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DERIVATION OF LOOP GAIN AND STABILITY TEST FOR LOW-PASS TOW-THOMAS BIQUAD FILTER

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Outline

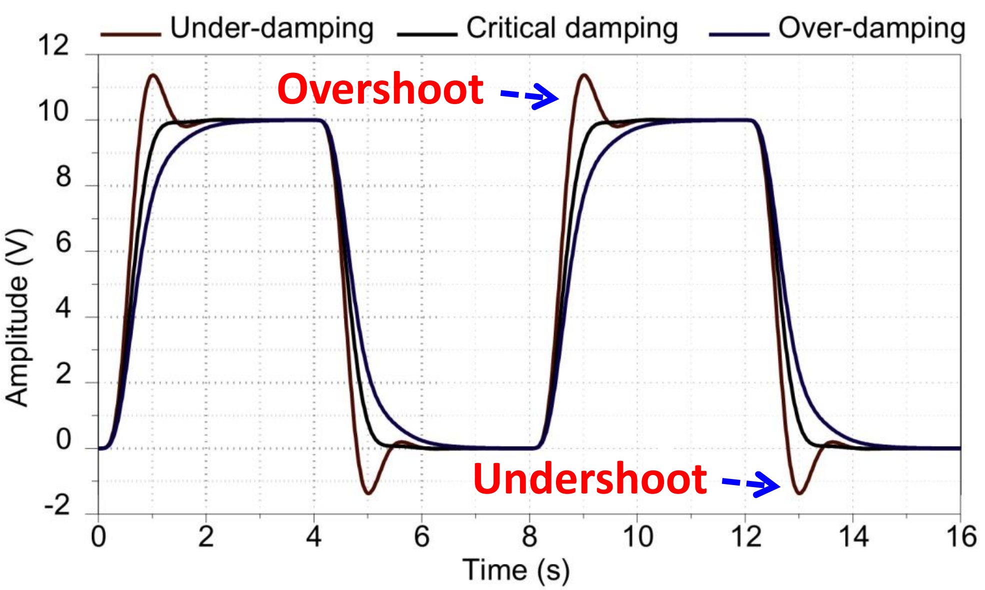
1. Research Background
- Reviews of Complex Functions
- Transfer Function and Its Self-loop Function
- Proposed Methods for Stability Test
2. Analysis of High-Order Transfer Functions
- Behaviors of Basic Ideal Op Amp Networks
- Effects of Miller's Capacitor in Two-stage Op Amp
3. Experimental Results
- Measurements of Self-loop Functions in Second-order Tow-Thomas Biquad Filter
4. Conclusions

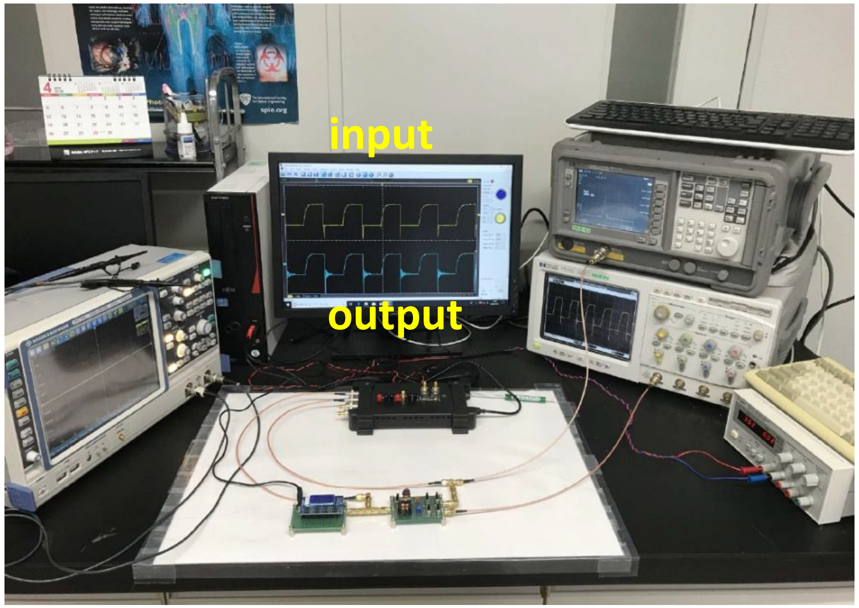
1. Research Background

Motivation of Study

○ **Ringing occurs in both with and without feedback systems.**

→Unstable system ➡ **STABILITY TEST**





1. Research Background

Objectives and Achievements

Objectives

- ○ Investigation of operating region of high-order active networks based on phase margin at unity gain of self-loop function
- ○ Design and stability test for Tow-Thomas LPF

Achievements

○ Implementation and stability test for second-order low-pass Tow-Thomas Biquad Filter

1. Research Background

Reviews of Complex Functions

Complex function with frequency variable

$$H(\omega) = \mathrm{Re}(\omega) + j\mathrm{Im}(\omega) = \mathrm{Real}\{H(\omega)\} + j\mathrm{Imag}\{H(\omega)\}$$

In complex plane domain

$$H(\omega) = \begin{cases} \mathrm{Re}(\omega) = \mathrm{Real}\{H(\omega)\} \\ \mathrm{Im}(\omega) = \mathrm{Imag}\{H(\omega)\} \\ \mathrm{Fre}(\omega) = \textit{angular frequency} \end{cases}$$

In spectrum domain

$$H(\omega) = |H(\omega)| e^{j\theta(\omega)}$$

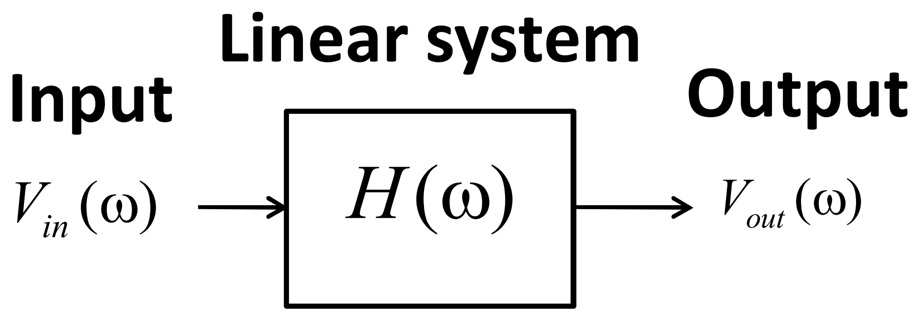
$$|H(\omega)| = \sqrt{\left[\mathrm{Re}\{H(\omega)\}\right]^2 + \left[\mathrm{Im}\{H(\omega)\}\right]^2}$$

$$\theta(\omega) = \arctan\left(\frac{\mathrm{Im}\{H(\omega)\}}{\mathrm{Re}\{H(\omega)\}}\right)$$

- **Polar chart (Nyquist chart)**
- **Magnitude-frequency, angular-frequency plots (Bode plots)**
- **Magnitude-angular diagrams (Nicholas diagrams)**

1. Research Background

Transfer Function and Its Self-loop Function



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

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

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

Transfer function

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

$$H(\omega) = \frac{A(\omega)}{0} = \infty$$

Unstable system

Constraint for oscillation

$$1 + L(\omega) = 0 \Rightarrow \begin{cases} |L(\omega)| = 1 \\ \angle L(\omega) = -180^o \end{cases}$$

PHASE MARGIN
AT UNITY GAIN

1. Research Background

Signal Flow Graph for Transfer Function

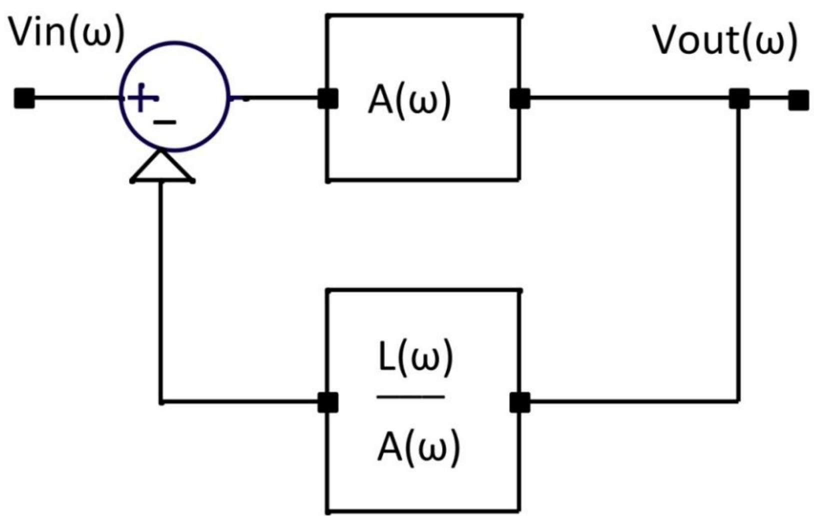
Transfer function

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

Output voltage

$$V_{out}(\omega) = A(\omega)\left[V_{in}(\omega) - \frac{L(\omega)}{A(\omega)} V_{out}(\omega)\right]$$

Negative feedback Network



Signal flow graph

To meet the specified requirements

- **High stability**
- **Fast transient response, and**
- **Good steady-state performance.**

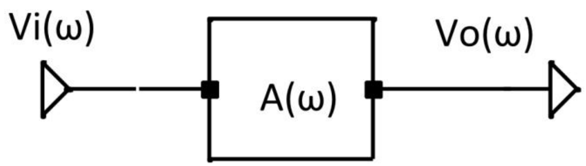
1. Research Background

Proposed Comparison Measurement Technique

Open loop function

Step1:

$$A(\omega) = \frac{V_i(\omega)}{V_o(\omega)}$$



Transfer function

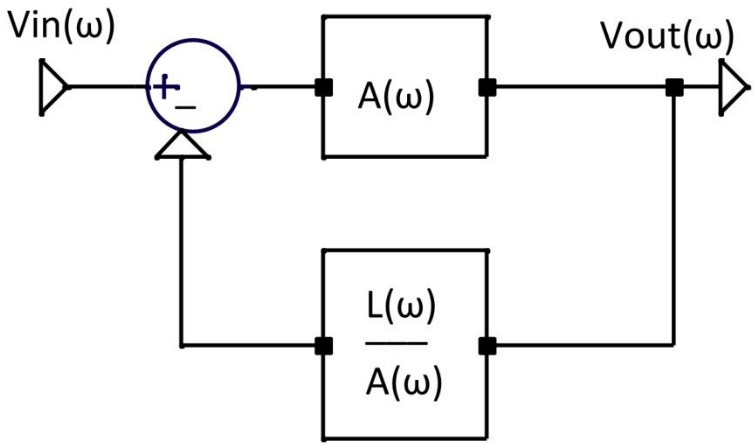
Step2:

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

Self-loop function

Step3:

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



Sequence of steps:

(i) Measurement of open loop function A(ω),

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

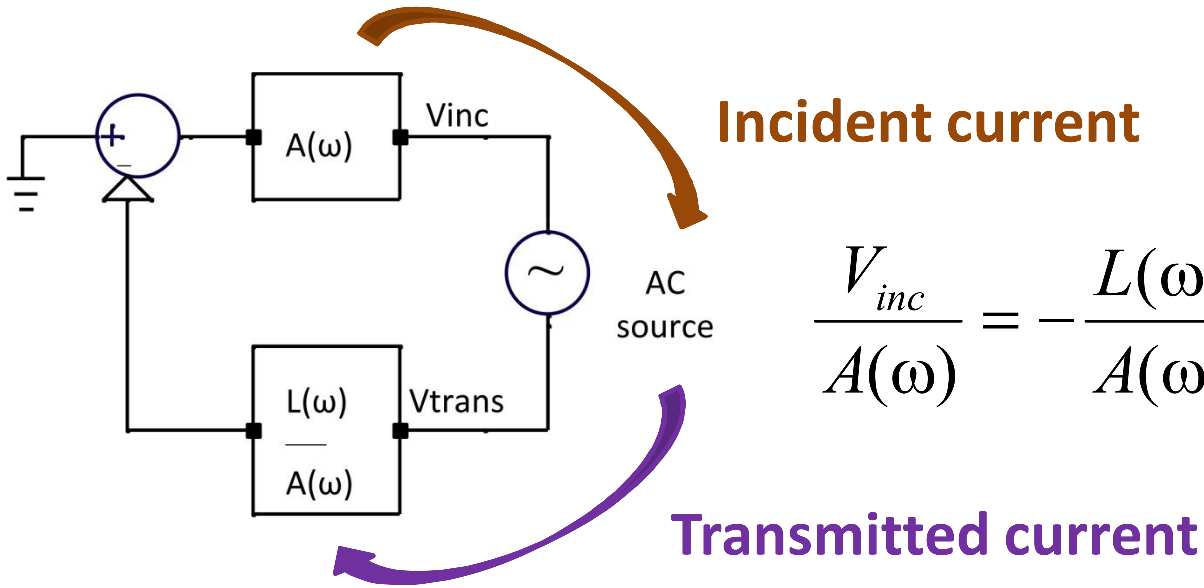
(iii) Derivation of self-loop function.

1. Research Background

Proposed Alternating Current Conservation (1)

Idea: Alternating current is conserved.

Incident current = Transmitted current



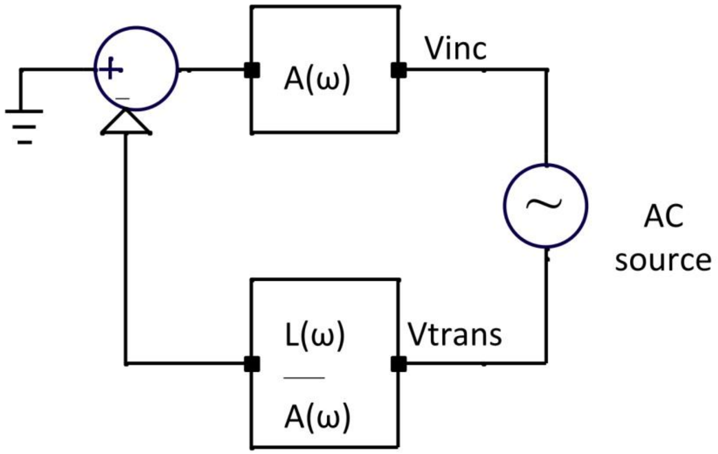
$$\frac{V_{inc}}{A(\omega)} = -\frac{L(\omega)}{A(\omega)} V_{trans}$$

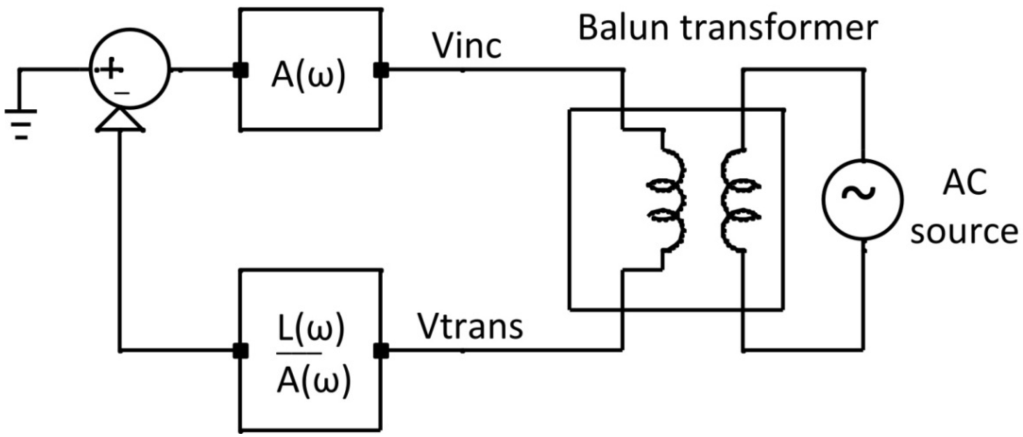
Self-loop function: $L(\omega) = -\frac{V_{inc}}{V_{trans}}$

1. Research Background

Proposed Alternating Current Conservation (2)

Alternating current conservation using balun transformer

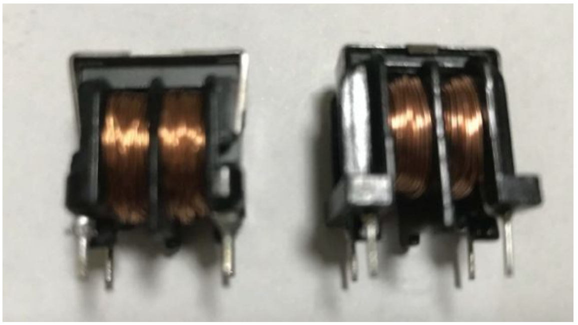




Self-loop function:

$$L(\omega) = -\frac{V_{inc}}{V_{trans}}$$

Balun transformer (10 mH inductance)

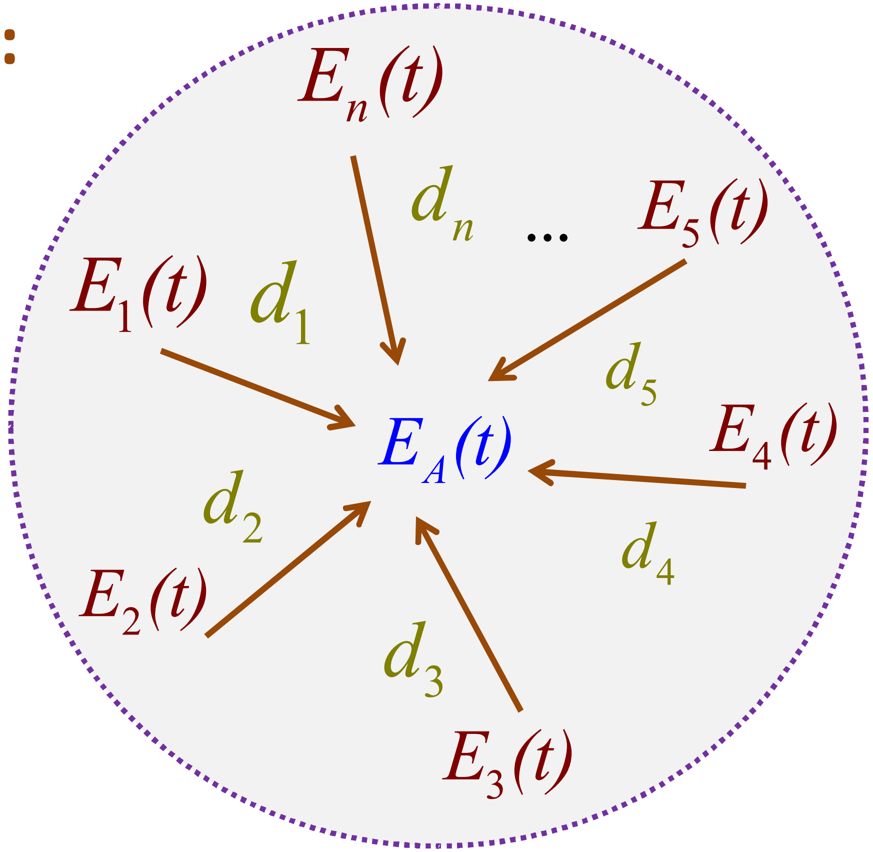


1. Research Background

Proposed Widened Superposition Principle

Widened Superposition Principle:

$$E_A(t)\sum_{i=1}^{n}\frac{1}{d_i}=\sum_{i=1}^{n}\frac{E_i(t)}{d_i}$$



$E_A(t)$: ***Energy at one place***

$E_i(t)$: ***Input sources***

$d_i(t)$: ***Resistance distances***

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

1. Research Background

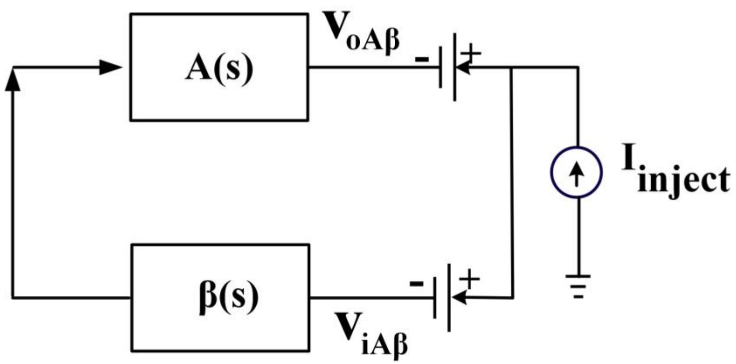
Limitations of Conventional Methods (1)

[8] Middlebrook, R.D., "Measurement of Loop Gain in Feedback Systems", Int. J. Electronics, vol 38, No. 4, pp. 485-512, 1975.

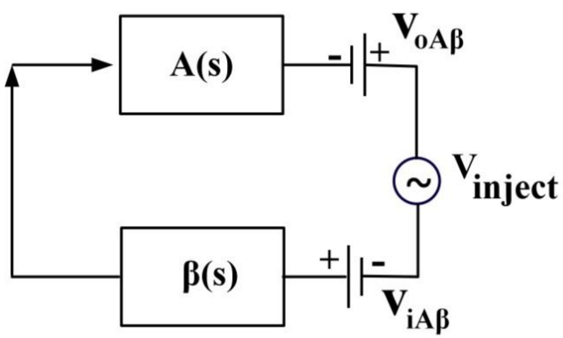
Measurement of loop gain

- ❖ Current injection
- ❖ Voltage injection

$$L(\omega) = \frac{V_{oA\beta}(\omega)}{v_{iA\beta}(\omega)}$$



Current injection method



Voltage injection method

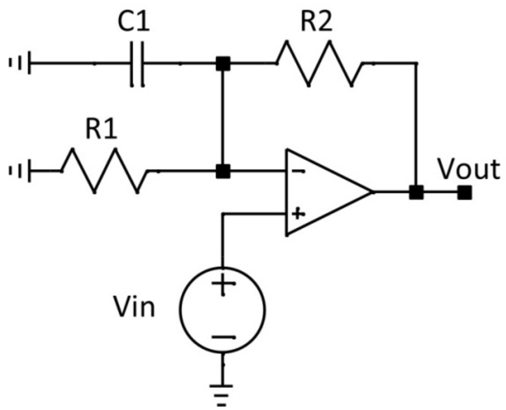
→**Difficult** to measure self-loop function in analog circuits

1. Research Background

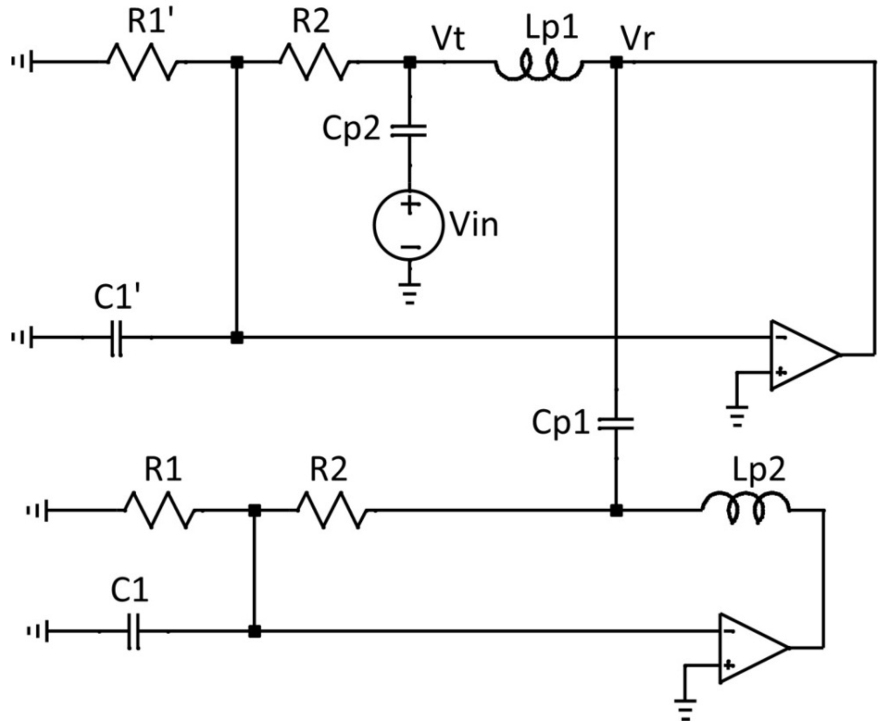
Limitations of Conventional Methods (2)

[9] A. S. Sedra and K. C. Smith, “Microelectronic Circuits,” 6th ed. Oxford University Press, New York, 2010.

Measurement of loop gain **❖Replica measurement**



$$L(\omega) = \frac{V_r(\omega)}{V_t(\omega)}$$



→Difficult to measure two real different circuits

1. Research Background

Limitations of Conventional Methods (3)

○ **Conventional Superposition:**

→Solving for every source voltage and current, perhaps several times.

○ **Conventional measurement of loop gain (Middle Brook's)**

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

○ **Conventional replica measurement of loop gain**

→Using two identical networks (difficult in practical measurement).

○ **Conventional Nyquist's stability condition**

→ Using in theoretical analysis for feedback systems (Lab simulation).

○ **Conventional concepts, analysis and measurement of loop gain are not unique.**

2. Analysis of High-Order Transfer Functions

Behaviors of Second-order Transfer Function

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

<table>
<tr><th>Case</th><th colspan="2">Over-damped</th><th colspan="2">Critically damped</th><th colspan="2">Under-damped</th></tr>
<tr><td>Delta (Δ)</td><td colspan="2">$\frac{1}{a_0}<\left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta=a_1^2-4a_0>0$</td><td colspan="2">$\frac{1}{a_0}=\left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta=a_1^2-4a_0=0$</td><td colspan="2">$\frac{1}{a_0}>\left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta=a_1^2-4a_0<0$</td></tr>
<tr><td>Module $\lvert H(\omega)\rvert$</td><td colspan="2">$\frac{\frac{1}{a_0}}{\sqrt{\omega^2+\left(\frac{a_1}{2a_0}-\sqrt{\left(\frac{a_1}{2a_0}\right)^2-\frac{1}{a_0}}\right)^2}\sqrt{\omega^2+\left(\frac{a_1}{2a_0}+\sqrt{\left(\frac{a_1}{2a_0}\right)^2-\frac{1}{a_0}}\right)^2}}$</td><td colspan="2">$\frac{\frac{1}{a_0}}{\left[\omega^2+\left(\frac{a_1}{2a_0}\right)^2\right]}$</td><td colspan="2">$\frac{\frac{1}{a_0}}{\sqrt{\left(\omega-\sqrt{\frac{1}{a_0}-\left(\frac{a_1}{2a_0}\right)^2}\right)^2+\left(\frac{a_1}{2a_0}\right)^2}\sqrt{\left(\omega+\sqrt{\frac{1}{a_0}-\left(\frac{a_1}{2a_0}\right)^2}\right)^2+\left(\frac{a_1}{2a_0}\right)^2}}$</td></tr>
<tr><td>Angular $\theta(\omega)$</td><td colspan="2">$-\arctan\left(\frac{\omega}{\frac{a_1}{2a_0}-\sqrt{\left(\frac{a_1}{2a_0}\right)^2-\frac{1}{a_0}}}\right)-\arctan\left(\frac{\omega}{\frac{a_1}{2a_0}+\sqrt{\left(\frac{a_1}{2a_0}\right)^2-\frac{1}{a_0}}}\right)$</td><td colspan="2">$-2\arctan\left(\frac{2a_0\omega}{a_1}\right)$</td><td colspan="2">$-\arctan\left(\frac{\omega-\sqrt{\frac{1}{a_0}-\left(\frac{a_1}{2a_0}\right)^2}}{\frac{a_1}{2a_0}}\right)-\arctan\left(\frac{\omega+\sqrt{\frac{1}{a_0}-\left(\frac{a_1}{2a_0}\right)^2}}{\frac{a_1}{2a_0}}\right)$</td></tr>
<tr><td>$\omega_{cut}=\frac{a_1}{2a_0}$</td><td>$\lvert H(\omega_{cut})\rvert<\frac{2a_0}{a_1}$</td><td>$\theta(\omega_{cut})>-\frac{\pi}{2}$</td><td>$\lvert H(\omega_{cut})\rvert=\frac{2a_0}{a_1}$</td><td>$\theta(\omega_{cut})=-\frac{\pi}{2}$</td><td>$\lvert H(\omega_{cut})\rvert>\frac{2a_0}{a_1}$</td><td>$\theta(\omega_{cut})<-\frac{\pi}{2}$</td></tr>
</table>

2. Analysis of High-Order Transfer Functions

Behaviors of Second-order Self-loop Function

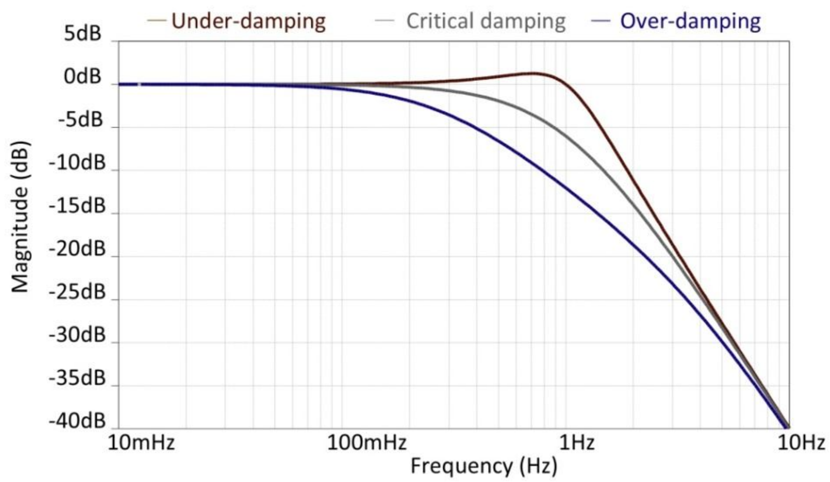
Second-order self-loop function: $L(\omega) = j\omega\left[a_0 j\omega + a_1\right]$

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

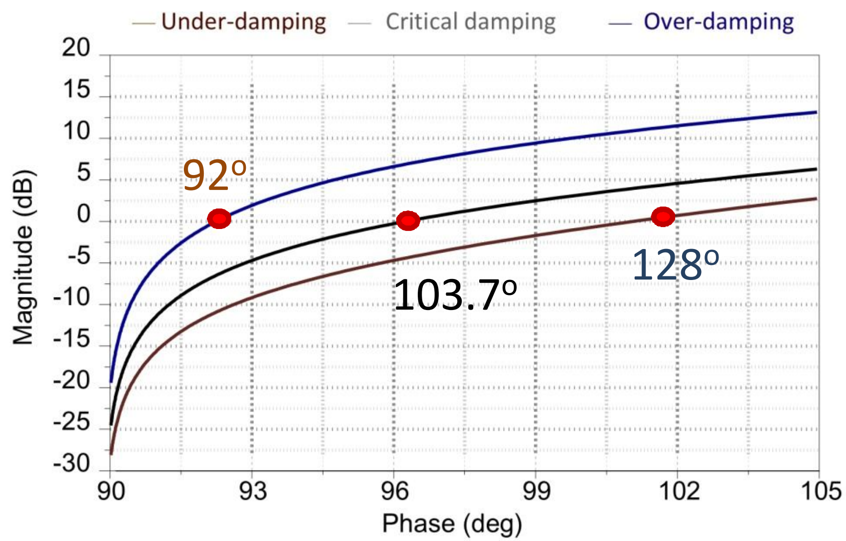
2. Analysis of High-Order Transfer Functions

Behaviors of Second-order System

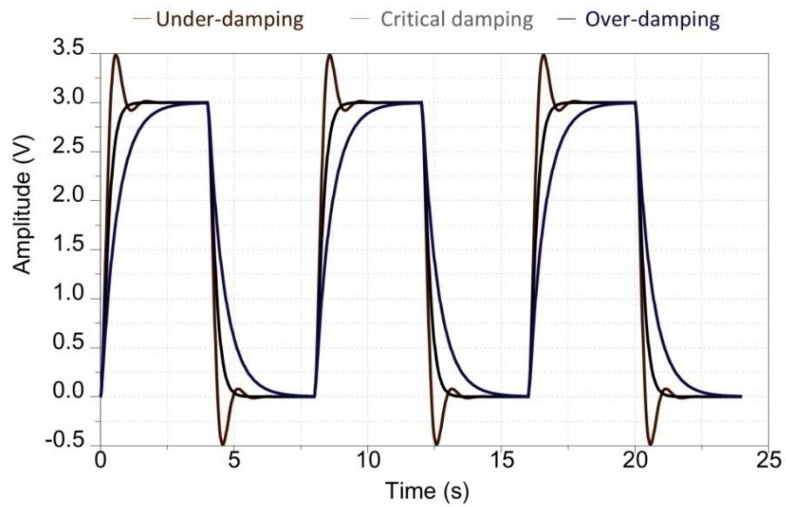
Magnitude response of transfer function



Magnitude-angular response of self-loop function



Transient response



Over-damping:

→Phase margin is 84 degrees.

Critical damping:

→Phase margin is 76.3 degrees.

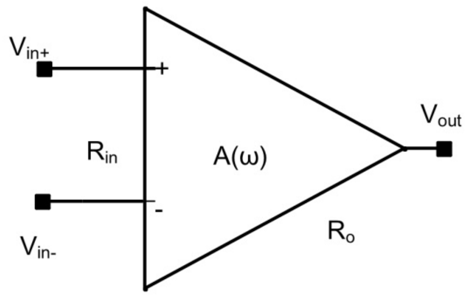
Under-damping:

→Phase margin is 52 degrees.

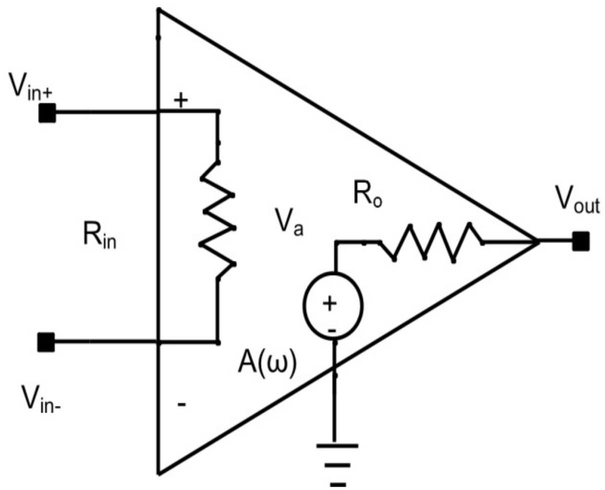
2. Analysis of High-Order Transfer Functions

Mathematical Model of Ideal Op Amp

Ideal op amp



Equivalent model of op amp



Open-loop function A(ω)

$$A(\omega) = \frac{V_{out}}{V_{in+} - V_{in-}} = \frac{A_0}{1 + \frac{j\omega}{\omega_{bw}}}$$

Gain-bandwidth (GBW), bandwidth fbw

$$GBW = A_0 f_{bw} \Rightarrow f_{bw} = \frac{GBW}{A_0}$$

Here, GBW =10 MHz, DC gain Ao = 100000

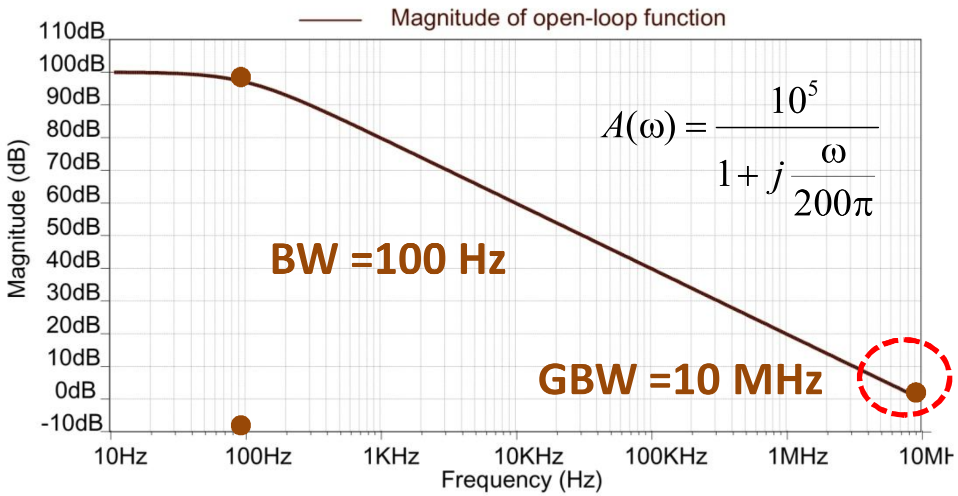
Open-loop function and self-loop function

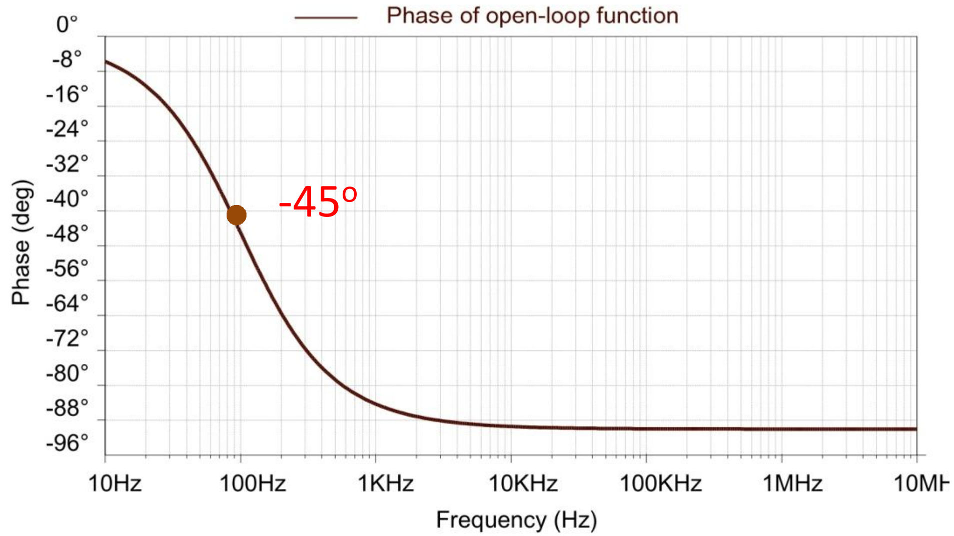
$$A(\omega) = \frac{10^5}{1 + j\frac{\omega}{200\pi}}\ ; L(\omega) = j\frac{\omega}{200\pi} = 10^5 \frac{V_{in}}{V_{out}} - 1$$

2. Analysis of High-Order Transfer Functions

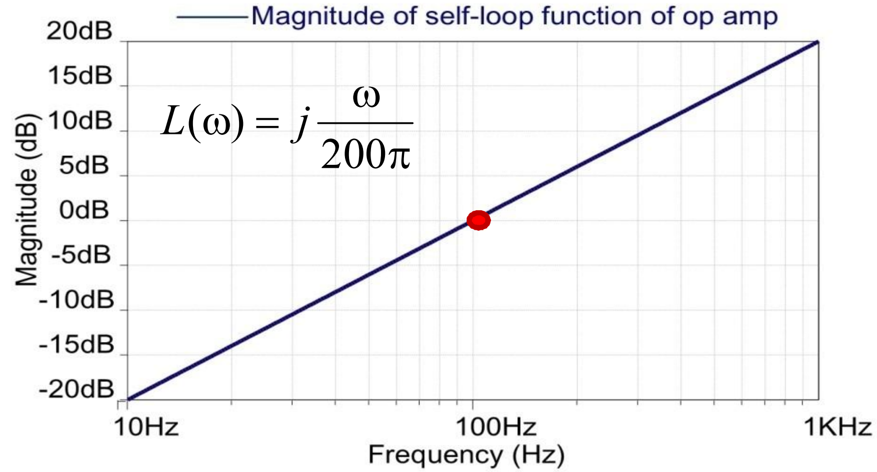
Behavior of Open-loop Function of Ideal Op Amp

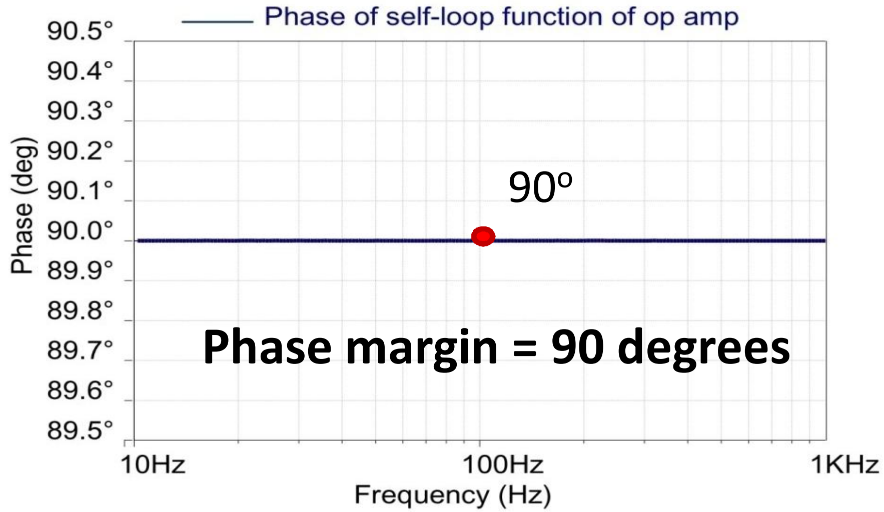
Bode plots of open-loop function





Bode plots of self-loop function

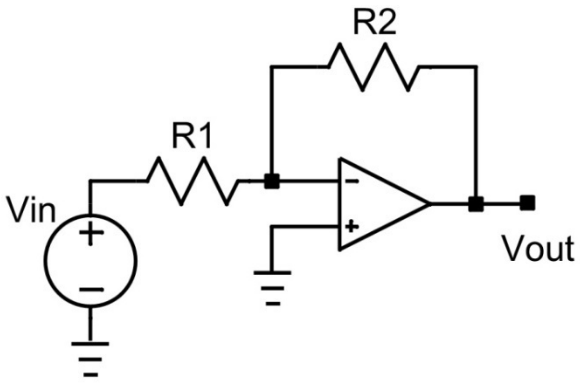




2. Analysis of High-Order Transfer Functions

Reviews of Basic Op Amp Networks

Inverting op amp



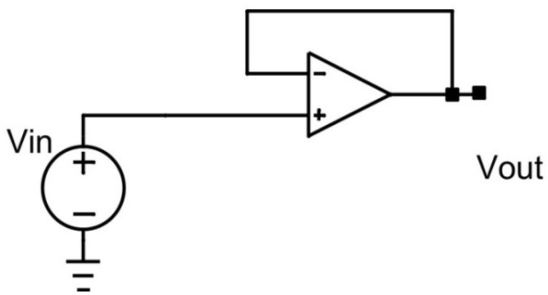
Transfer function of inverting op amp

$$H(\omega) = \frac{V_{out}}{V_{in}} = \frac{-A(\omega)\,R_2}{R_1 + R_2 + A(\omega)\,R_1} = \frac{-\frac{R_2}{R_1}}{1 + \frac{R_1 + R_2}{10^5\,R_1}\left(1 + \frac{j\omega}{200\pi}\right)} \approx -\frac{R_2}{R_1}$$

Self-loop function of inverting op amp

$$L(\omega) = \frac{R_1 + R_2}{10^5\,R_1}\left(1 + \frac{j\omega}{200\pi}\right)$$

Buffer using ideal op amp



Transfer function of buffer using op amp

$$H(\omega) = \frac{V_{out}}{V_{in}} = \frac{A(\omega)}{1 + A(\omega)} = \frac{1}{1 + \frac{1}{10^5}\left(1 + \frac{j\omega}{200\pi}\right)} \approx 1$$

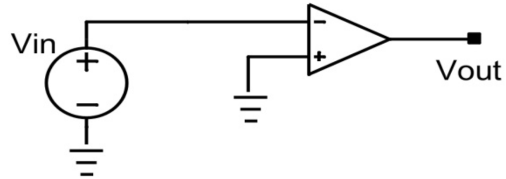
Self-loop function of buffer

$$L(\omega) = \frac{1}{10^5}\left(1 + \frac{j\omega}{200\pi}\right)$$

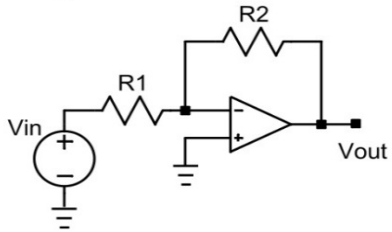
2. Analysis of High-Order Transfer Functions

Simulations of Loop Gains in Op Amp Networks

Gain of Op Amp: $A(\omega) = -\dfrac{10^5}{1 + j\dfrac{\omega}{200\pi}}$



Inverting Op Amp



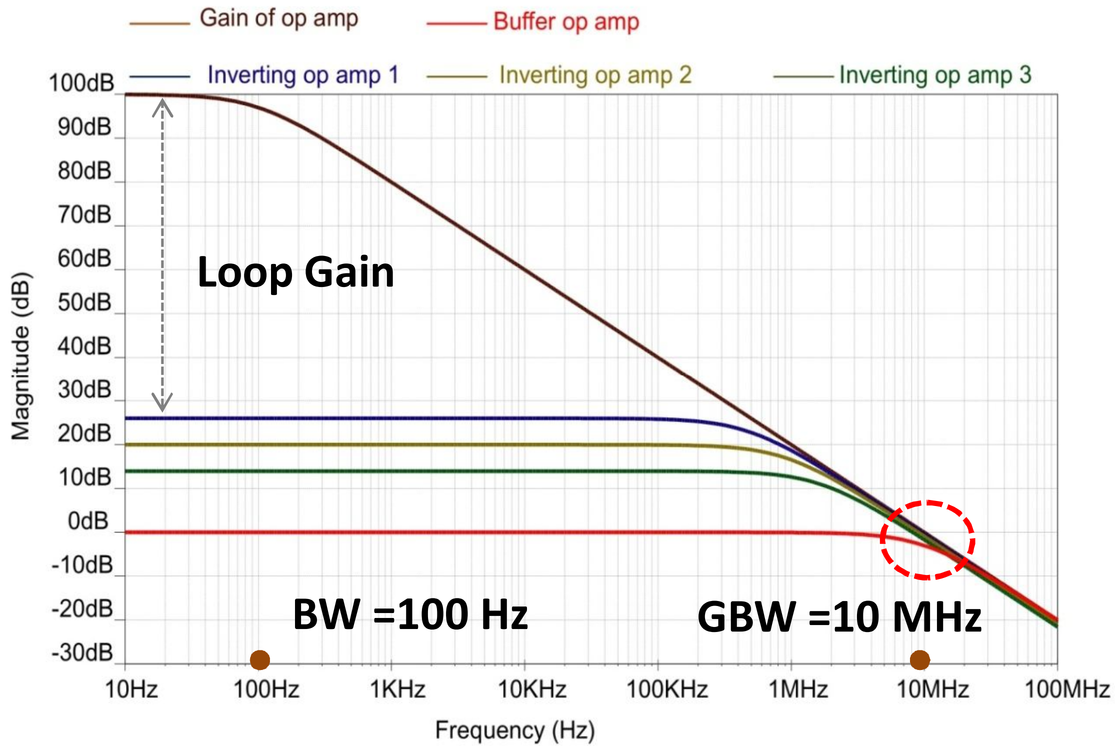
$$H(\omega) = \frac{-\dfrac{R_2}{R_1}}{1 + \dfrac{R_1 + R_2}{10^5 R_1}\left(1 + \dfrac{j\omega}{200\pi}\right)} \approx -\frac{R_2}{R_1}$$

Here, R1 = 1 kΩ,

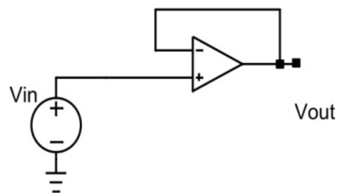
Inverting op amp 1: R2 = 20 kΩ

Inverting op amp 2: R2 = 10 kΩ

Inverting op amp 3: R2 = 5 kΩ



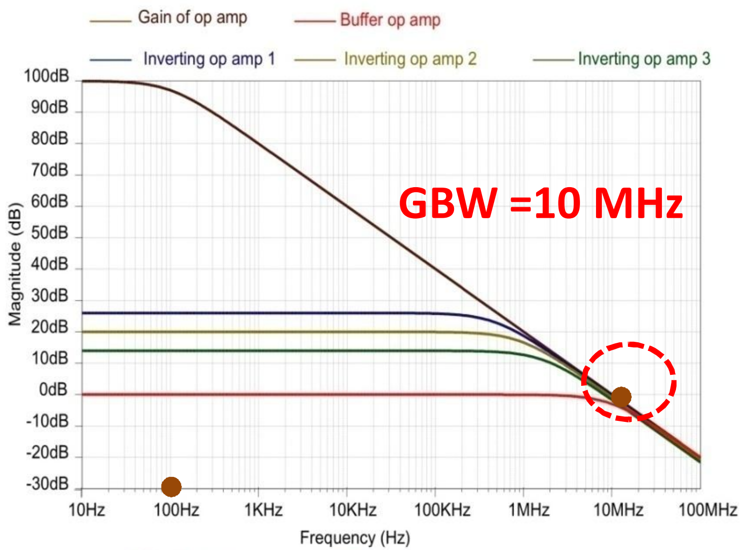
Buffer using Op Amp: $H(\omega) = \dfrac{1}{1 + \dfrac{1}{10^5}\left(1 + \dfrac{j\omega}{200\pi}\right)} \approx 1$

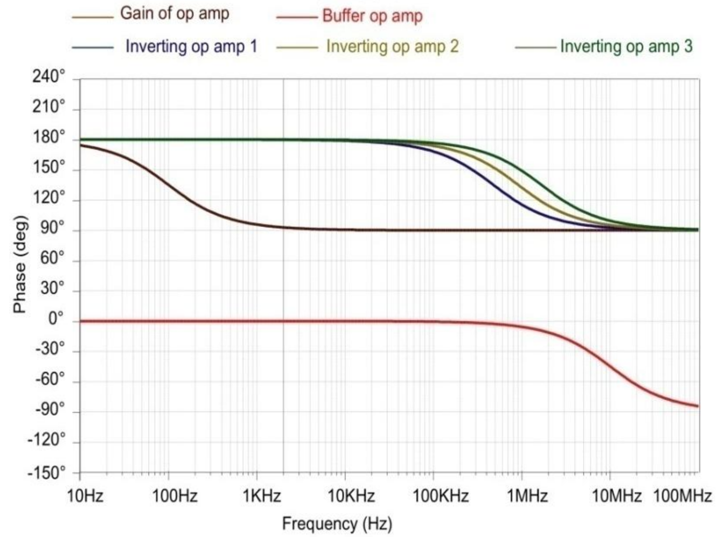


2. Analysis of High-Order Transfer Functions

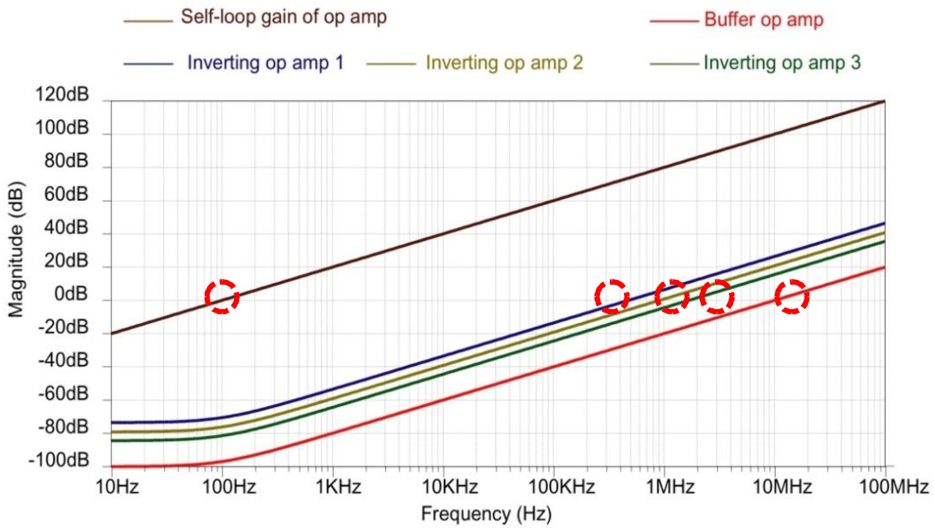
Transfer & Self-loop Functions in Op Amp Networks

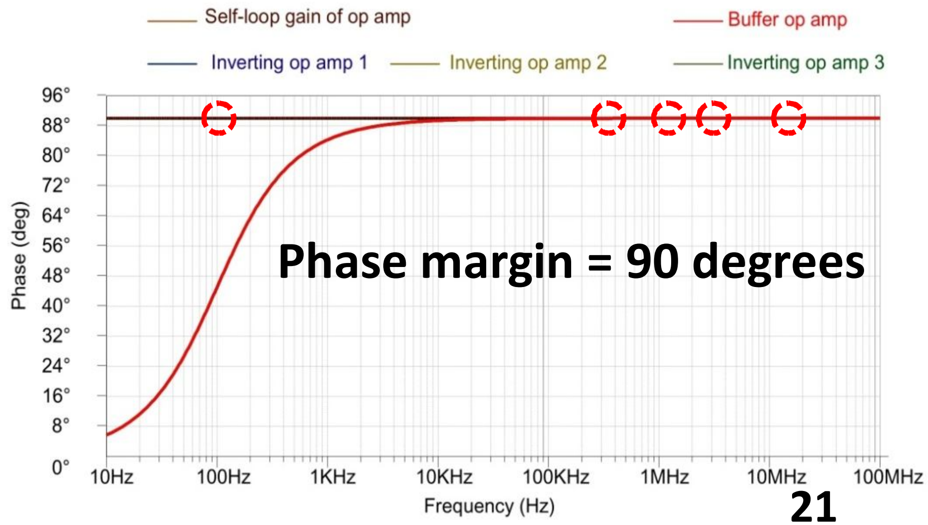
Behaviors of transfer functions





Behaviors of self-loop functions

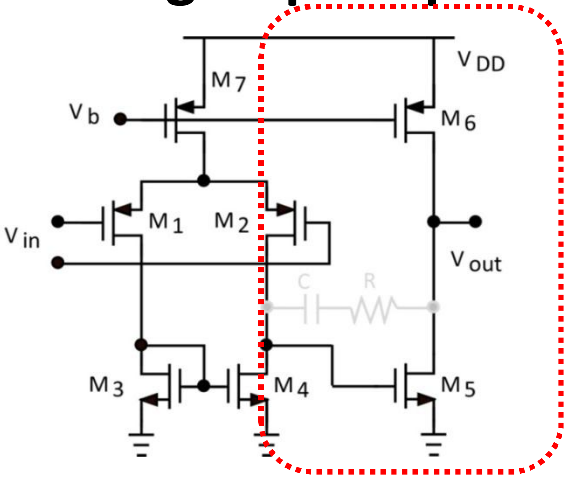




2. Analysis of High-Order Transfer Functions

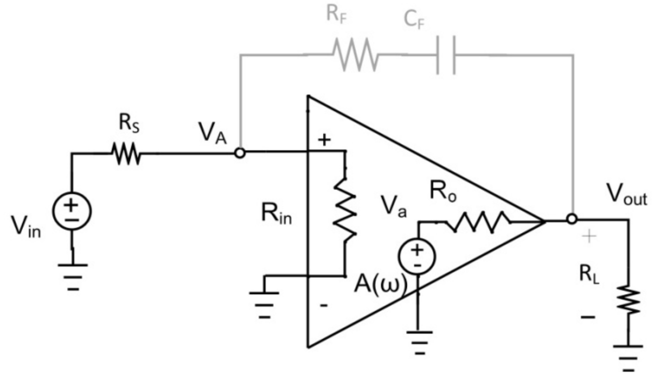
Behavior of Two-stage Op Amp in Feedback Circuits

Two-stage Op Amp without Miller's Capacitor

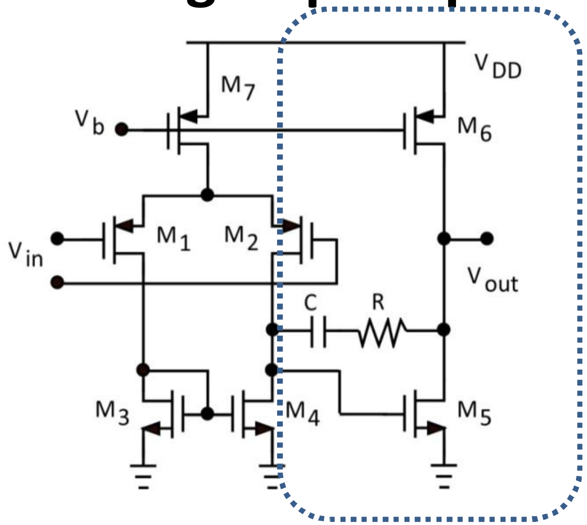


Second-stage
without
frequency
compensation

Simplified model

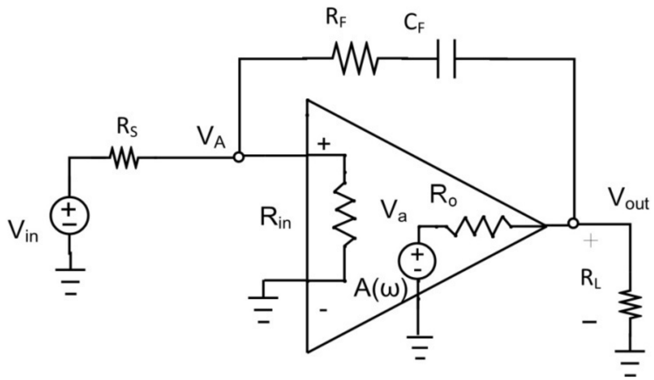


Two-stage Op Amp with Miller's Capacitor



Second-stage
with
frequency
compensation

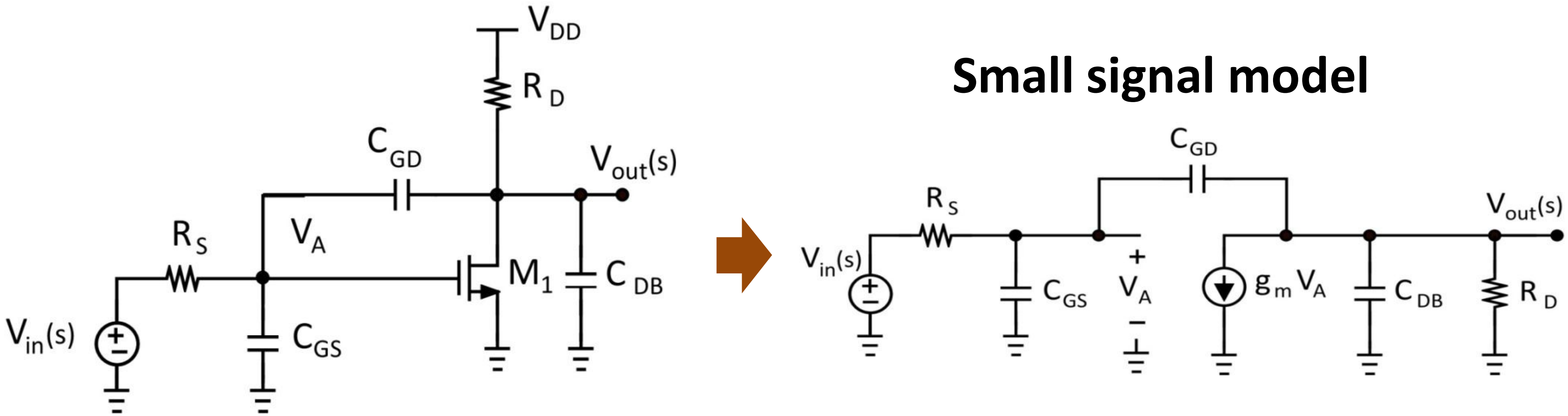
Simplified model



2. Analysis of High-Order Transfer Functions

Two-stage Op Amp without Miller's Capacitor

Second-stage without frequency compensation



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

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

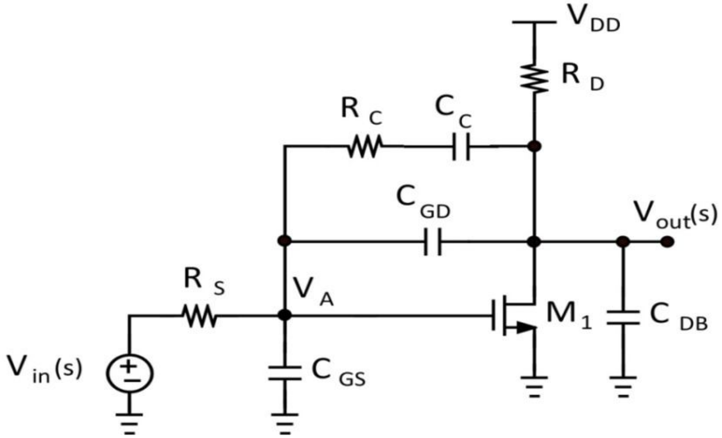
Here, $a_0 = R_D C_{GD}$; $a_1 = -R_D g_m$; $b_0 = R_D R_S \left[(C_{GD} + C_{DB})(C_{GS} + C_{GD}) - C_{GD}^2 \right]$

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

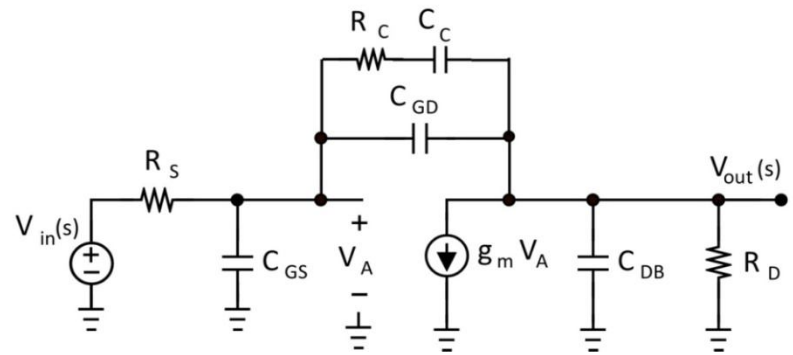
2. Analysis of High-Order Transfer Functions

Two-stage Op Amp with Miller's Capacitor

Second-stage with frequency compensation



Small signal model



Apply superposition principle at Va, and Vout

$$V_A\left(\frac{1}{R_S}+\frac{1}{Z_{CGS}}+\frac{1}{Z_{CGD}}+\frac{1}{R_C+Z_{CC}}\right)=\frac{V_{in}}{R_S}+V_{out}\left(\frac{1}{Z_{CGD}}+\frac{1}{R_C+Z_{CC}}\right)$$

$$V_{out}\left(\frac{1}{Z_{CGD}}+\frac{1}{R_C+Z_{CC}}+\frac{1}{Z_{CDB}}+\frac{1}{R_D}\right)=V_A\left(\frac{1}{Z_{CGD}}+\frac{1}{R_C+Z_{CC}}-g_m\right)$$

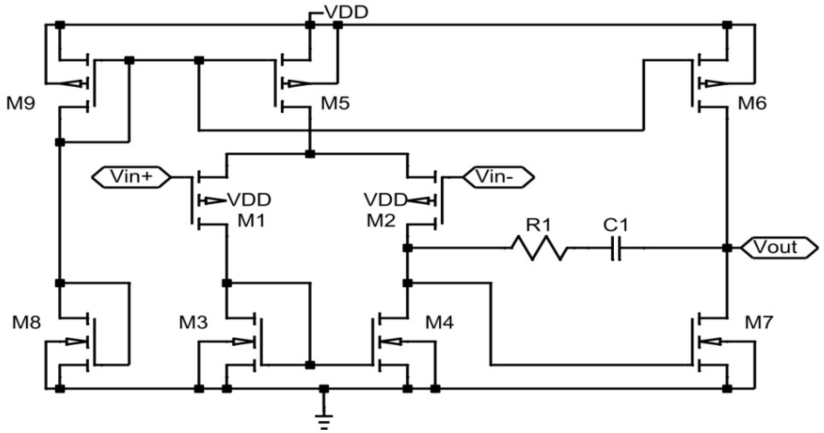
Transfer function H(ω) and self-loop function L(ω)

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

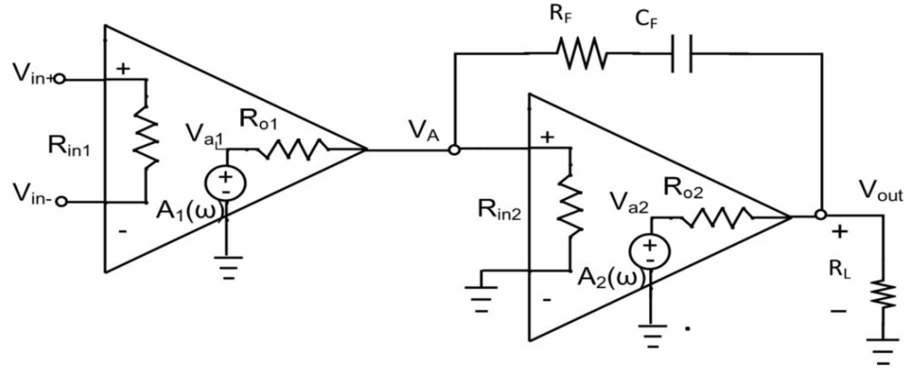
2. Analysis of High-Order Transfer Functions

Effects of Miller's Capacitor on Buffer Op Amp

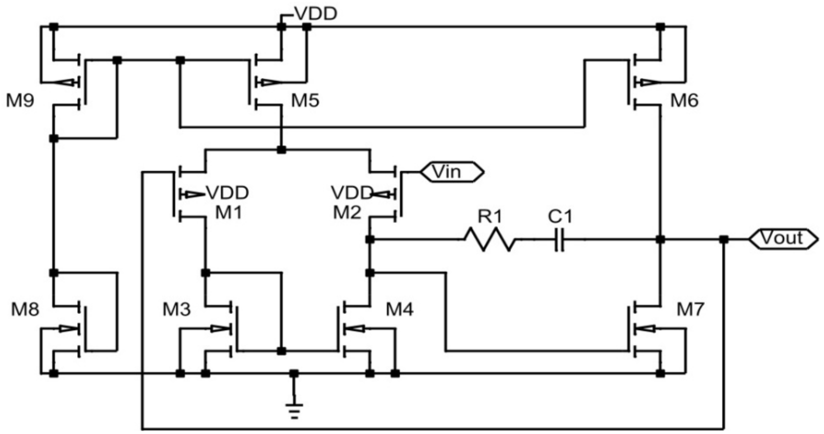
Model of two-stage op amp



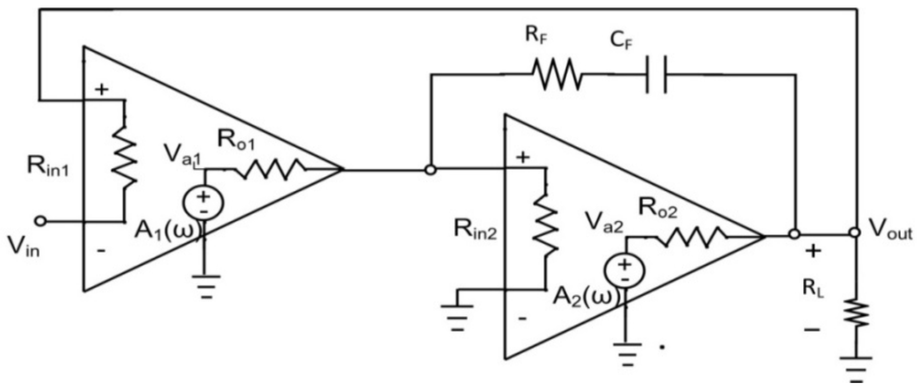
Simplified model of two-stage op amp



Buffer circuit using two-stage op amp



Simplified model of buffer circuit



2. Analysis of High-Order Transfer Functions

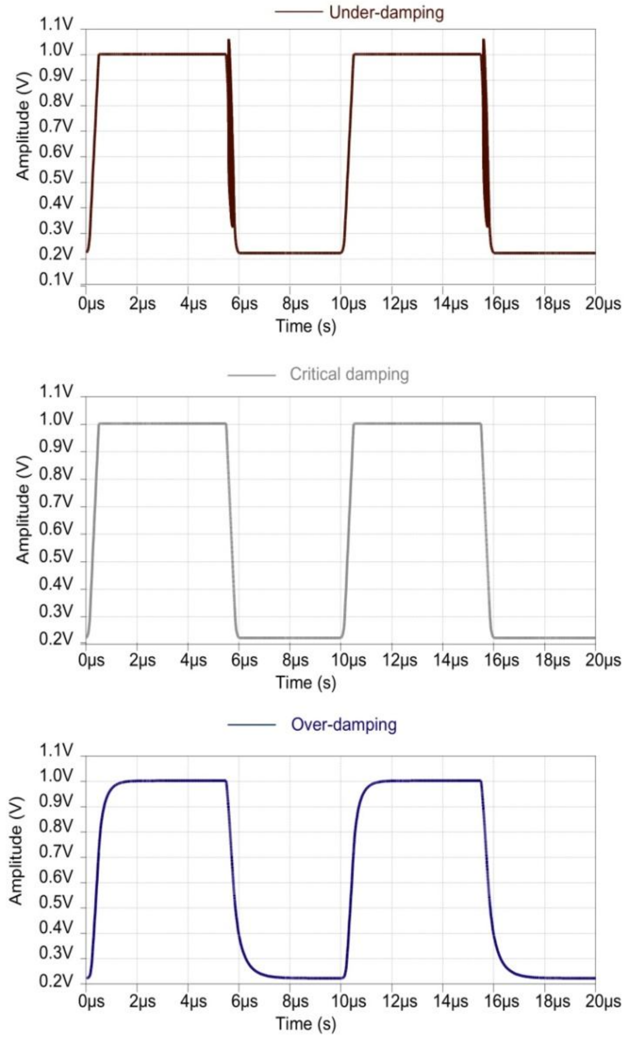
Effects of Miller's Capacitor on Buffer Op Amp

Under-damping
Rf = 10 Ω
Cf = 0.5 pF

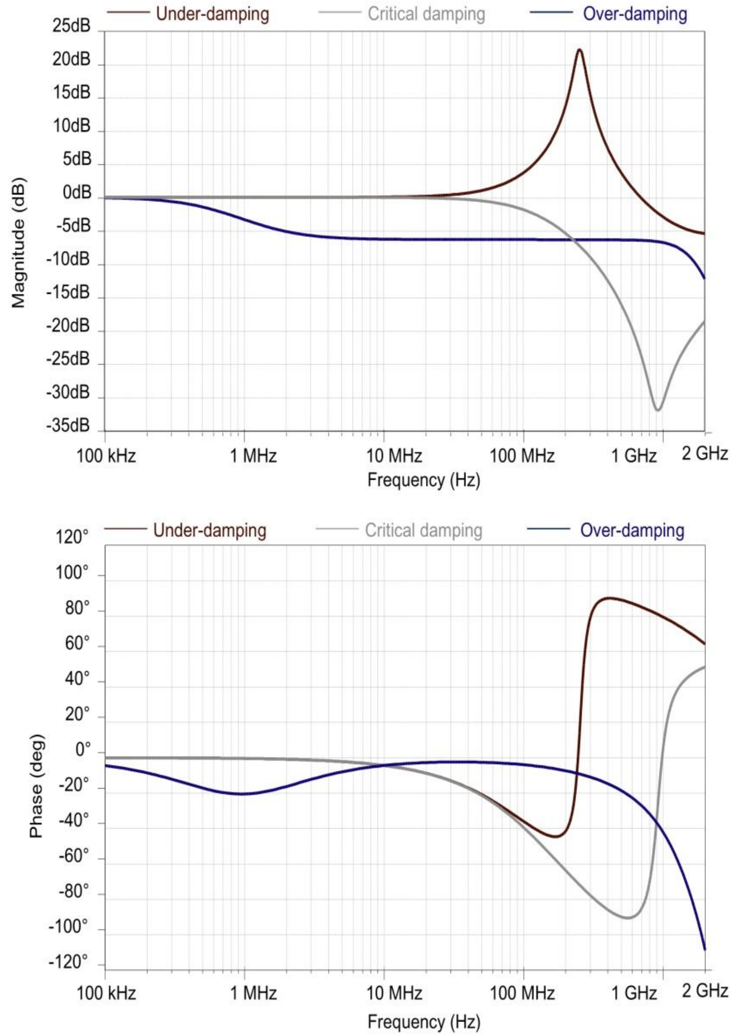
Critical damping
Rf = 10 kΩ
Cf = 0.5 pF

Over-damping
Rf = 5 kΩ
Cf = 50 pF

Transient responses



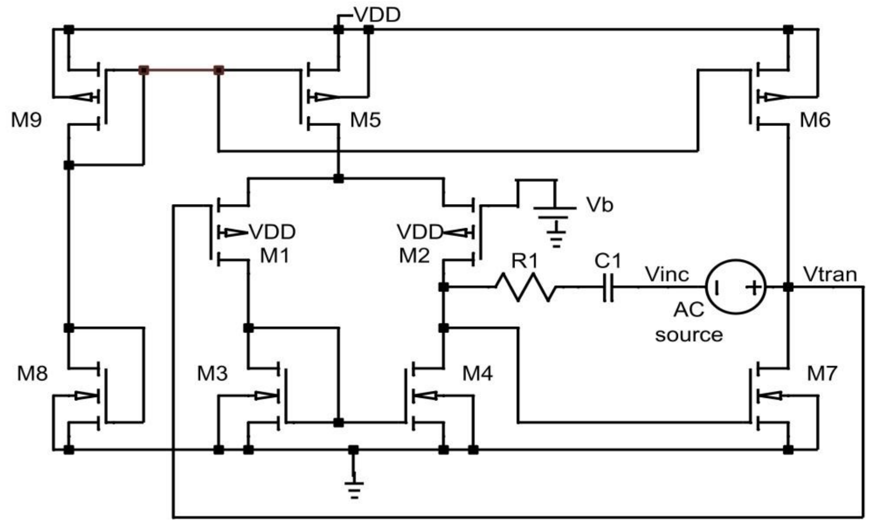
Transfer function



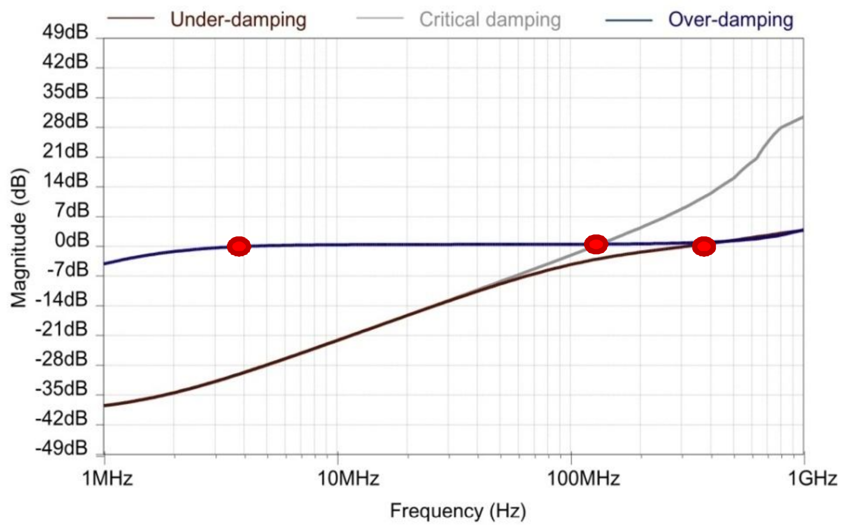
2. Analysis of High-Order Transfer Functions

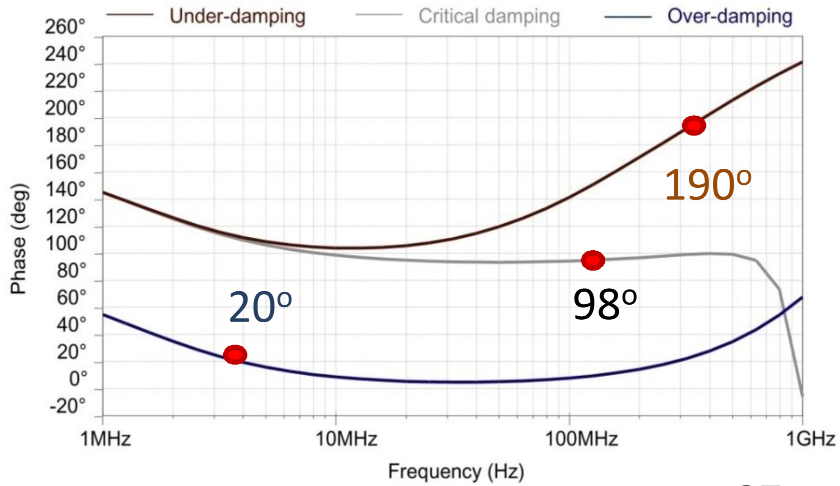
Effects of Miller's Capacitor on Buffer Op Amp

Derivation of self-loop function



Self-loop function





Over-damping:

→Phase margin is 160 degrees.

Critical damping:

→Phase margin is 82 degrees.

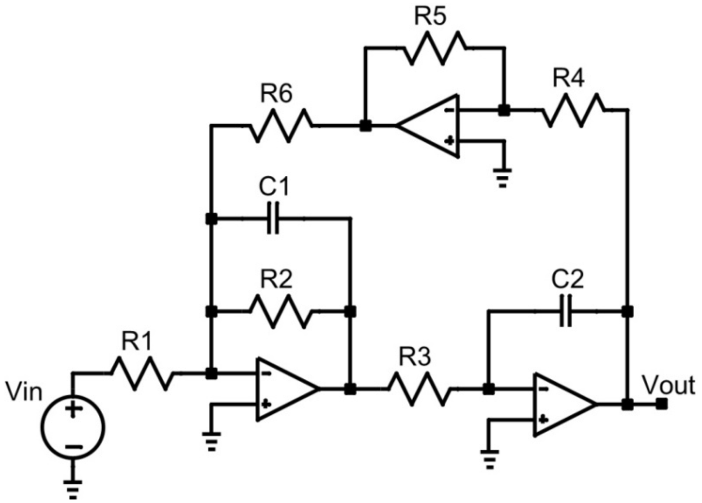
Under-damping:

→Phase margin is 10 degrees.

3. Design of High-Order Transfer Functions

Analysis of Second-order Tow-Thomas Biquad LPF

Tow-Thomas Biquad Network

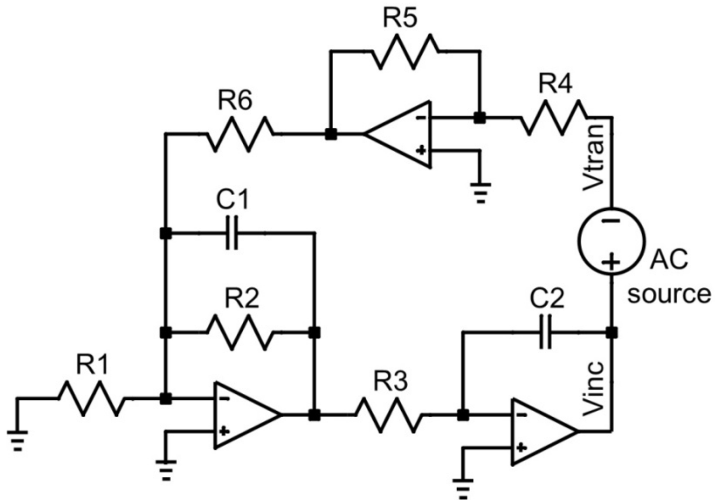


Transfer function H(ω) and self-loop function L(ω)

$$H(\omega) = \frac{\frac{R_4 R_6}{R_1 R_5}}{(j\omega)^2 \frac{R_3 R_4 R_6}{R_5} C_1 C_2 + j\omega \frac{R_3 R_4 R_6}{R_5 R_2} C_2 + 1}$$

$$L(\omega) = (j\omega)^2 \frac{R_3 R_4 R_6}{R_5} C_1 C_2 + j\omega \frac{R_3 R_4 R_6}{R_5 R_2} C_2$$

Derivation of self-loop function



Based on alternating current conservation principle,

$$\frac{V_{inc}}{A(\omega)} = -\frac{L(\omega)}{A(\omega)} V_{trans}$$

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

3. Design of High-Order Transfer Functions

Analysis of Second-order Tow-Thomas Biquad LPF

Operating regions of Tow-Thomas biquad low-pass filter

$$H(\omega) = \frac{4R_2^2C_1}{R_1R_3C_2}\frac{1}{\left[\left(2R_2C_1\right)^2\left(j\omega\right)^2 + 2j\omega\left(2R_2C_1\right)+1\right]+\left(2R_2C_1\right)^2\left[\dfrac{R_5}{R_3R_4R_6C_1C_2}-\left(\dfrac{1}{2R_2C_1}\right)^2\right]}$$

$$\frac{R_5}{R_3R_4R_6C_1C_2} > \left(\frac{1}{2R_2C_1}\right)^2 \rightarrow \text{Instability}$$

$$\frac{R_5}{R_3R_4R_6C_1C_2} = \left(\frac{1}{2R_2C_1}\right)^2 \rightarrow \text{Marginal stability}$$

$$\frac{R_5}{R_3R_4R_6C_1C_2} < \left(\frac{1}{2R_2C_1}\right)^2 \rightarrow \text{Stability}$$

Under-damping: R2 = 10 kΩ,

Critical damping: R2 = 3.5 kΩ,

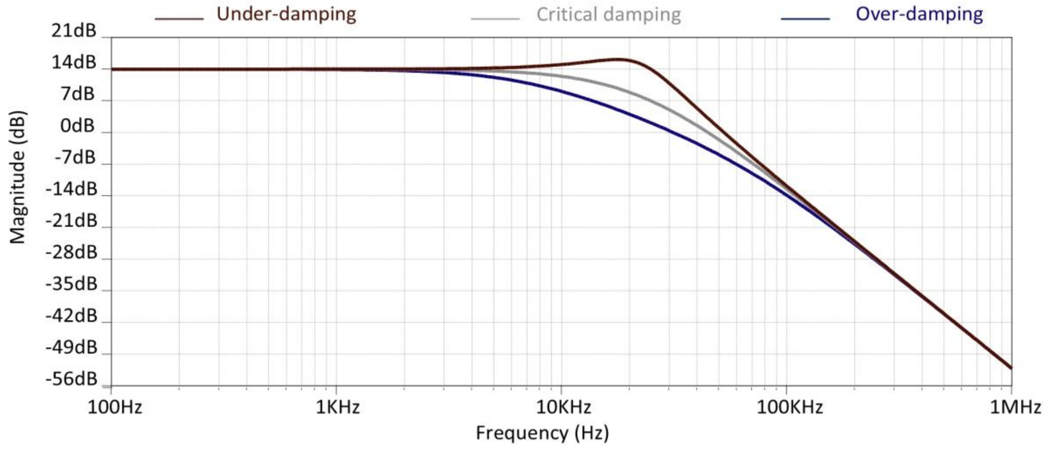
Over-damping: R2 = 10 kΩ

GBW = 10MHz, DC gain (Ao) = 100000, fo = 25kHz, C1 =1 nF,
C2 = 100 pF, R1= R4 = R5 = 1kΩ, R3 = 100 kΩ, R6 = 5 kΩ.

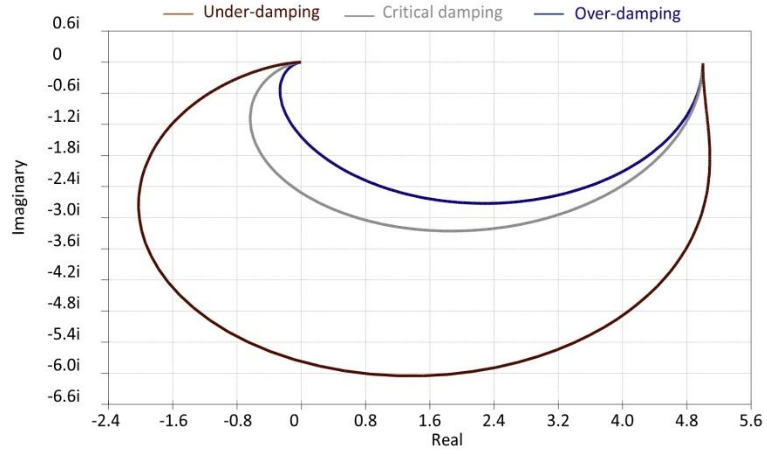
3. Design of High-Order Transfer Functions

Simulations of Transfer Function of Tow-Thomas LPF

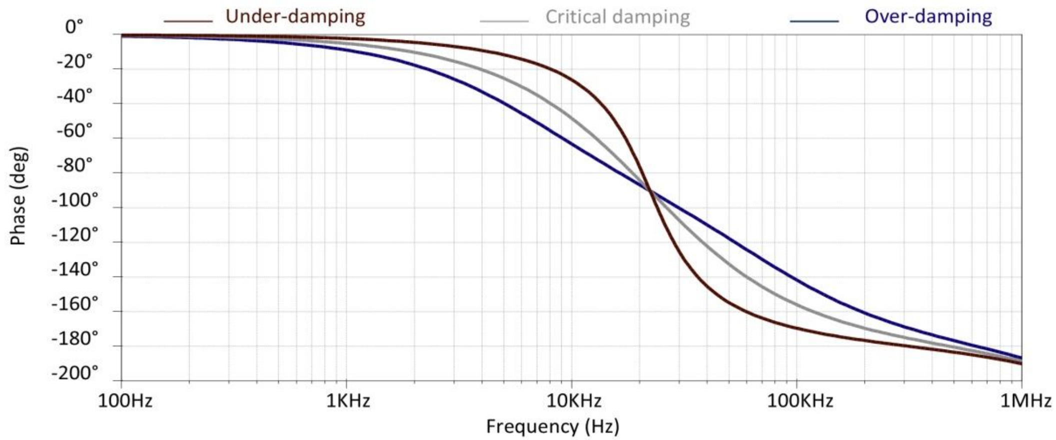
Magnitude plot of transfer function



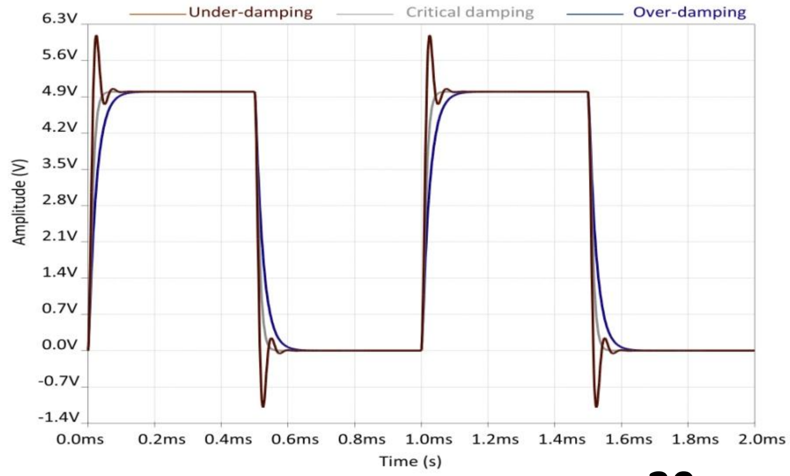
Nyquist plot of transfer function



Phase plot of transfer function



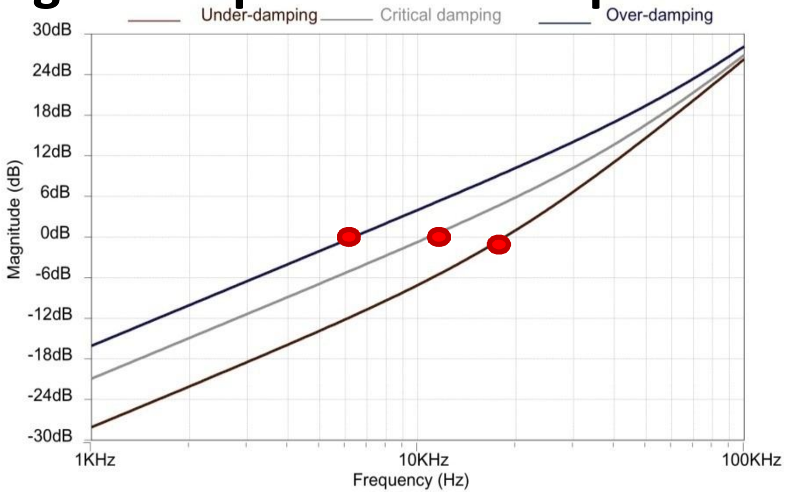
Transient response



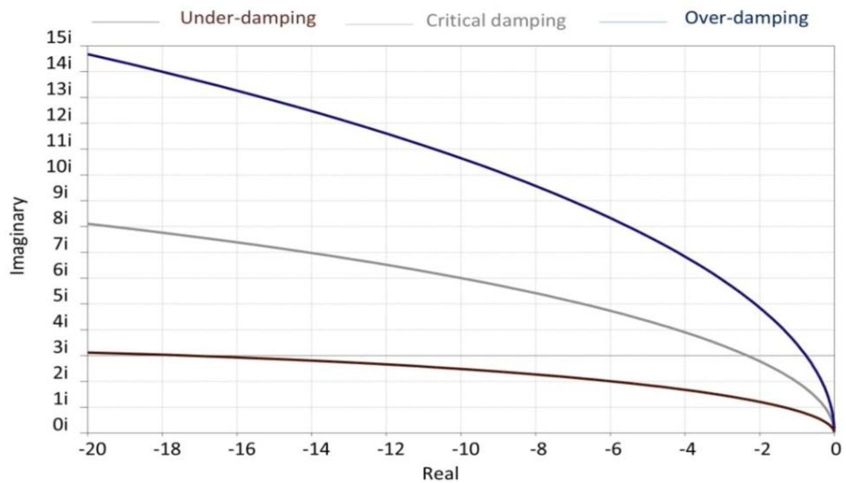
3. Design of High-Order Transfer Functions

Simulations of Self-loop Function of Tow-Thomas LPF

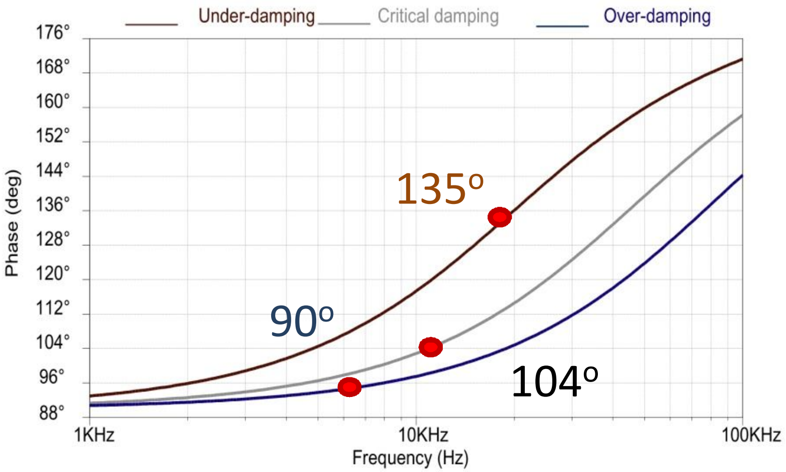
Magnitude plot of self-loop function



Nyquist plot of self-loop function



Phase plot of self-loop function



Over-damping:

→Phase margin is 90 degrees.

Critical damping:

→Phase margin is 76 degrees.

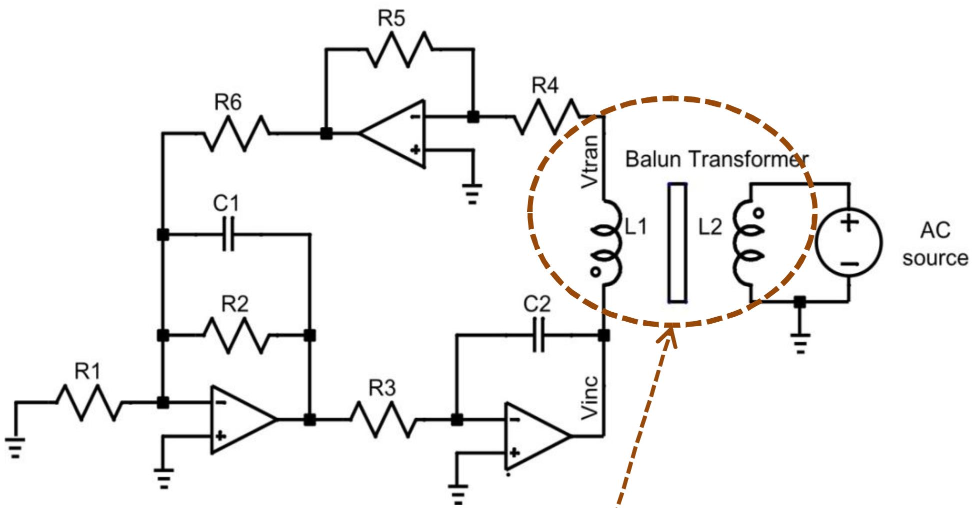
Under-damping:

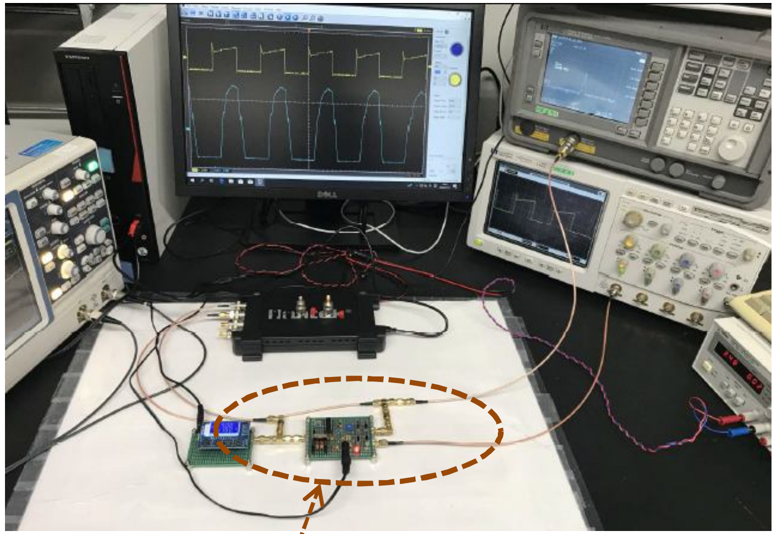
→Phase margin is 45 degrees.

3. Proposed Designs and Experimental Results

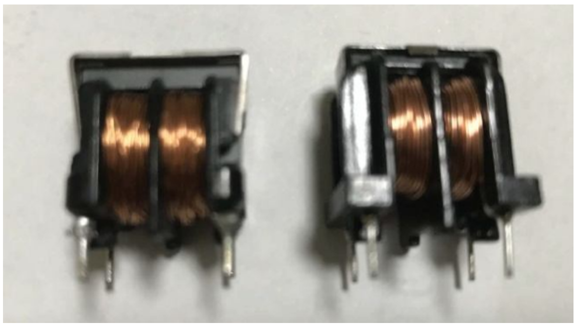
Implementation of Tow-Thomas Biquad LPF

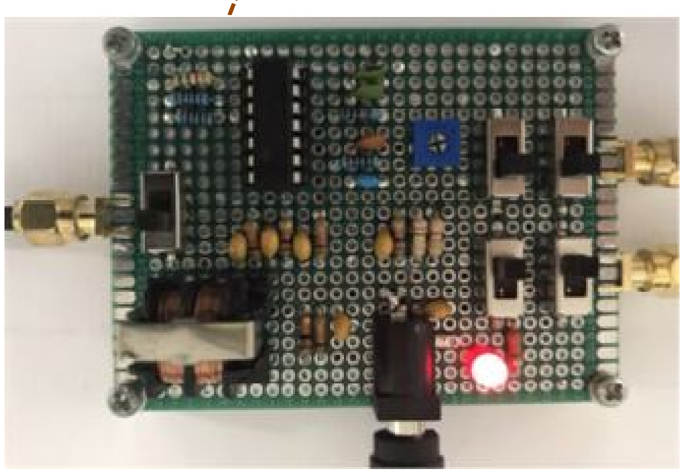
Measurement of self-loop function





Balun transformer (10 mH inductance)

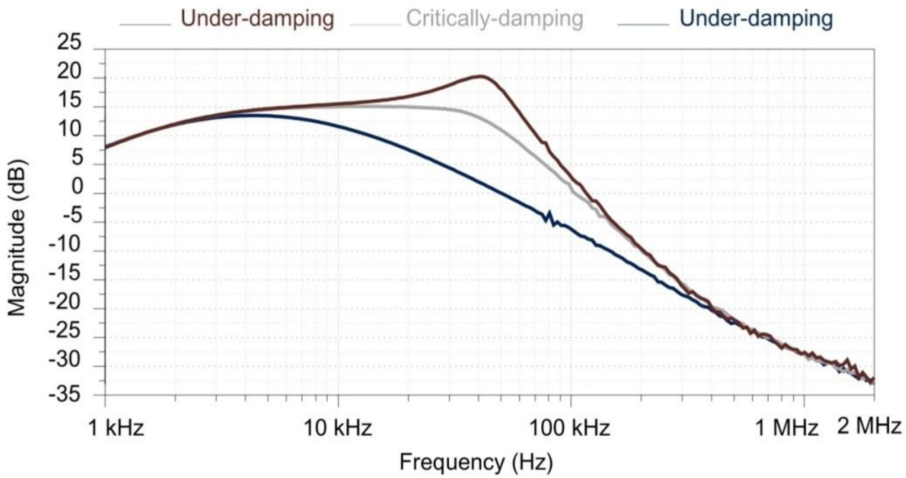




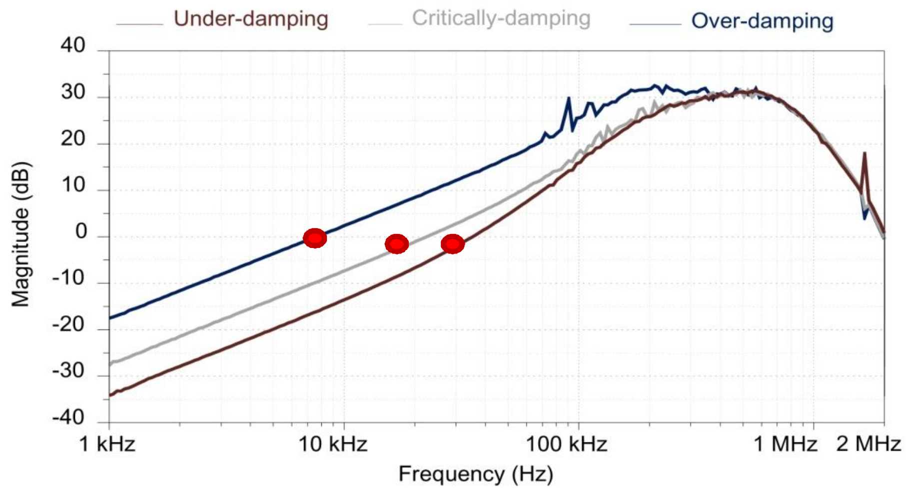
3. Proposed Designs and Experimental Results

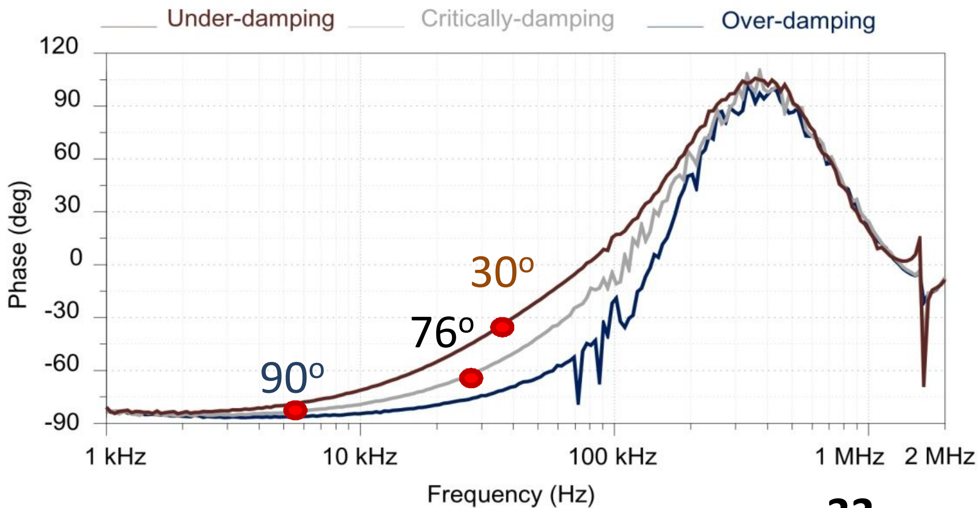
Measurement results of Tow-Thomas Biquad LPF

Behaviors of transfer function



Behaviors of self-loop function





Over-damping:

→Phase margin is 90 degrees.

Nearly Critical damping:

→Phase margin is 76 degrees.

Under-damping:

→Phase margin is 30 degrees.

4. Conclusions

This work:

- **Reviews of complex functions and basic op amp networks**
- **Proposed methods for measurement of self-loop function in basic op amp networks**
- **Implementation and stability test for second-order Tow-Thomas biquad filter**
- **Theoretically, if phase margin is smaller than 76.3-degrees, overshoot occurs in second-order systems.**

Future of work:

- **Stability test for polyphase filters & complex filters**

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Thank you very much!

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