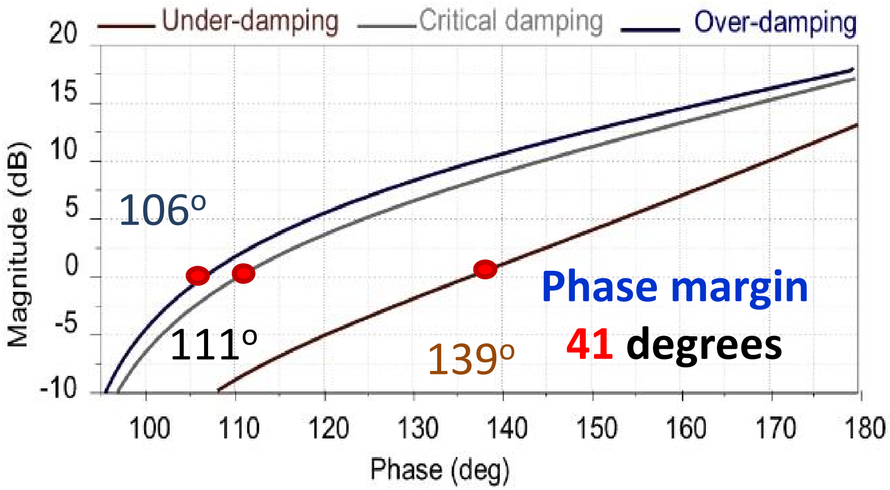
Simulated transient response



Bode plot of transfer function



Nichols plot of self-loop function



Phase margin

41 degrees

Outline

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1. Research Background
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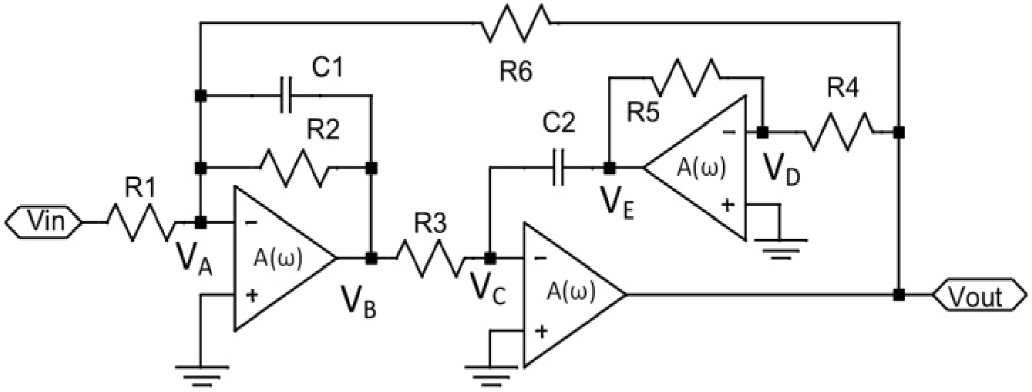
- Stability test for unity-gain and inverting amplifiers
4. **Ringing Test for High-Order Low-Pass Filters**
- **Stability test for 2nd-order Åkerberg-Mossberg filters**
5. Conclusions

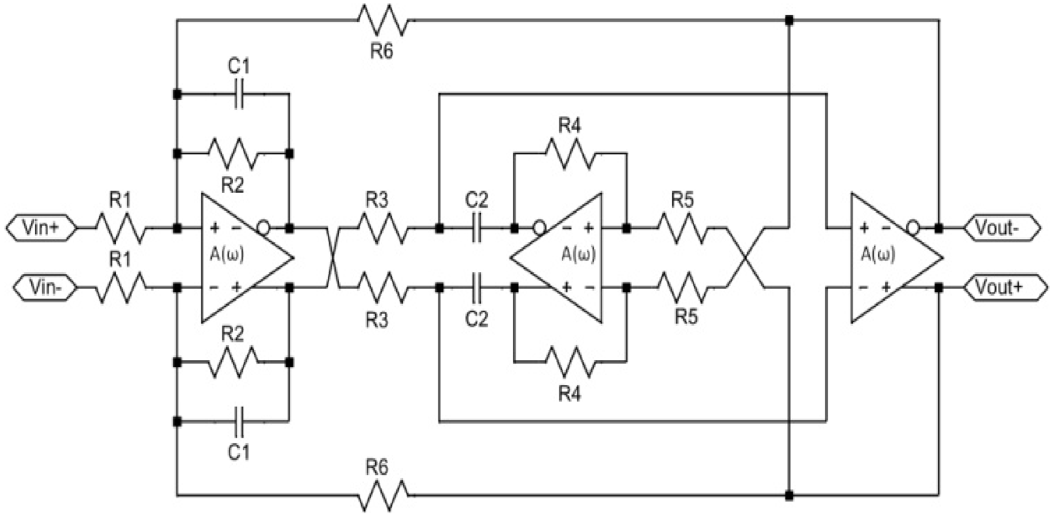
4. Ringing Test for High-Order Low-Pass Filters

Analysis of 2nd-Order Åkerberg-Mossberg LPF

Single ended Åkerberg-Mossberg LPF



Fully differential Åkerberg-Mossberg 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, $b_0 = \frac{R_6}{R_1};$

$$a_0 = \frac{R_3}{R_4} R_5 R_6 C_1 C_2; a_1 = \frac{R_3 R_5 R_6}{R_4 R_2} C_2;$$

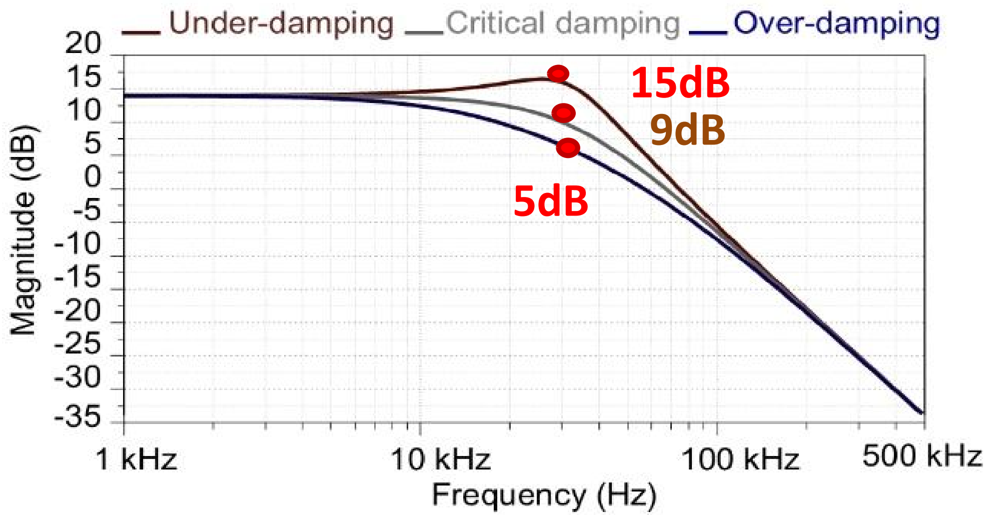
R1 = 100 Ω, R2 = 50 kΩ, R3 = R4 = 50 kΩ, C1 = 5 nF, C2 = 10 nF, C3 = 3.18 nF, at f_0 = 100 kHz.

- **Over-damping (R5 = 0.5 kΩ),**
- **Critical damping (R5 = 1 kΩ), and**
- **Under-damping (R5 = 2 kΩ).**

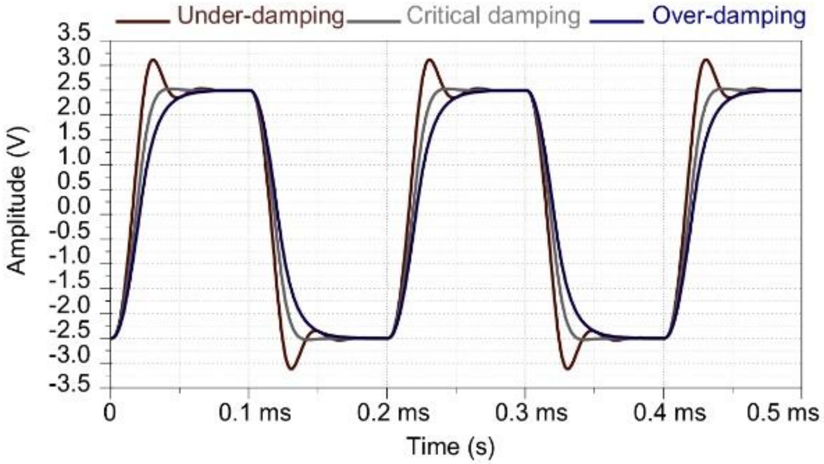
4. Ringing Test for High-Order Low-Pass Filters

Simulation Results of 2nd-Order Ladder LPF

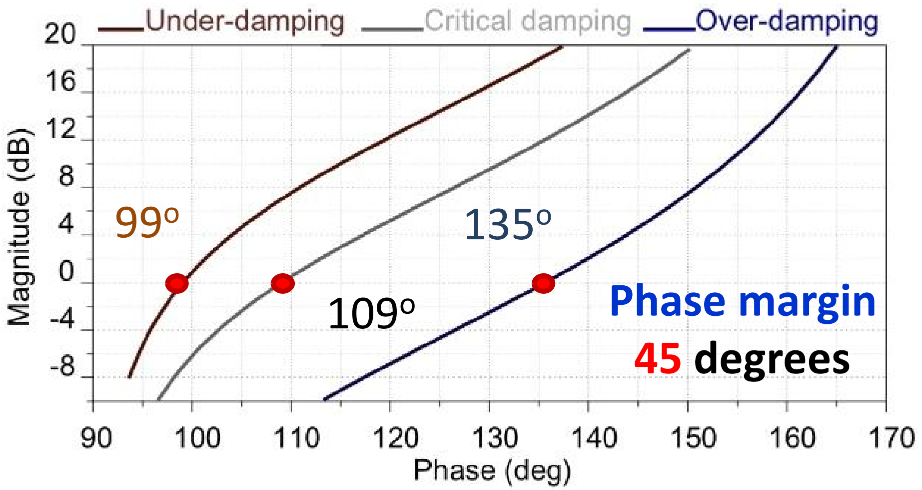
Bode plot of transfer function



Transient response



Nichols plot of self-loop function



Over-damping:

→**Phase margin is 81 degrees.**

Critical damping:

→**Phase margin is 71 degrees.**

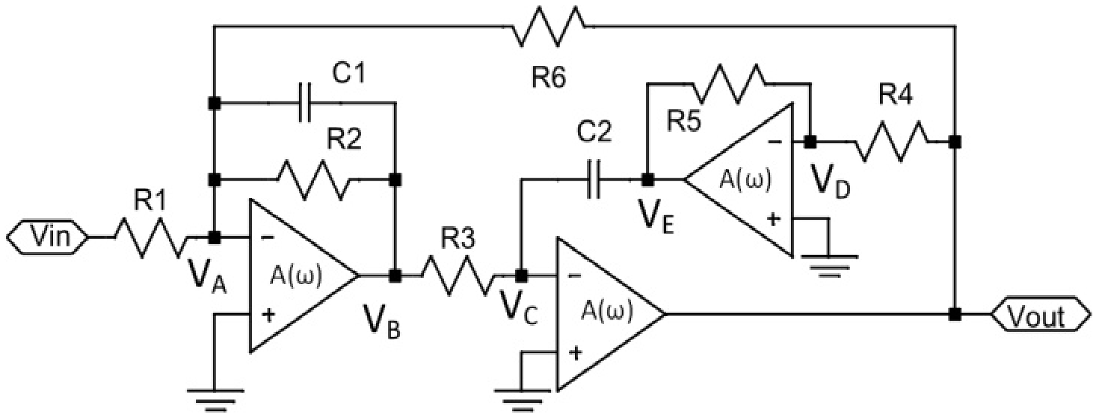
Under-damping:

→**Phase margin is 45 degrees.**

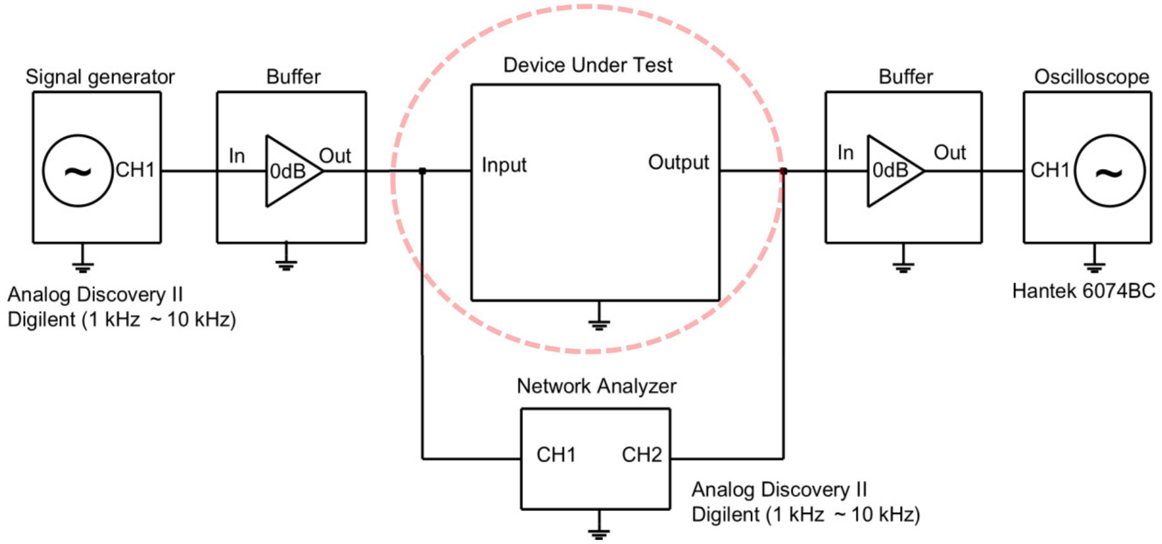
4. Ringing Test for High-Order Low-Pass Filters

Implemented Circuit of Åkerberg-Mossberg LPF

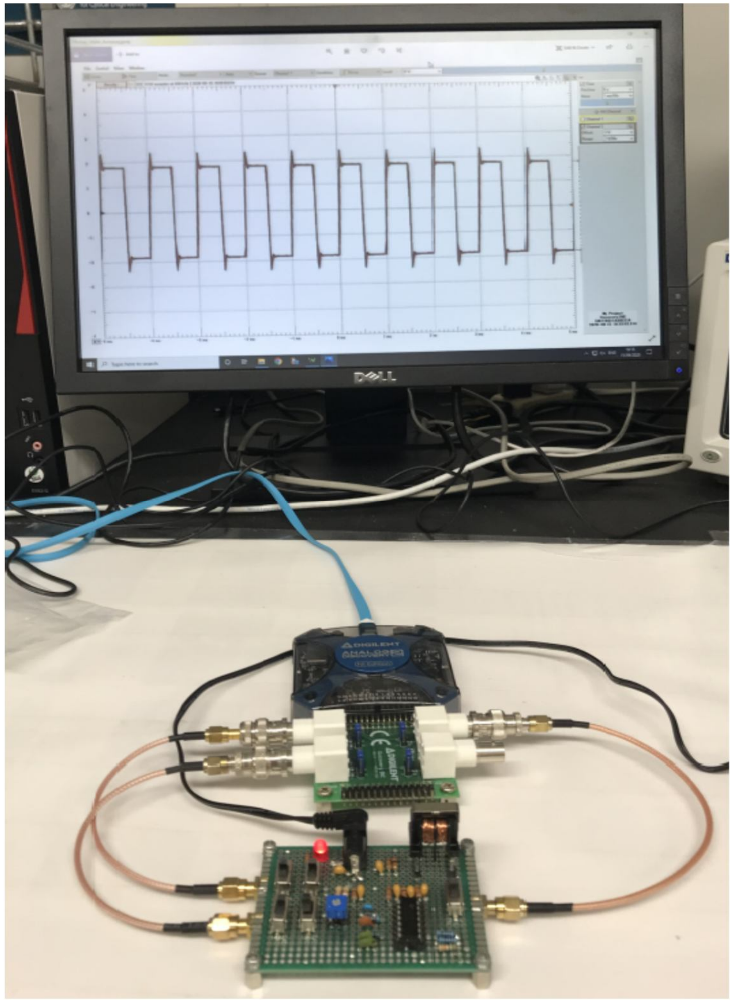
Schematic of Åkerberg-Mossberg LPF



Device Under Test



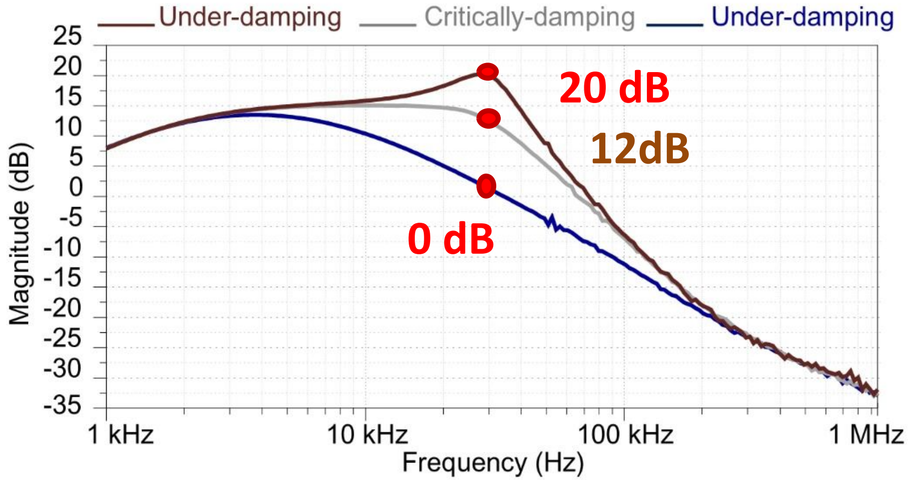
Measurement set up



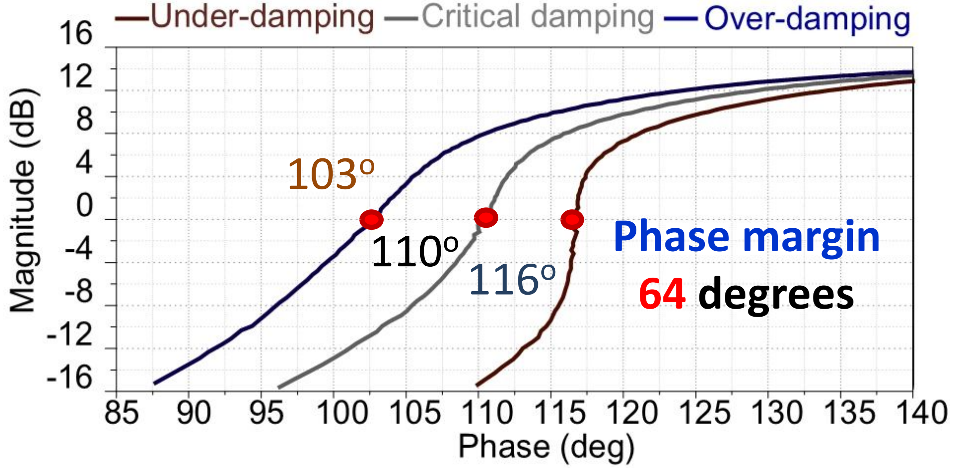
4. Ringing Test for High-Order Low-Pass Filters

Measurement Results of Åkerberg-Mossberg LPF

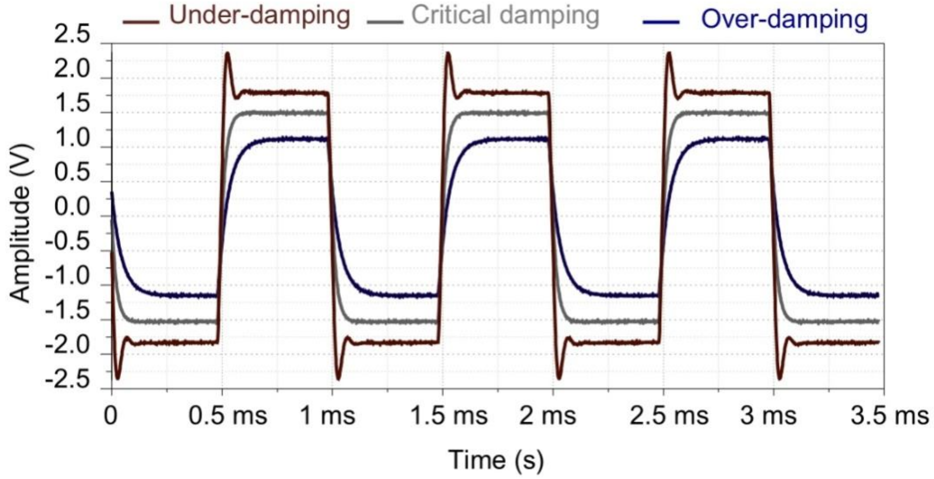
Bode plot of transfer function



Nichols plot of self-loop function



Transient response



Over-damping:

→Phase margin is 77 degrees.

Critical damping:

→Phase margin is 70 degrees.

Under-damping:

→Phase margin is 64 degrees.

Outline

1. Research Background
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    - Stability test for 2nd-order Åkerberg-Mossberg filters
5. **Conclusions**

5. Comparison

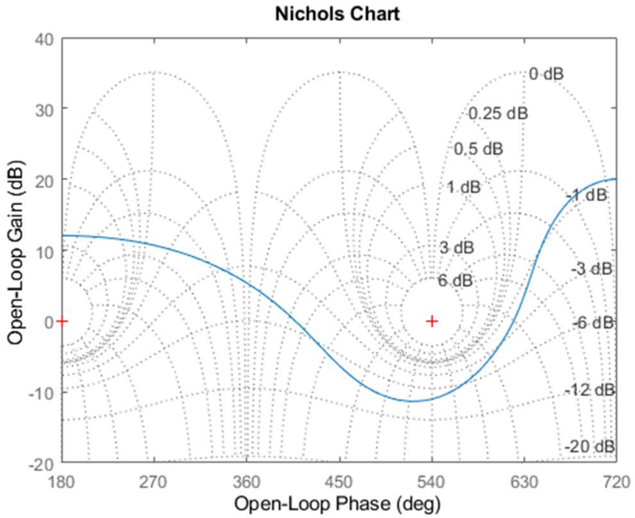
Features	Comparison measurement	Replica measurement	Middlebrook's method
Main objective	Self-loop function	Loop gain	Loop gain
Transfer function accuracy	Yes	No	No
Breaking feedback loop	No	Yes	Yes
Operating region accuracy	Yes	No	No
Phase margin accuracy	Yes	No	No
Passive networks	Yes	No	No

5. Discussions

- Loop gain is independent of frequency variable.

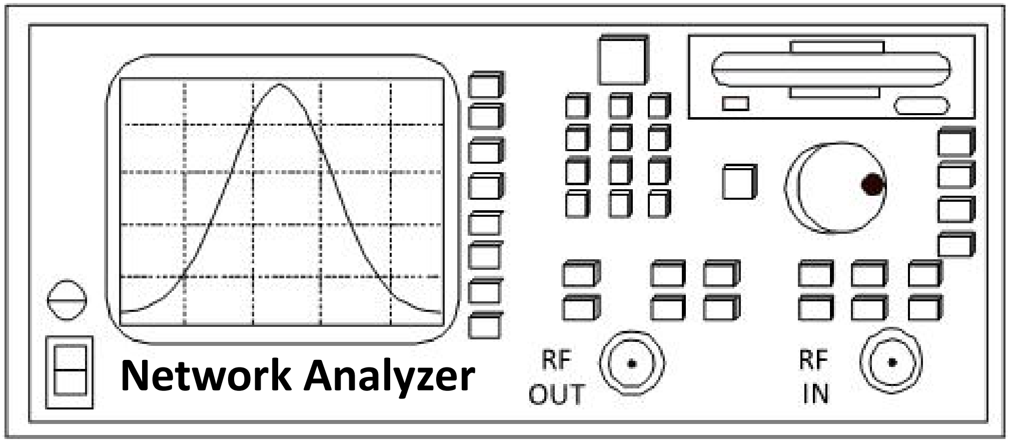
→Loop gain in adaptive feedback network is significantly different from self-loop function in linear negative feedback network.

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**

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Thank you very much!

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Laboratory