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# Ringing Test for Second-Order Sallen-Key Low-Pass Filters

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# Outline

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2. **Analysis of Behaviors of High-order Systems**
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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 Sallen-Key low-pass filters
5. **Conclusions**

# 1. Research Background

## Effects of Ringing on 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:

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

### Common types of noise:

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

**Ringing does the following things:**

- Causes EMI noise,
- Increases the 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)

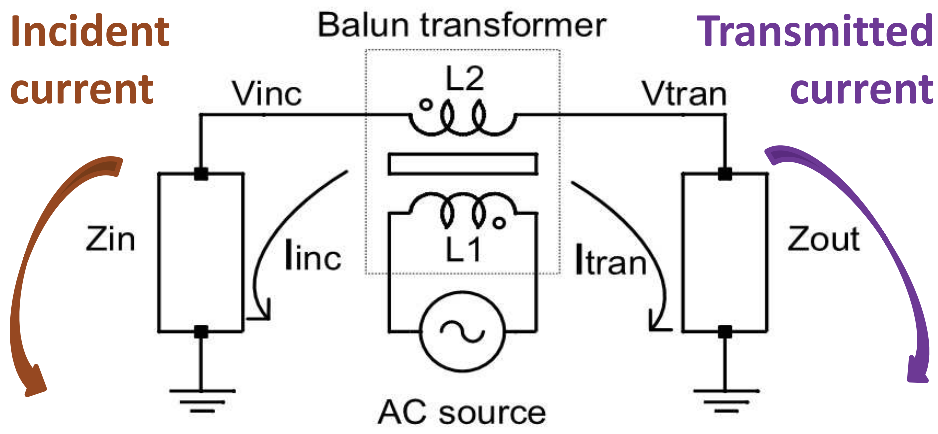
# 1. Research Background

## Achievements of Study

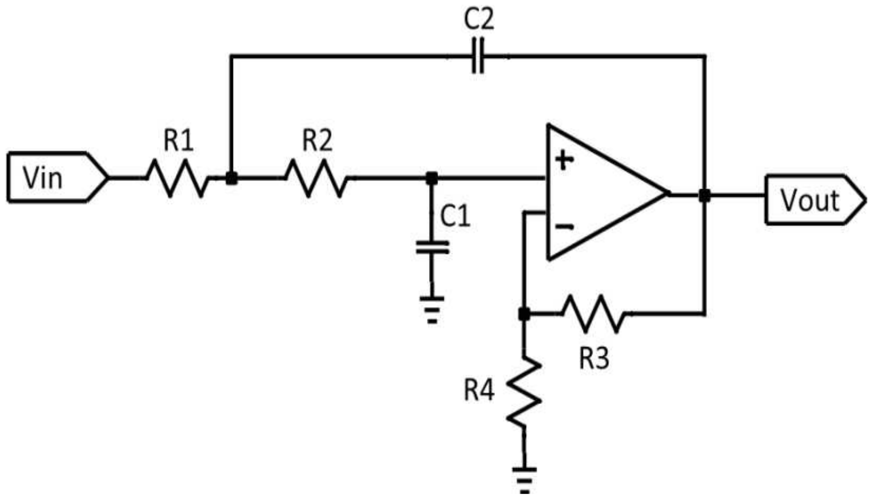
### Comparison measurement

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

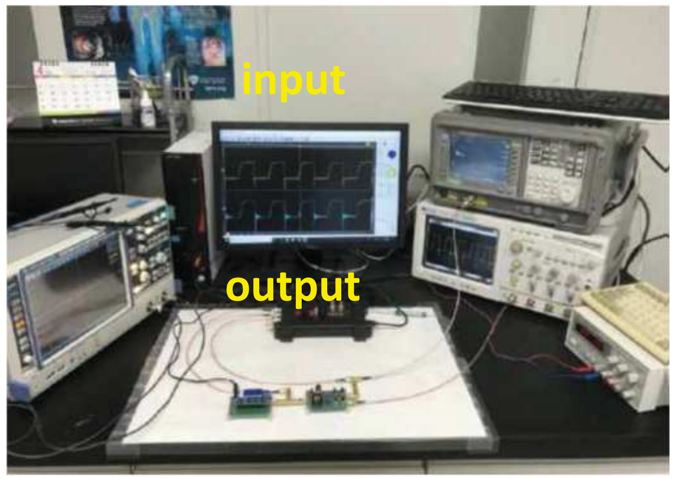
### Alternating current conservation




### 2nd-order Sallen-Key low-pass LPF



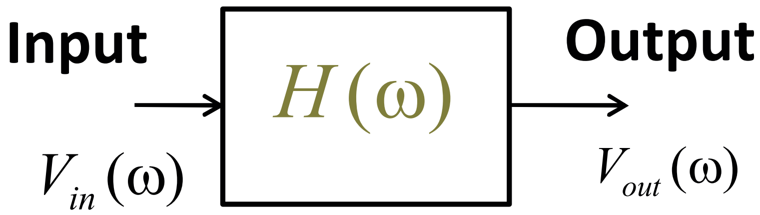

### Implemented circuit



# 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**

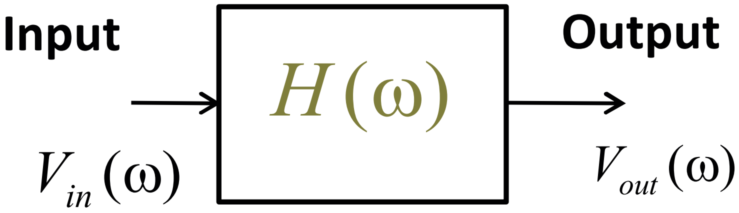
} Bode plots

- ○ **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

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

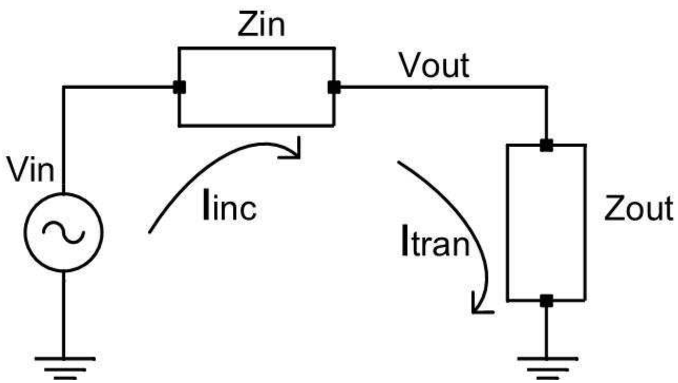
# 1. Research Background

## Alternating Current Conservation

### Transfer function

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

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

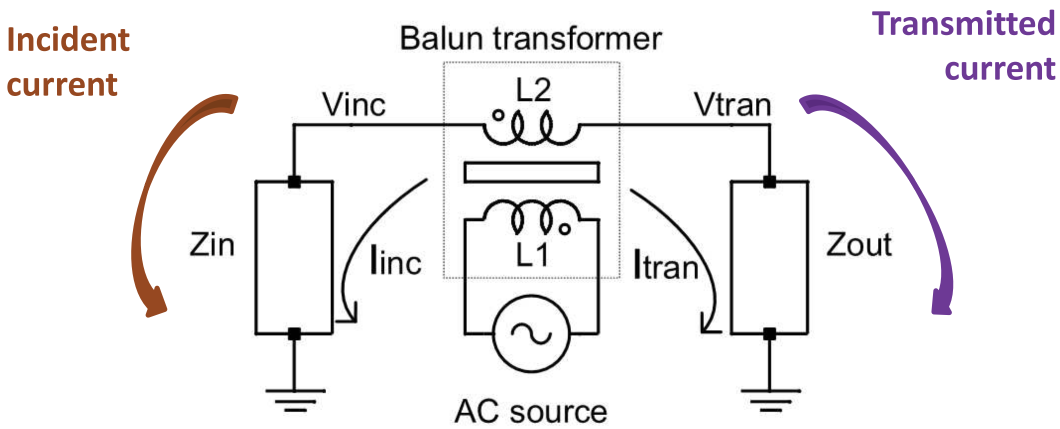



**Simplified linear system**

### Self-loop function

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

**10 mH inductance**

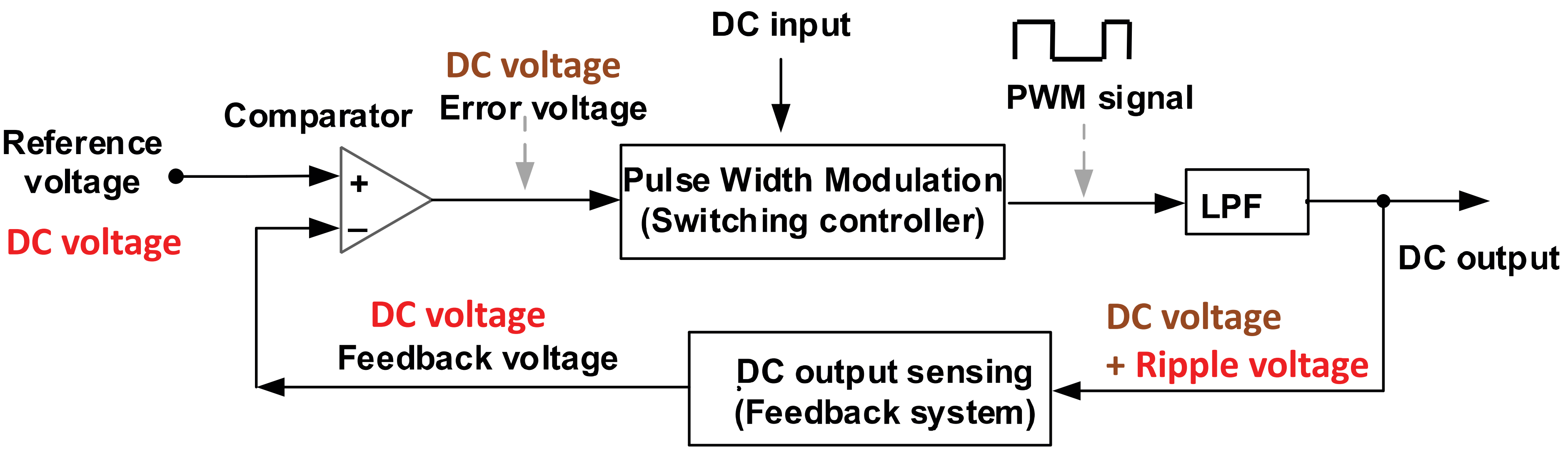



**Derivation of self-loop function**

# 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).**

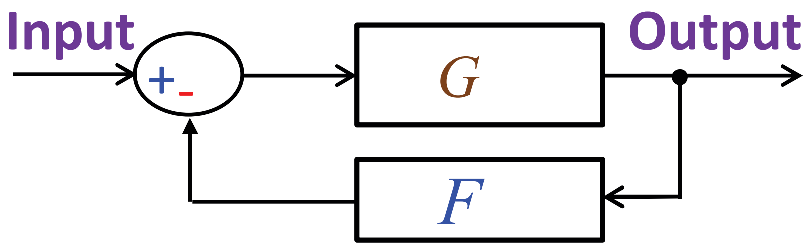
**Transfer function of an adaptive feedback network is significantly different from transfer function of a linear negative feedback network.**

**→ 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

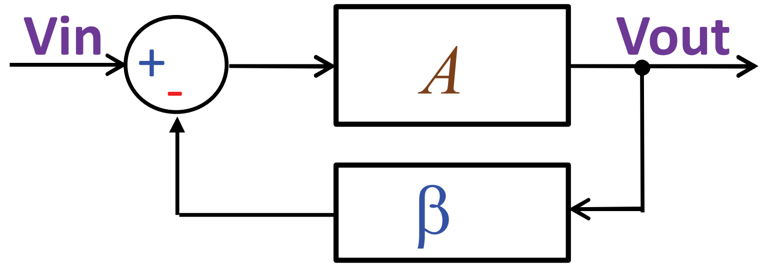



**Transfer function**

**GF : loop gain**

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

### Inverting amplifier

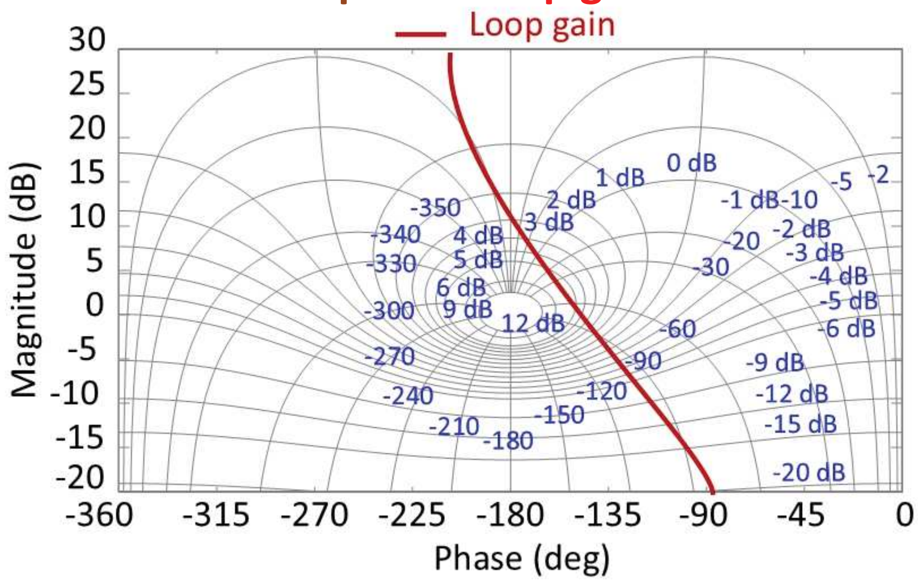



**Transfer function**

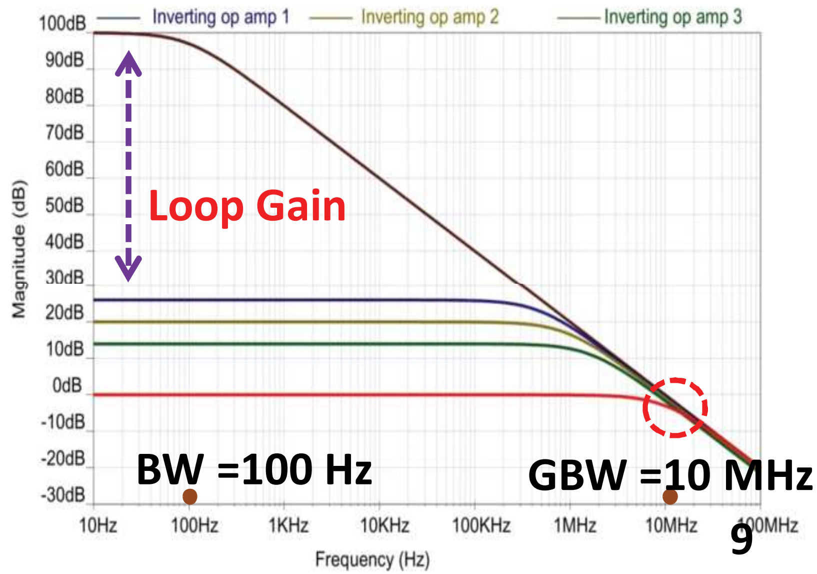
**Aβ : loop gain**

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

### Nichols plot of loop gain




### Gain reduction



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5. Conclusions

# 2. Analysis of Behaviors of High-order Systems

## Characteristics of 2nd-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** ($\Delta$) | $\frac{1}{a_0} < \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^2 - 4a_0 > 0$ | $\frac{1}{a_0} = \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^2 - 4a_0 = 0$ | $\frac{1}{a_0} > \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^2 - 4a_0 < 0$ |
| **Module** $\lvert H(\omega)\rvert$ | $\dfrac{\frac{1}{a_0}}{\sqrt{\omega^2 + \left(\frac{a_1}{2a_0} - \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}\right)^2}\sqrt{\omega^2 + \left(\frac{a_1}{2a_0} + \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}\right)^2}}$ | $\dfrac{1}{a_0}\dfrac{1}{\left[\omega^2 + \left(\frac{a_1}{2a_0}\right)^2\right]} = \dfrac{1}{2} = -6dB$ | $\dfrac{\frac{1}{a_0}}{\sqrt{\left(\omega - \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}\right)^2 + \left(\frac{a_1}{2a_0}\right)^2}\sqrt{\left(\omega + \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}\right)^2 + \left(\frac{a_1}{2a_0}\right)^2}}$ |
| **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** $(\Delta)$ | $\Delta = a_1^2 - 4a_0 > 0$ | | $\Delta = a_1^2 - 4a_0 = 0$ | | $\Delta = a_1^2 - 4a_0 < 0$ | |
| $\lvert L(\omega)\rvert$ | $\omega\sqrt{(a_0\omega)^2 + a_1^2}$ | | $\omega\sqrt{(a_0\omega)^2 + a_1^2}$ | | $\omega\sqrt{(a_0\omega)^2 + a_1^2}$ | |
| $\theta(\omega)$ | $\frac{\pi}{2} + \arctan\frac{a_0\omega}{a_1}$ | | $\frac{\pi}{2} + \arctan\frac{a_0\omega}{a_1}$ | | $\frac{\pi}{2} + \arctan\frac{a_0\omega}{a_1}$ | |
| $\omega_1 = \frac{a_1}{2a_0}\sqrt{\sqrt{5}-2}$ | $\lvert L(\omega_1)\rvert > 1$ | $\pi - \theta(\omega_1) > 76.3^o$ | $\lvert L(\omega_1)\rvert = 1$ | $\pi - \theta(\omega_1) = 76.3^o$ | $\lvert L(\omega_1)\rvert < 1$ | $\pi - \theta(\omega_1) < 76.3^o$ |
| $\omega_2 = \frac{a_1}{2a_0}$ | $\lvert L(\omega_2)\rvert > \sqrt{5}$ | $\pi - \theta(\omega_2) > 63.4^o$ | $\lvert L(\omega_2)\rvert = \sqrt{5}$ | $\pi - \theta(\omega_2) = 63.4^o$ | $\lvert L(\omega_2)\rvert < \sqrt{5}$ | $\pi - \theta(\omega_2) < 63.4^o$ |
| $\omega_3 = \frac{a_1}{a_0}$ | $\lvert L(\omega_3)\rvert > 4\sqrt{2}$ | $\pi - \theta(\omega_3) > 45^o$ | $\lvert L(\omega_3)\rvert = 4\sqrt{2}$ | $\pi - \theta(\omega_3) = 45^o$ | $\lvert L(\omega_3)\rvert < 4\sqrt{2}$ | $\pi - \theta(\omega_3) < 45^o$ |

# 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:**

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

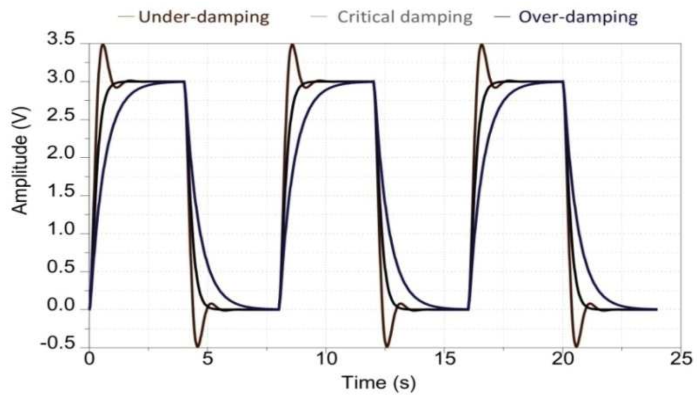
$$H_2(\omega) = \frac{1}{(j\omega)^2 + 2j\omega + 1};$$

- **Over-damping:**

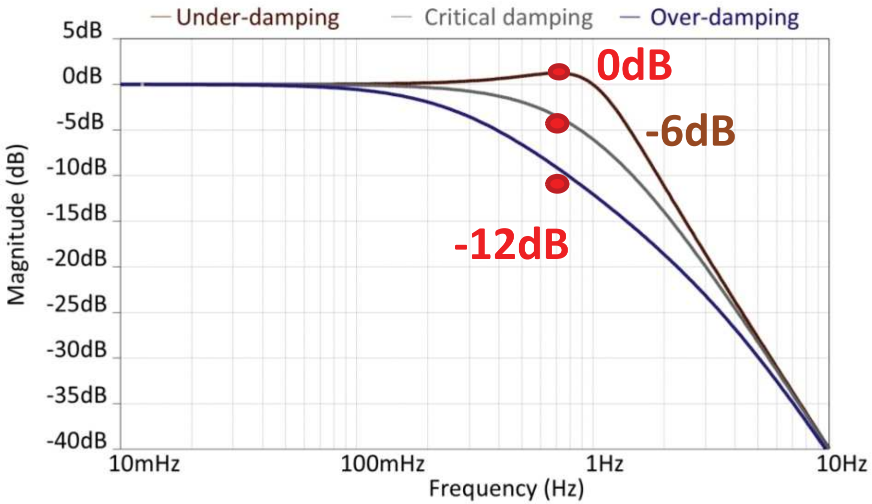
$$L_3(\omega) = (j\omega)^2 + 3j\omega;$$

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

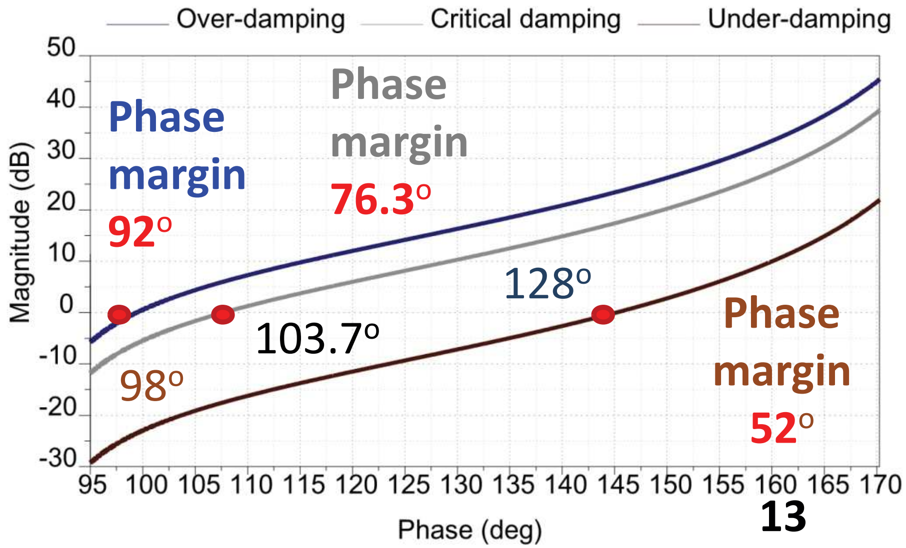
### Transient response




### Bode plot of transfer function




### Nichols plot of self-loop function



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   - **Stability test for shunt-shunt feedback amplifiers**
   - **Stability test for unity-gain and inverting amplifiers**
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   - Stability test for passive and active RLC circuits
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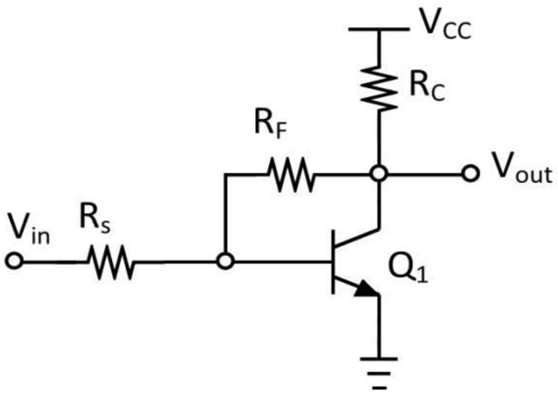
5. Conclusions

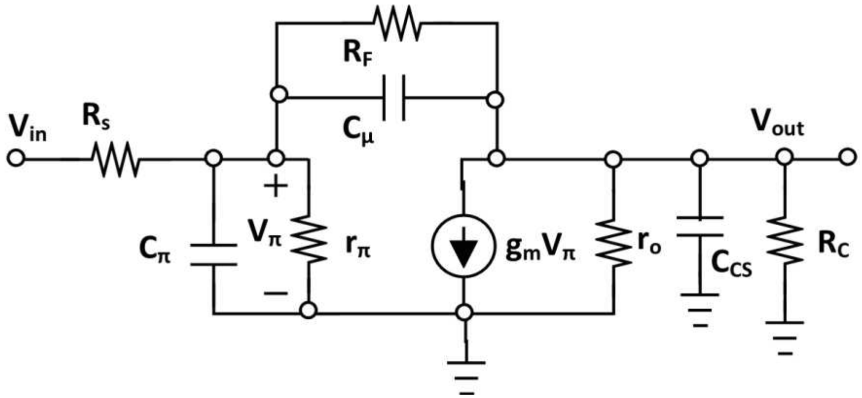
# 3.Ringing Test for Feedback Amplifiers

## Analysis of Shunt-Shunt Feedback Amplifier

**BJT shunt-shunt feedback amplifier**




**Small signal model**




**Apply superposition at the nodes $V_{\pi}$ 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 and self-loop function**

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

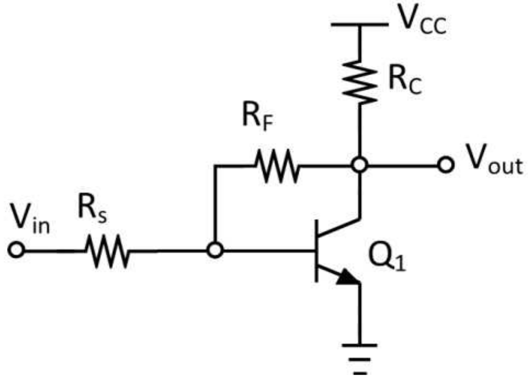
**Where,** $b_0=R_L C_{GD1};\ b_1=-R_L g_{m1};\ a_0=R_S R_L\left(C_{GD1}C_{GS1}+C_{GD1}C_{DB1}+C_{DB1}C_{GS1}\right);$

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

# 3.Ringing Test for Feedback Amplifiers

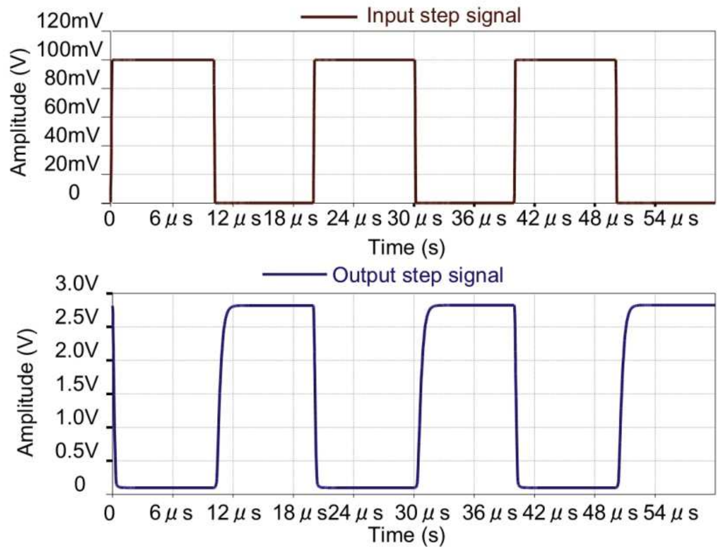
## Characteristics of Shunt-Shunt Feedback Amplifier

**BJT shunt-shunt feedback amplifier**

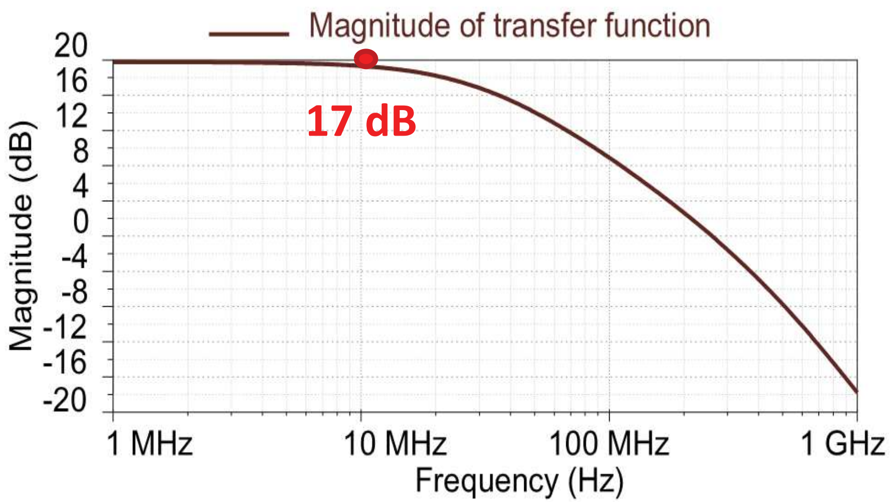



**$R_f$ = 1 kΩ, $R_C$ = 10 kΩ, $R_S$ = 950 Ω.**

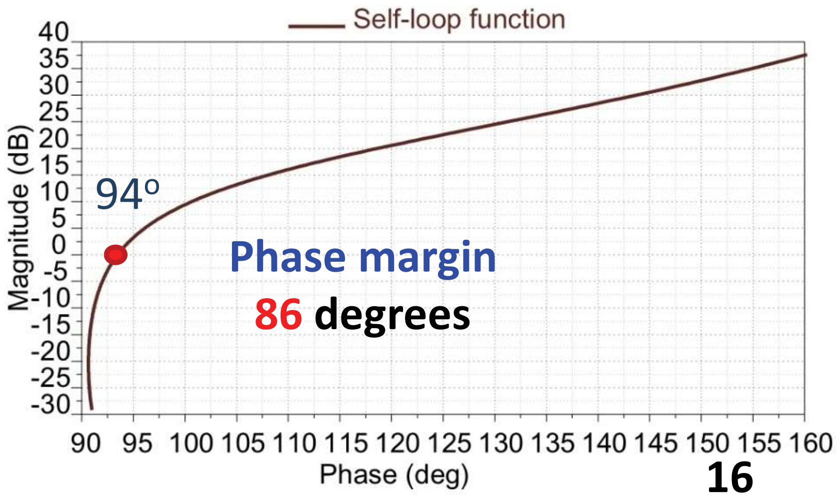
**Transient response**




**Bode plot of transfer function**




**Nichols plot of self-loop function**



# 3.Ringing Test for Feedback Amplifiers

## Analysis of Op Amp without Miller's Capacitor

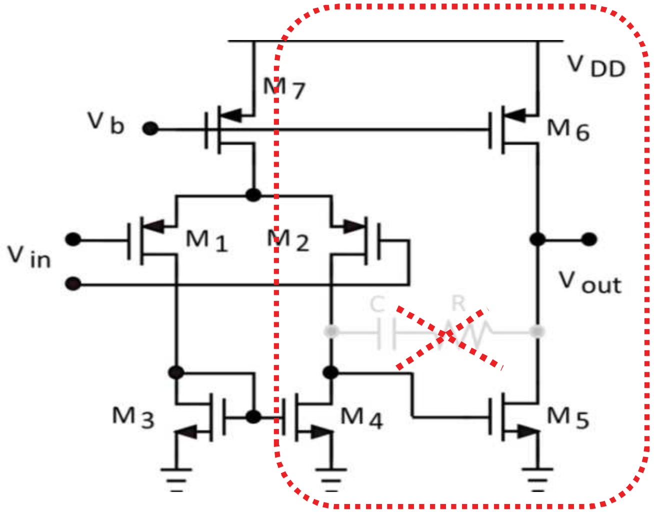
**Open-loop function**

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

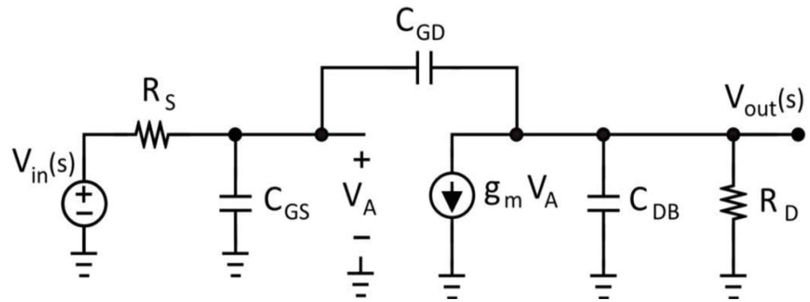
**Self-loop function**

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

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

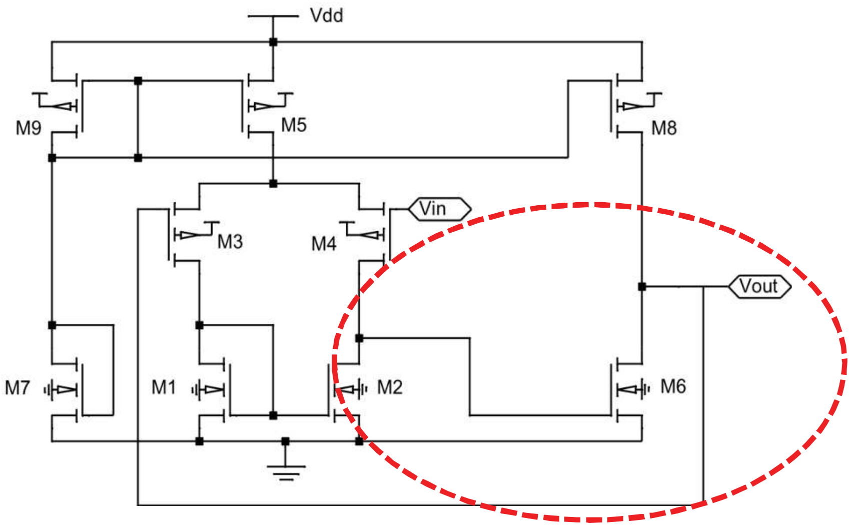
$$b_0=R_D R_S\left[(C_{GD}+C_{DB})(C_{GS}+C_{GD})-C_{GD}^2\right];$$

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

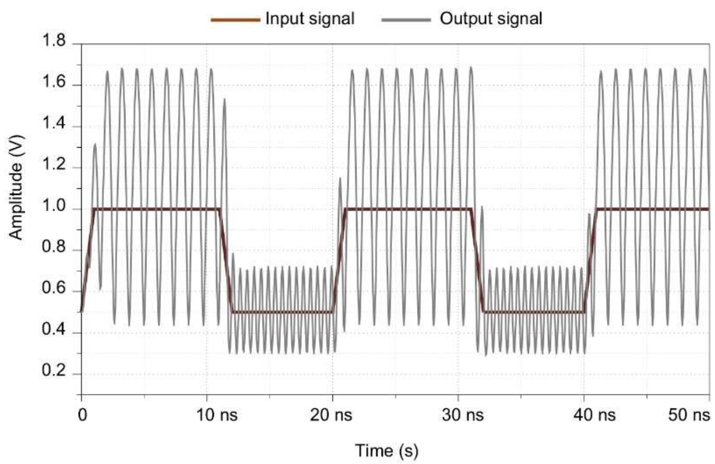
# 3.Ringing Test for Feedback Amplifiers

## Unity-Gain Amplifier without Miller's Capacitor

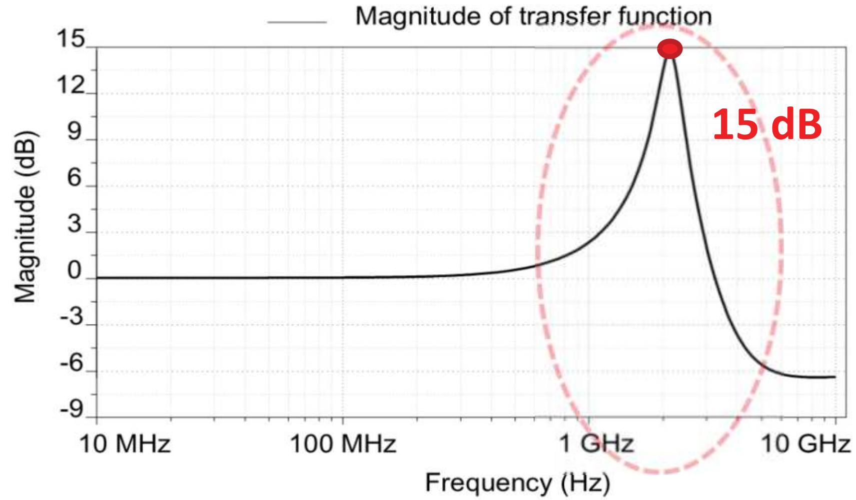
### Unity-Gain Amplifier



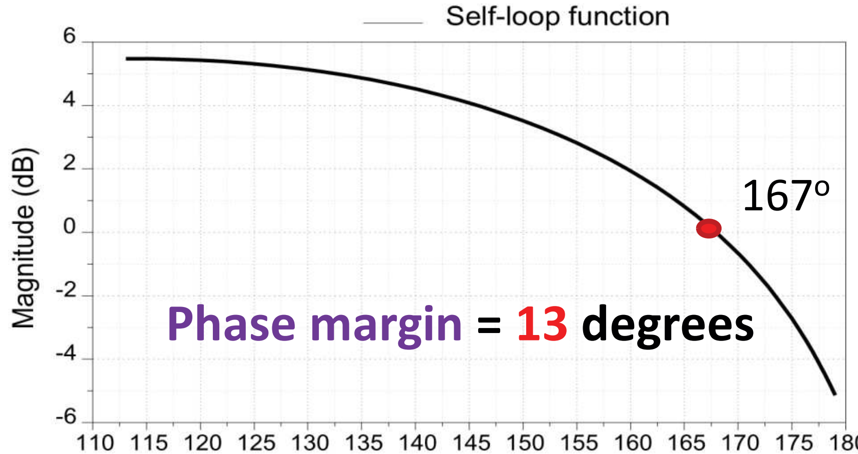

### Transient response




### Bode plot of transfer function H(ω)




### Nichols plot of self-loop function L(ω)



# 3.Ringing Test for Feedback Amplifiers

## Two-stage Op Amp with Frequency Compensation

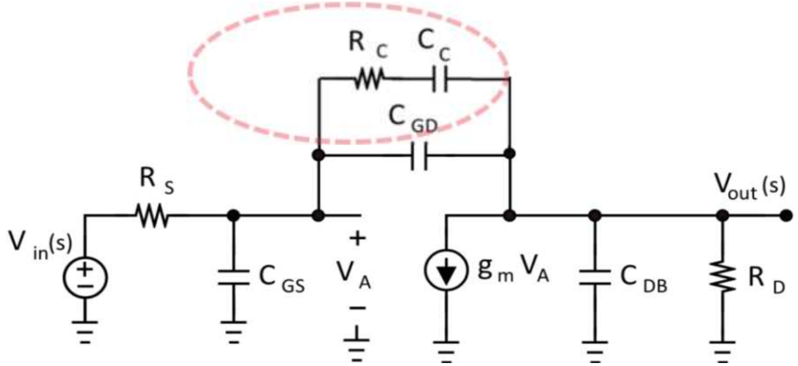
### Open-loop function

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

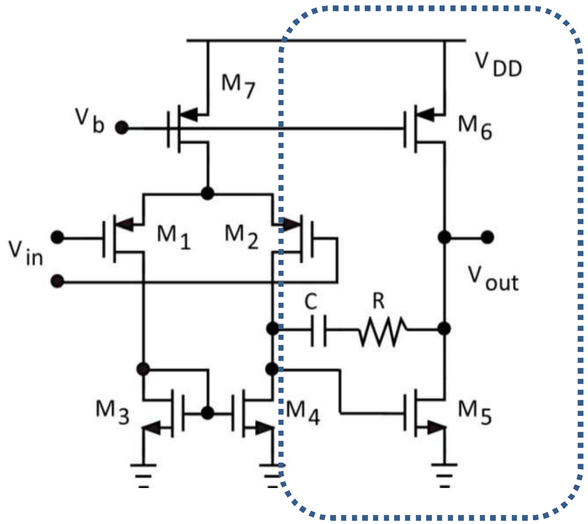
### Self-loop function

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

### Small signal model of 2nd-stage




### With Miller's capacitor and resistor




### Transfer function

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

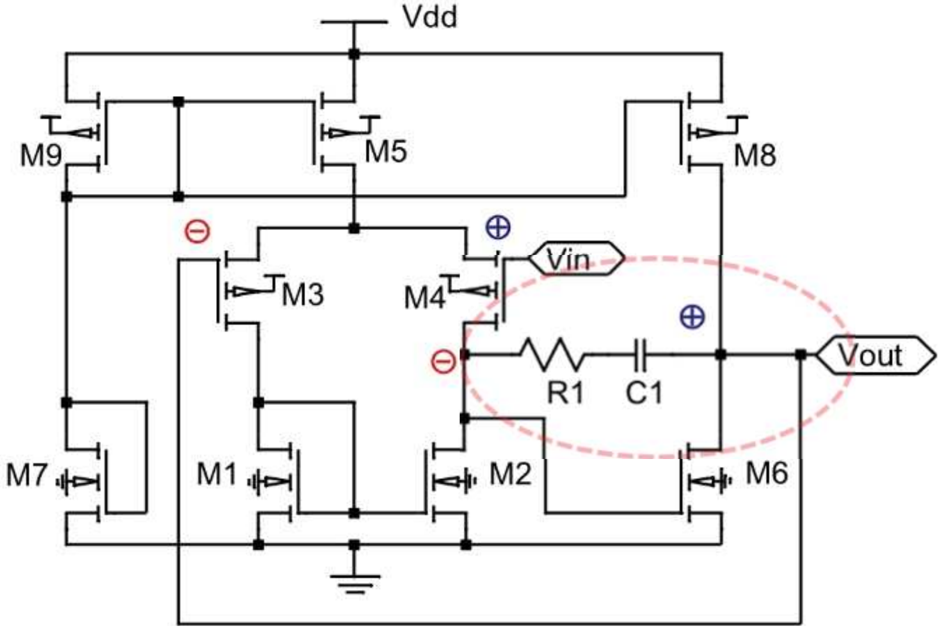
### Self-loop function

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

# 3.Ringing Test for Feedback Amplifiers

## Unity-Gain Amplifier with Miller's Capacitor

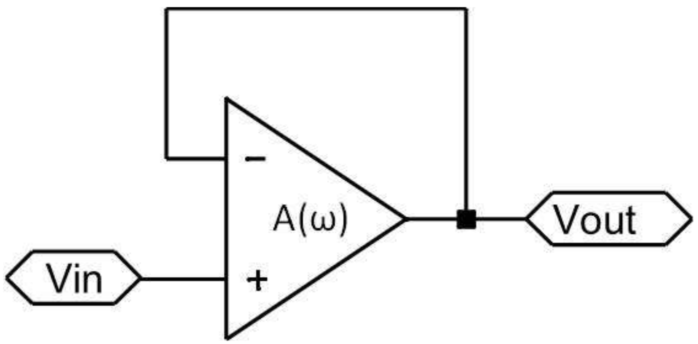
**Unity-gain amplifier with Miller's capacitor**




**Transfer function and self-loop function**

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

**Simplified model**




**Under-damping:**

**R1= 2 kΩ, C1 = 1 pF**

**Critical damping:**

**R1 = 3.5 kΩ, C1 = 0.2 pF**

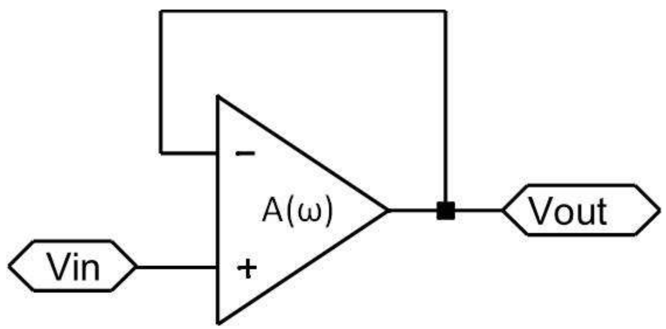
**Over-damping:**

**R1 = 3.5 kΩ, C1 = 0.8 pF**

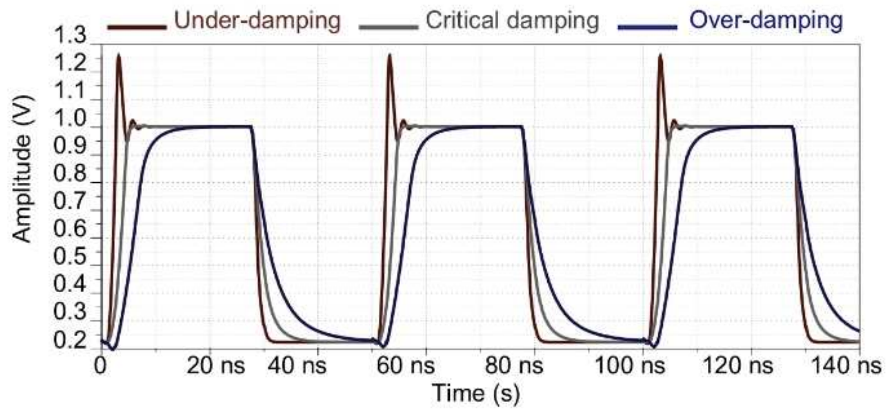
# 3.Ringing Test for Feedback Amplifiers

## Behaviors of Unity-Gain Amplifier

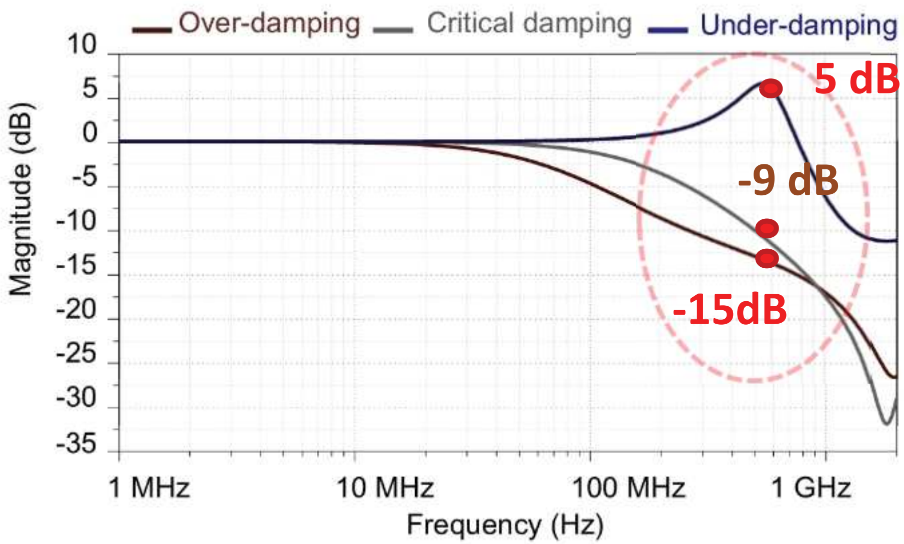
### Simplified model of unity gain amplifier



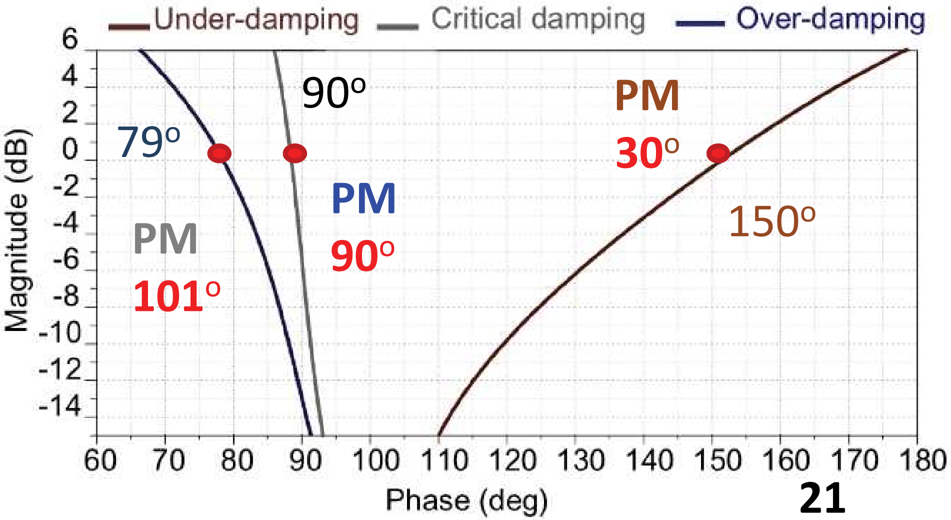

### Simulated transient response




### Bode plot of transfer function



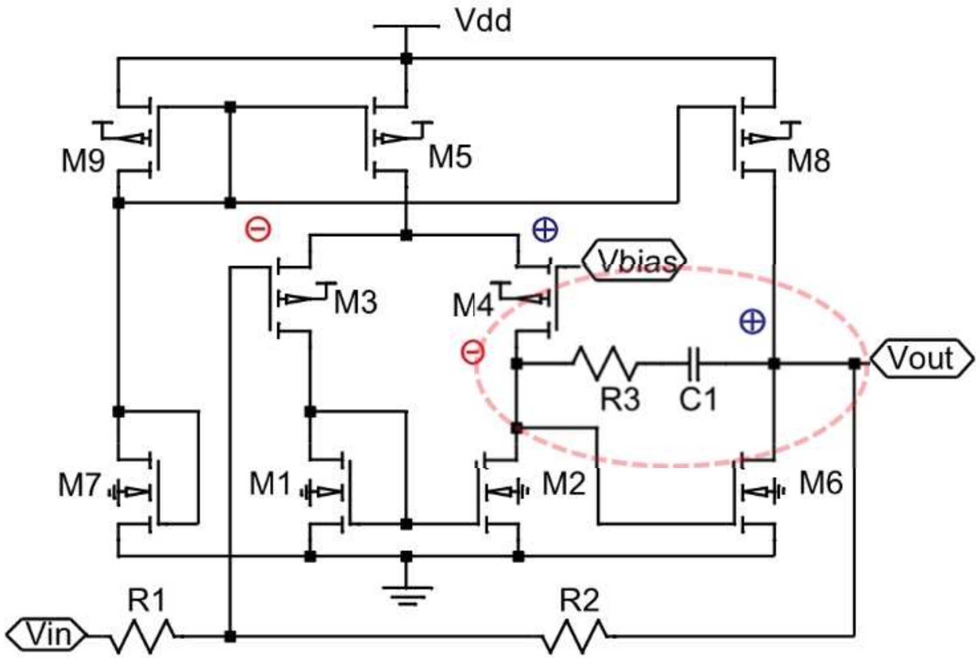

### Nichols plot of self-loop function



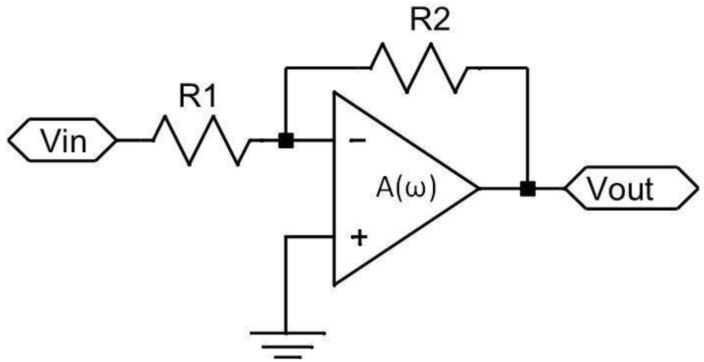
# 3.Ringing Test for Feedback Amplifiers

## Inverting Amplifier with Miller's Capacitor

**Inverting amplifier**




**Simplified model**




**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**

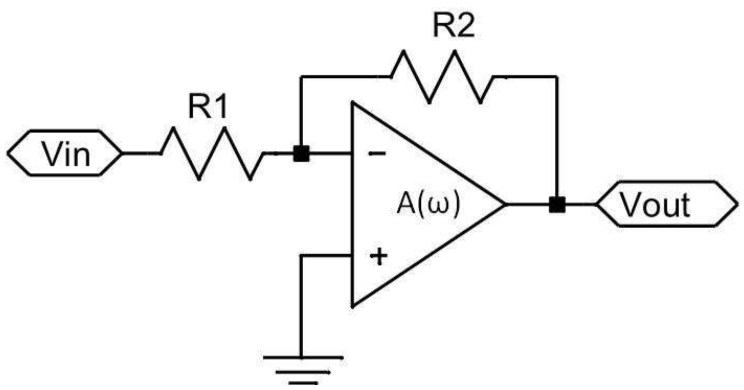
**Transfer function and self-loop function**

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

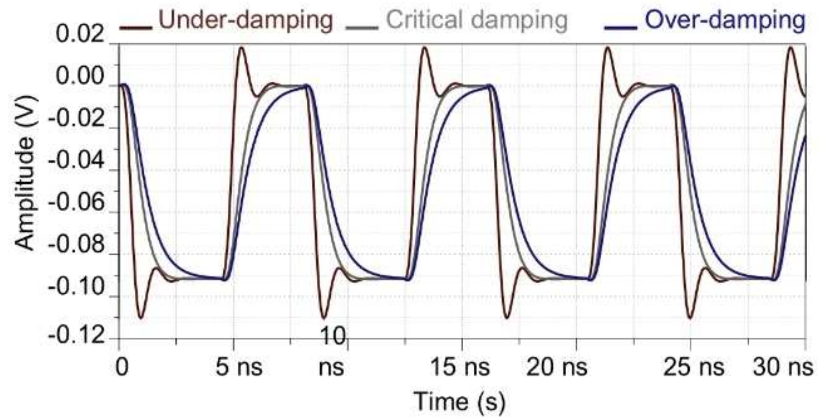
# 3.Ringing Test for Feedback Amplifiers

## Behaviors of Inverting Amplifier

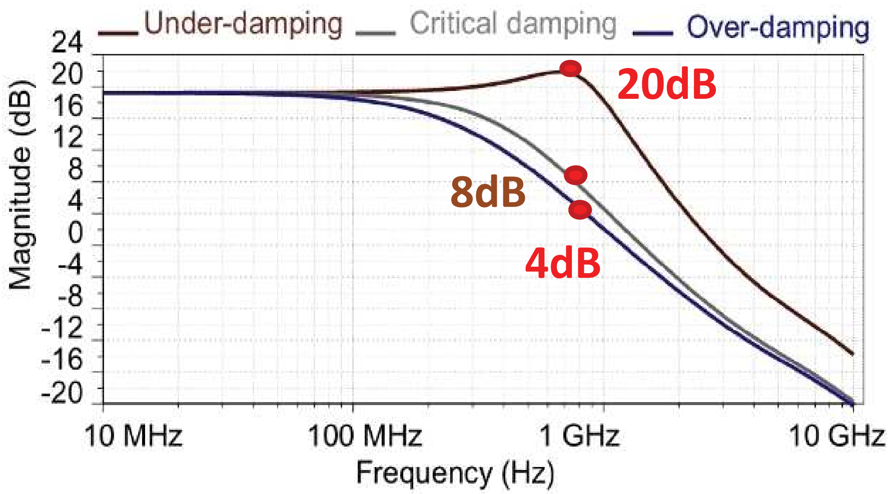
**Simplified model of inverting amplifier**



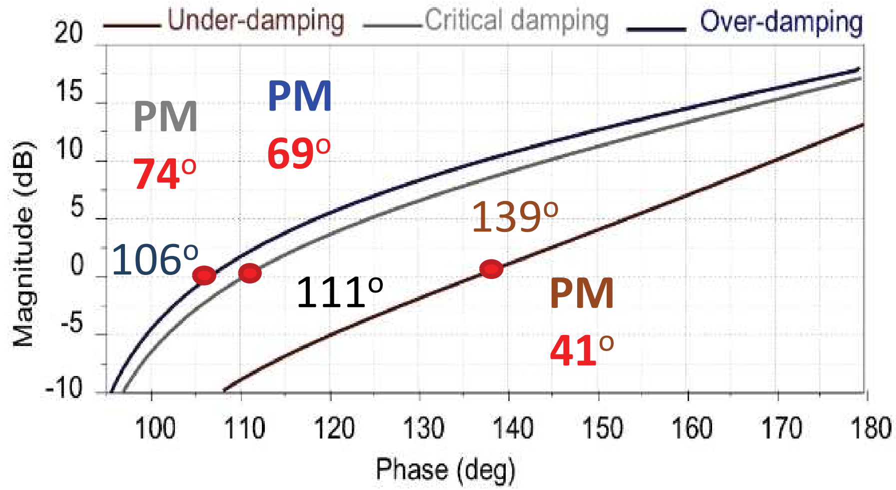

**Simulated transient response**




**Bode plot of transfer function**




**Nichols plot of self-loop function**



# Outline

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

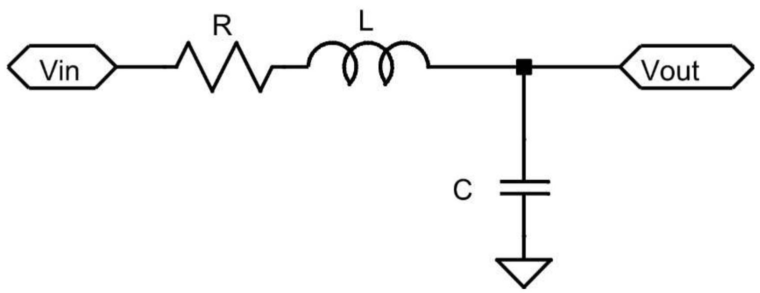
4. Ringing Test for High-order Low-Pass Filters
- **Stability test for passive and active RLC circuits**
- **Stability test for Sallen-Key low-pass filters**

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

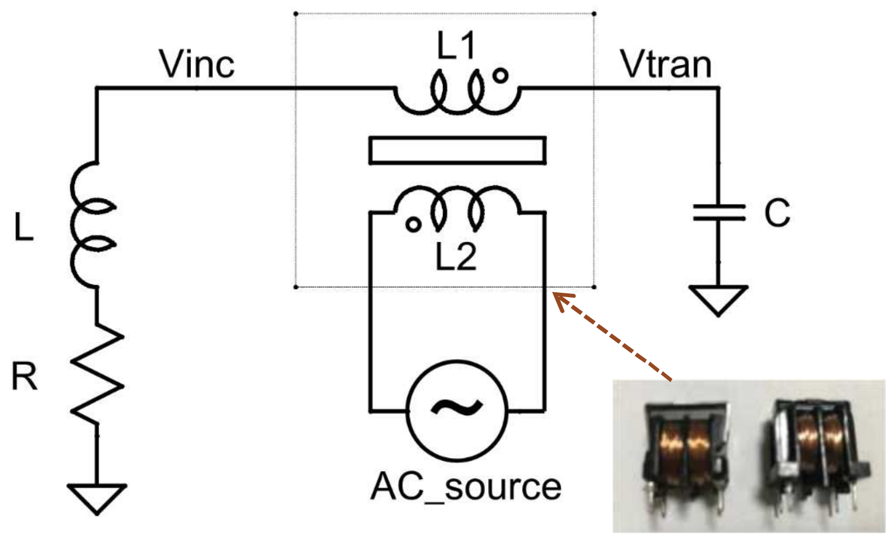
$$H(\omega) = \frac{V_{out}}{V_{in}} = \frac{1}{a_0 (j\omega)^2 + a_1 j\omega + 1};$$

### Self-loop function

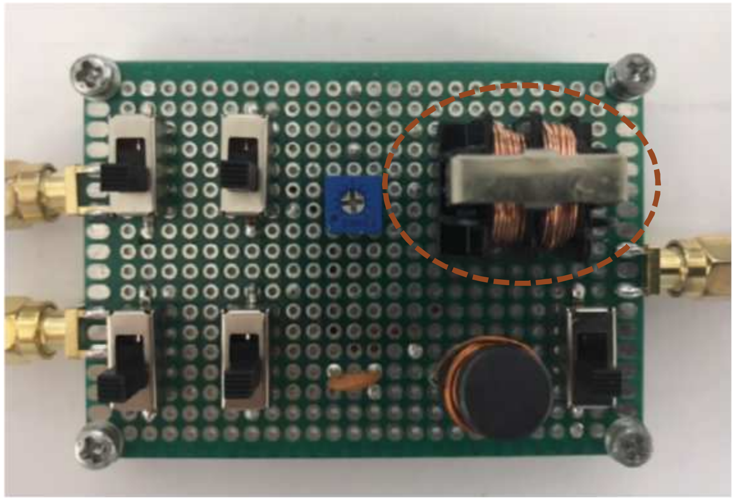
$$L(\omega) = a_0 (j\omega)^2 + a_1 j\omega;$$

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

### Derivation of self-loop function



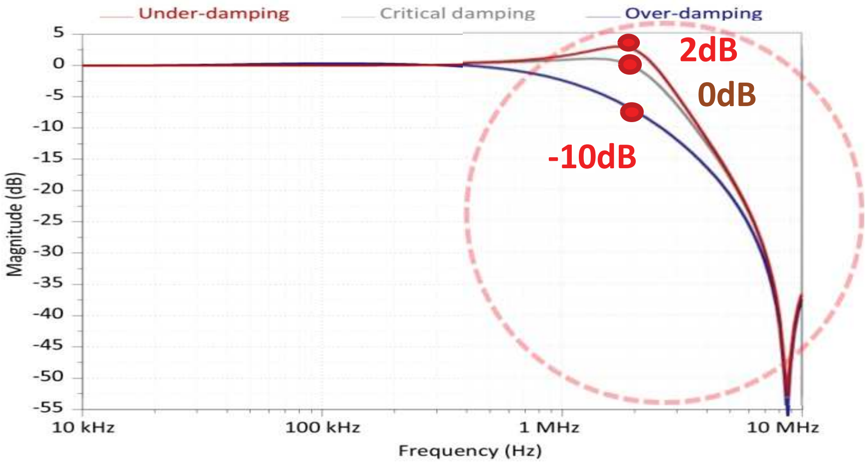

### Implemented circuit



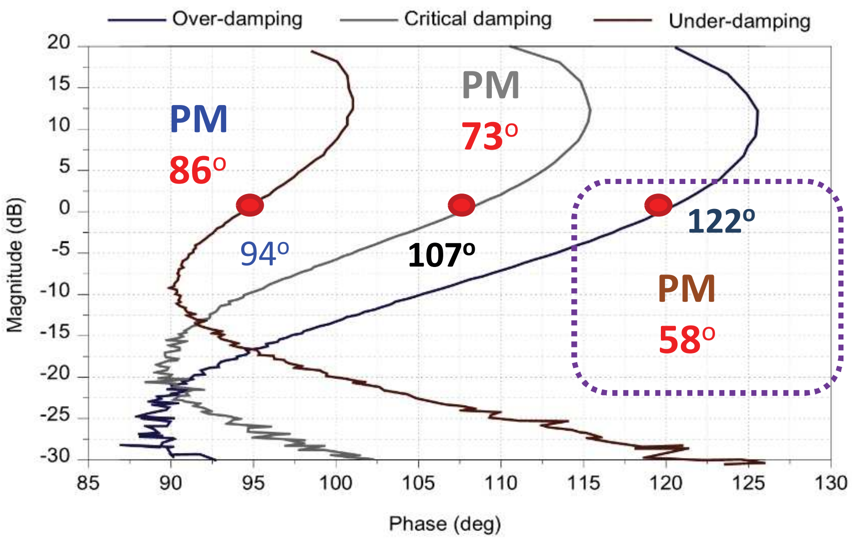
# 4. Ringing Test for High-order Low-Pass Filters

## Measurement Results for 2nd-Order Passive RLC LPF

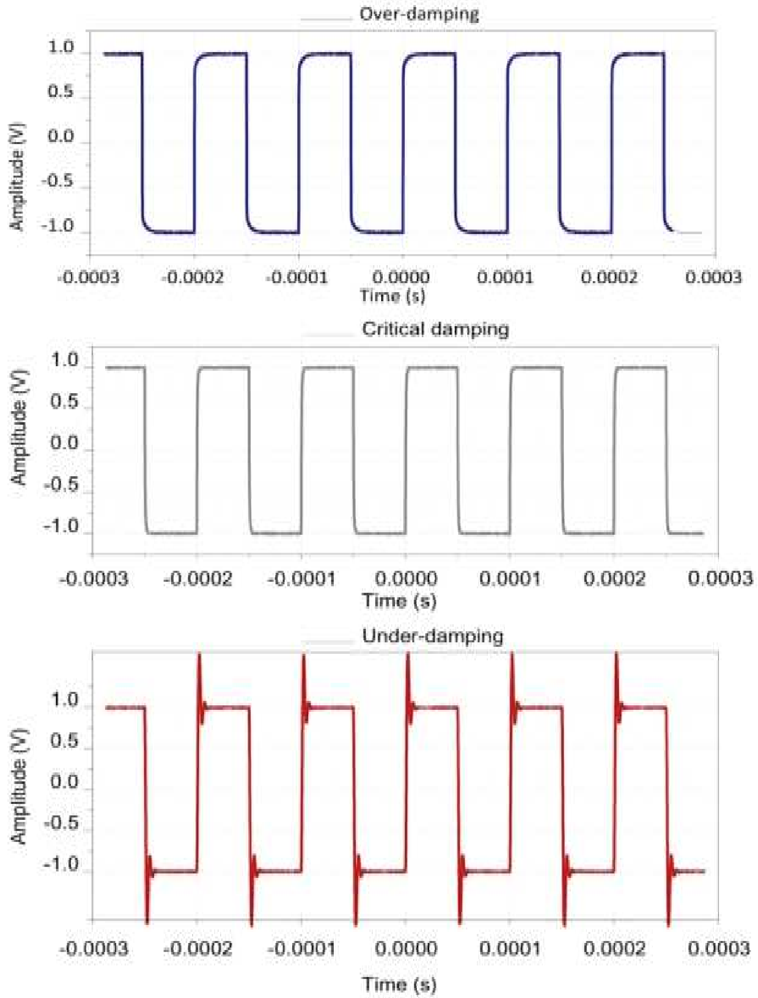
### Bode plot of transfer function




### Nichols plot of self-loop function



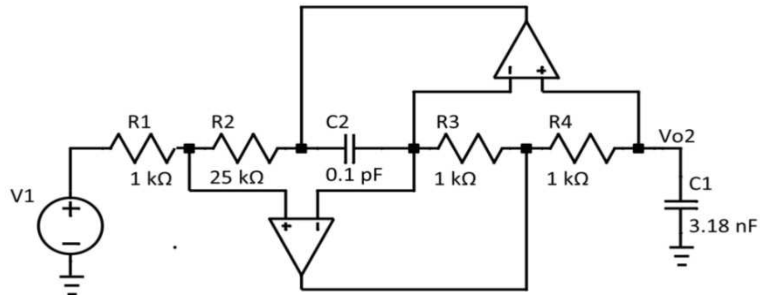

### Transient responses



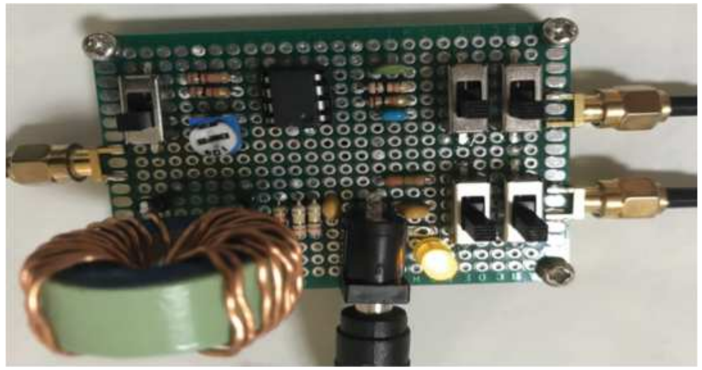
# 4. Ringing Test for High-order Low-Pass Filters

## Stability Test for 2nd-Order Active Ladder LPF

### Active ladder low-pass filter




### Implemented circuit



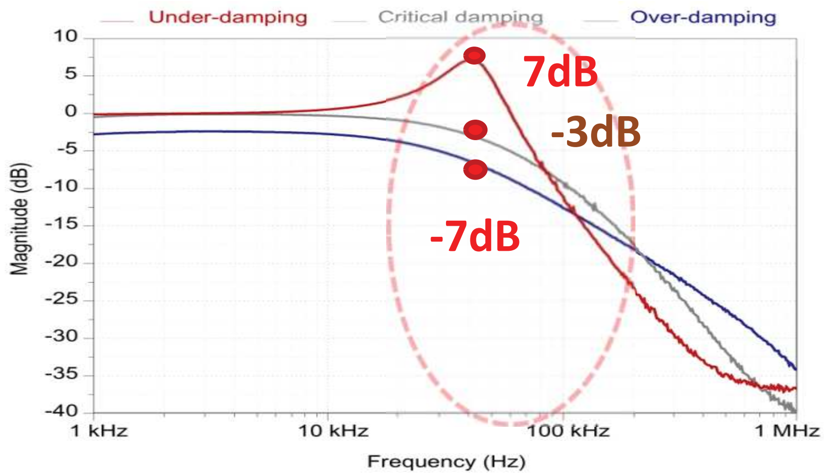
### Transfer function

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

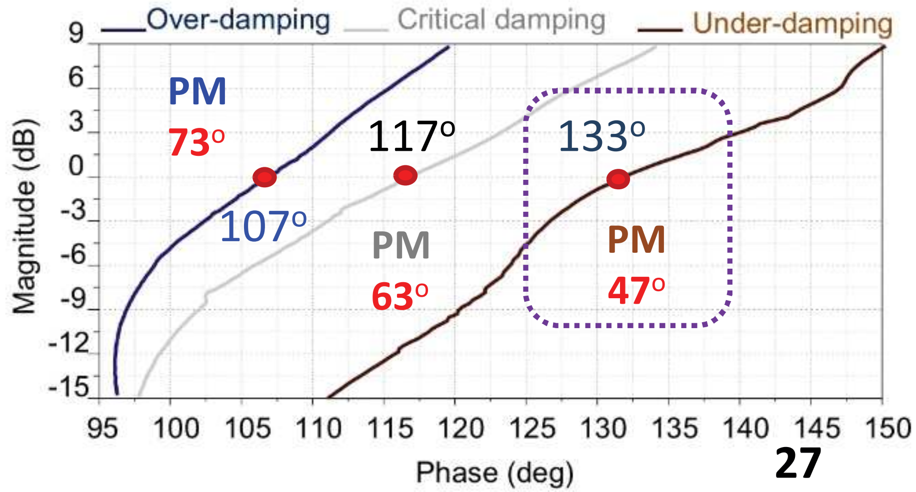
### Self-loop function

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

### Bode plot of transfer function



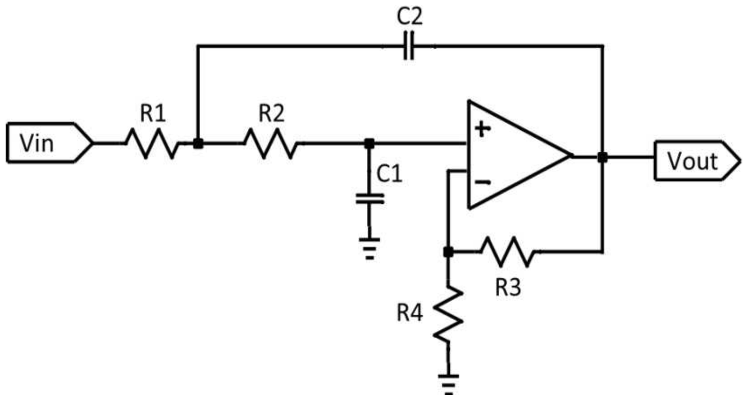

### Nichols plot of self-loop function



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

## Analysis of 2nd-Order Sallen-Key low-pass LPF

**Single ended Sallen-Key low-pass LPF**




**Transfer function & self-loop function**

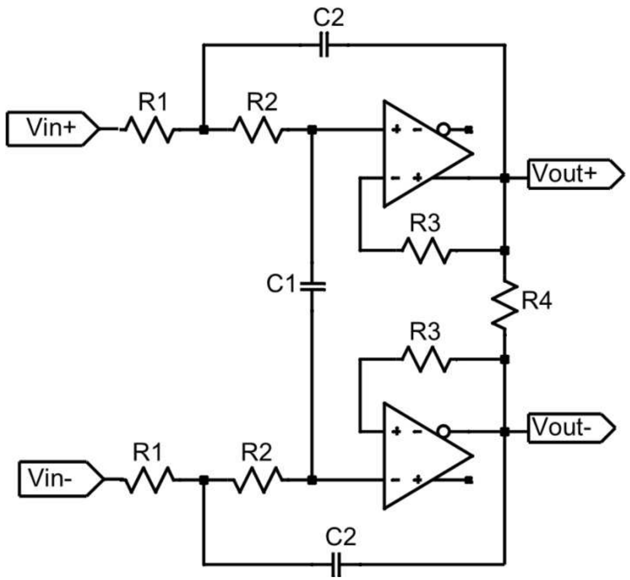
$$H(\omega) = \frac{b_0}{a_0 (j\omega)^2 + a_1 j\omega + 1};$$

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

**where,** $b_0 = 1 + \frac{R_3}{R_4};$

$$a_0 = R_1 C_1 R_2 C_2; a_1 = C_1 (R_1 + R_2) - \frac{R_3}{R_4} R_1 C_2;$$

**Fully differential Sallen-Key low-pass LPF**



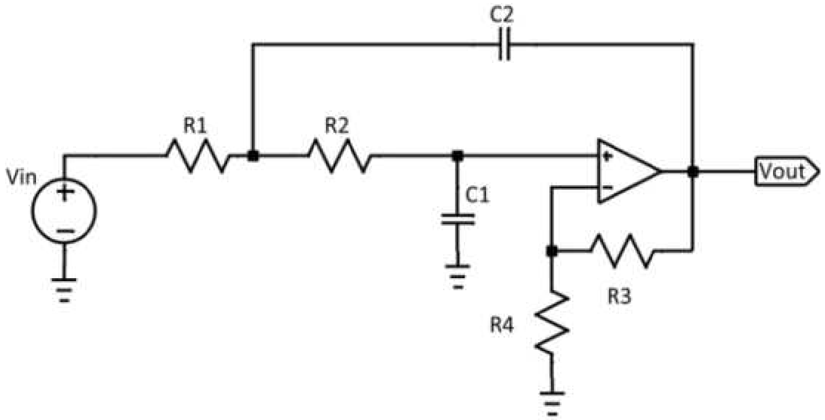

**R1 = R2 = 10 kΩ, R3 = = 100 Ω, R4 = 100 kΩ, C2 = 2 nF, at $f_0$ = 25 kHz.**

- **Over-damping (C1 = 3 nF),**
- **Critical damping (C1 = 1.5 nF), and**
- **Under-damping (C1 = 0.2 nF).**

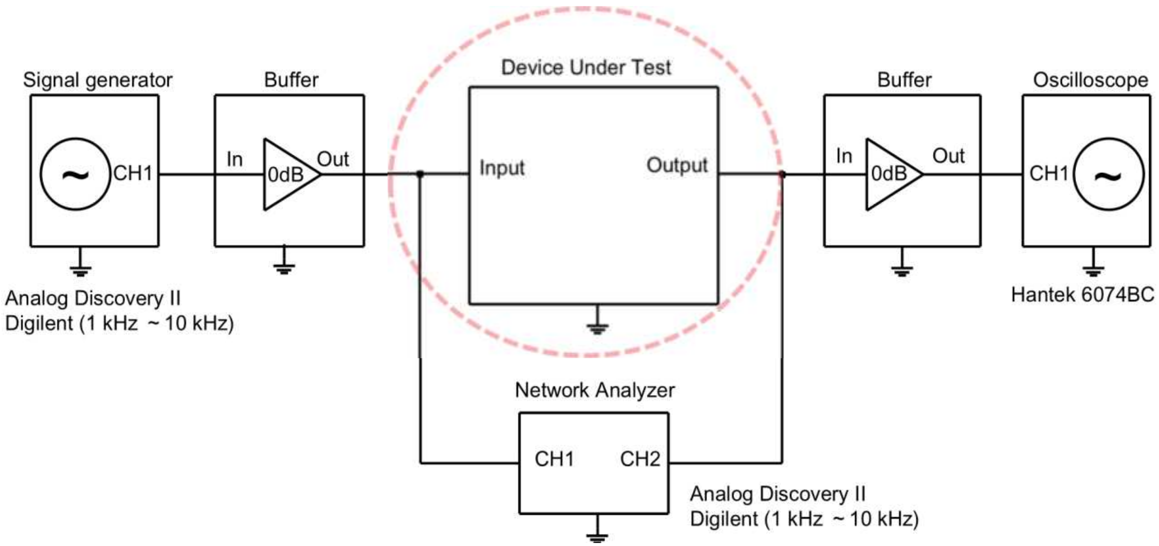
# 4. Ringing Test for High-order Low-Pass Filters

## Measurement Setup for Sallen-Key low-pass LPF

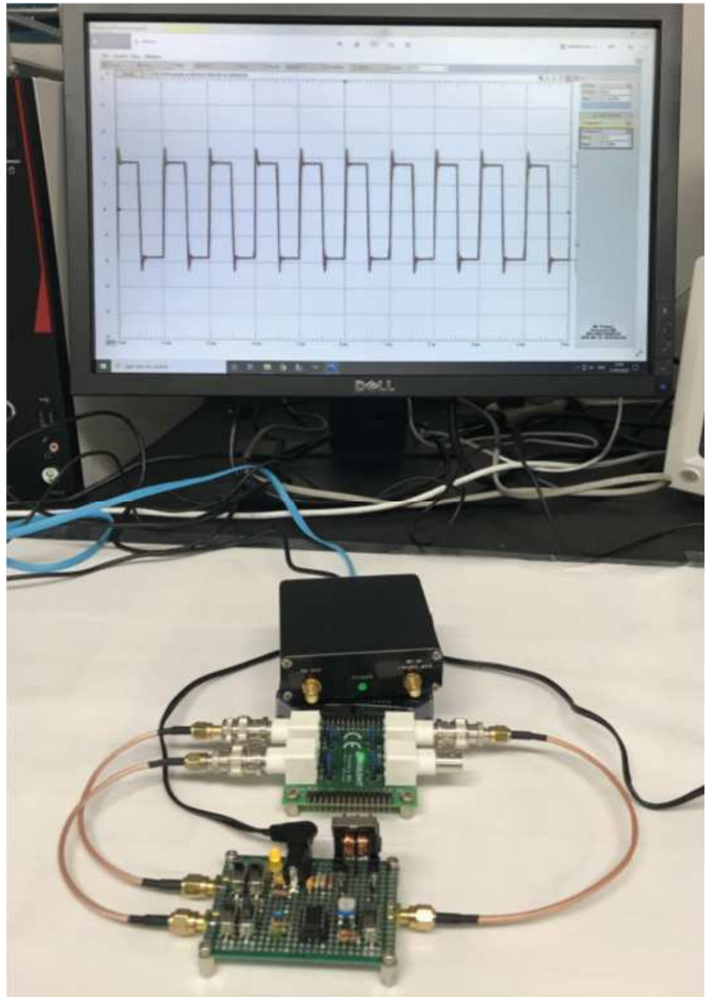
### Schematic of Sallen-Key low-pass LPF




### System Under Test



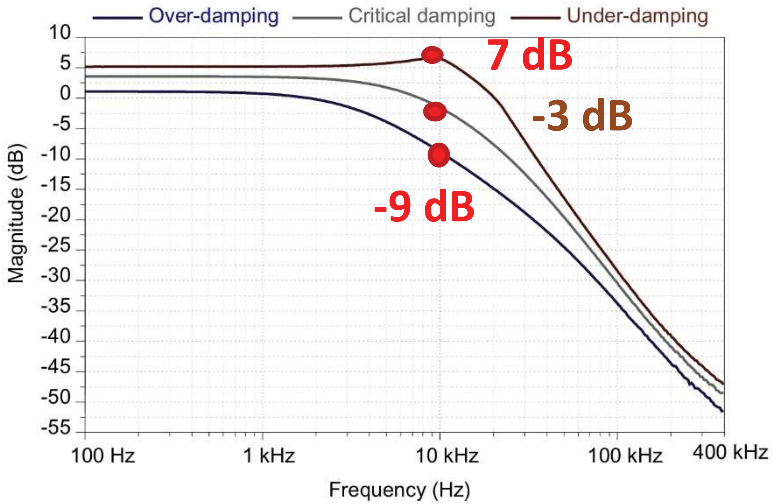

### Measurement set up



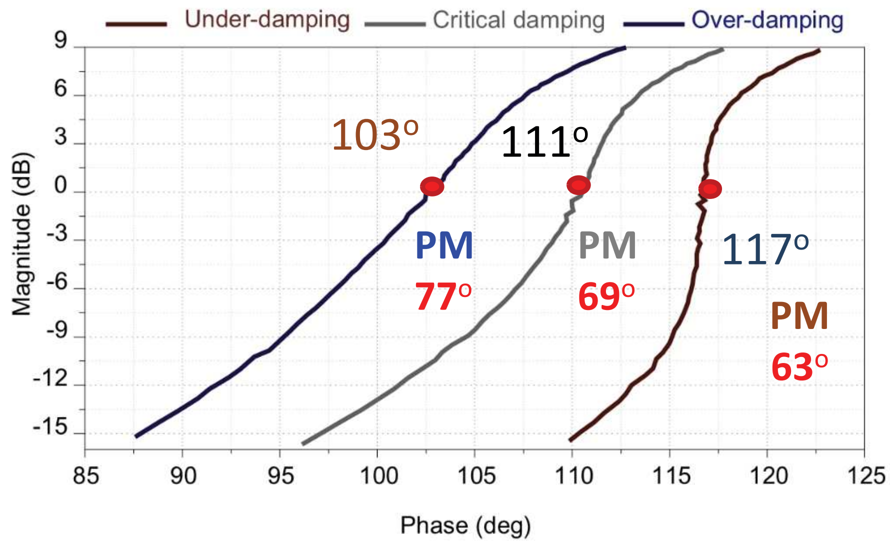
# 4. Ringing Test for High-order Low-Pass Filters

## Measurement Results of Sallen-Key LPF

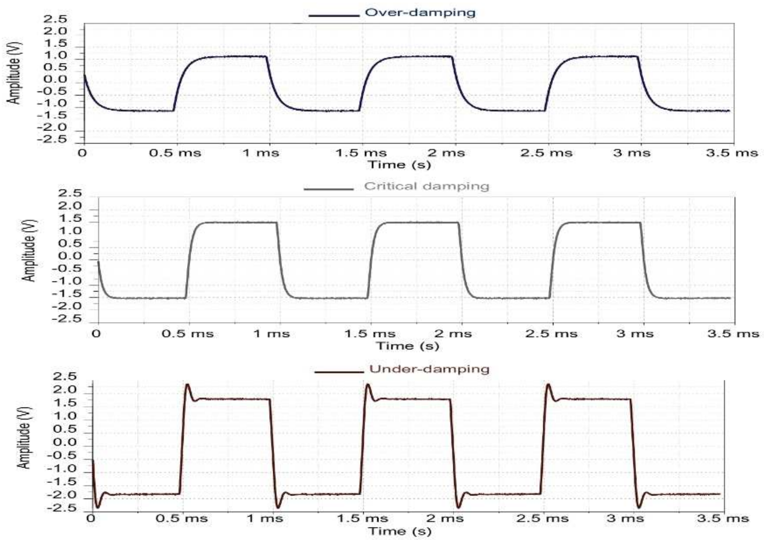
**Bode plot of transfer function**




**Nichols plot of self-loop function**




**Transient response**




**Over-damping:**

→**Phase margin is 77 degrees.**

**Critical damping:**

→**Phase margin is 69 degrees.**

**Under-damping:**

→**Phase margin is 63 degrees.**

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# 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

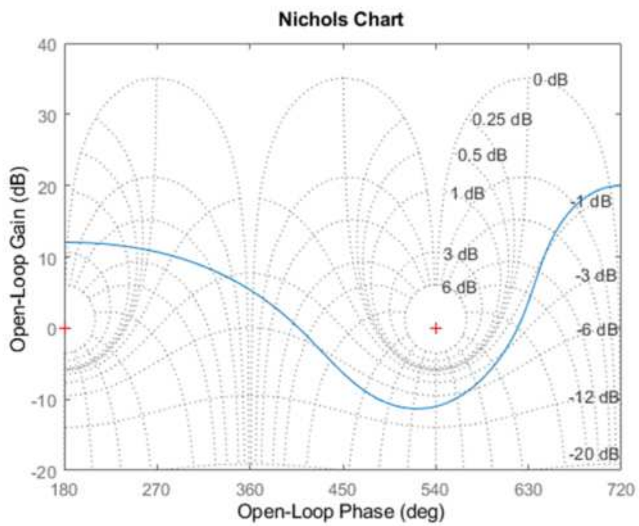
| Features | Comparison measurement | Alternating current conservation | Replica measurement | Middlebrook's method |
|---|---|---|---|---|
| Main objective | Self-loop function | Self-loop function | Loop gain | Loop gain |
| Transfer function accuracy | Yes | Yes | No | No |
| Breaking feedback loop | 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.**

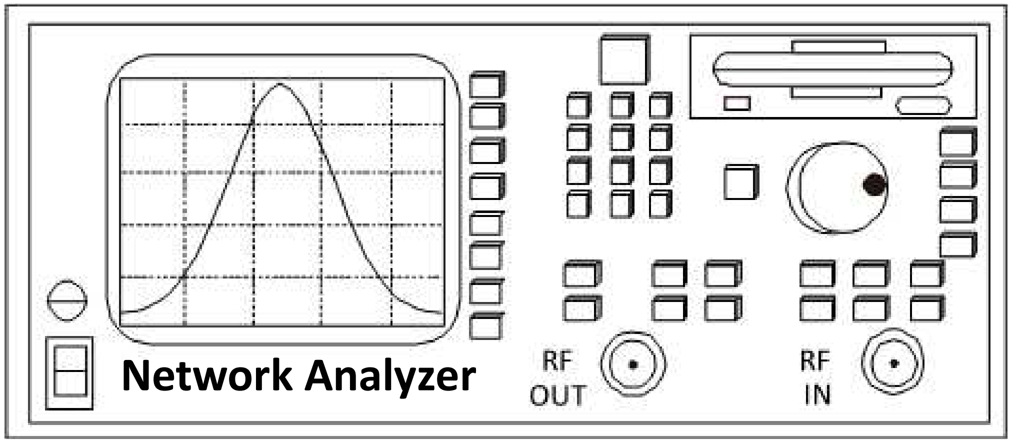
**→Loop gain in adaptive feedback network is significantly different from self-loop function in linear negative feedback network.**

**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**

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# 2020 IEEE 2nd International Conference on Circuits and Systems (IEEE ICCS 2020)

## 2020年第二届IEEE电路与系统国际会议 中国成都

# Thank you very much!

# 谢 谢


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