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DESIGN OF ACTIVE INDUCTOR AND STABILITY TEST FOR PASSIVE RLC LOW-PASS FILTERS

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Outline

1. Research Background
- Reviews of Complex Functions
- Transfer Function and Its Self-loop Function
- Limitations of Conventional Methods
2. Analysis of High-Order Transfer Functions
- Behaviors of High-order Passive Transmission Spaces
- Numerical Examples and Design of Active Inductor
3. Experimental Results
- Measurements of Self-loop Functions in RLC networks
- Operating region of Active Serial RLC Low-pass Filter
4. Conclusions

1. Research Background

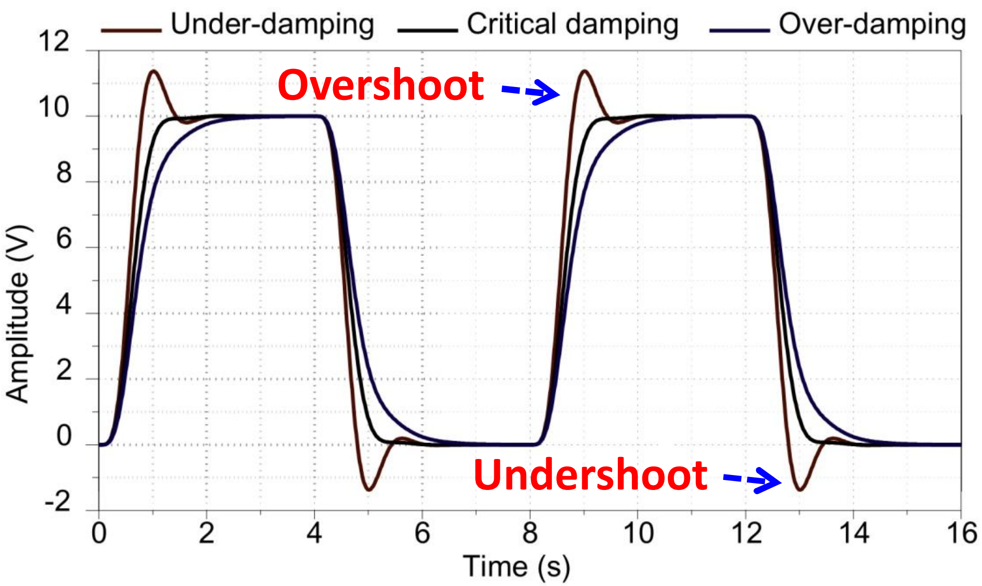
Motivation of Study

Large overshoots + ringing + unwanted voltage transients

→ **Damped oscillation noise**

→ **Unstable system**

STABILITY TEST



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

○ **Ringing affects both input and output signals.**

1. Research Background

Objectives and Achievements

Objectives

- ○ Investigation of operating region of high-order systems in both time and frequency domains

→ Over-damping (high delay in rising time)

→ Critical damping (max power propagation)

→ Under-damping (overshoot and ringing)

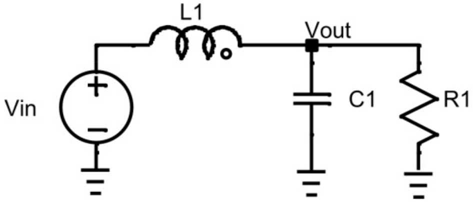
Achievements

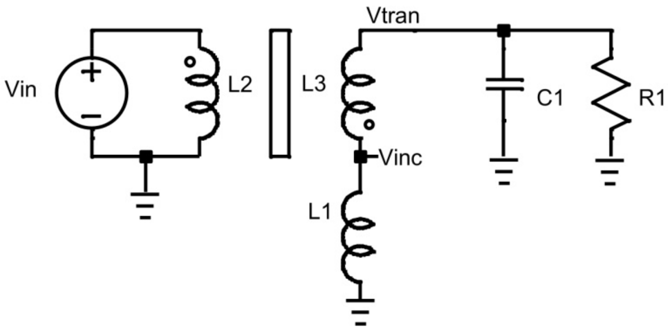
- ○ Design of active inductor and measurement of self-loop function in active serial RLC LPF

1. Research Background

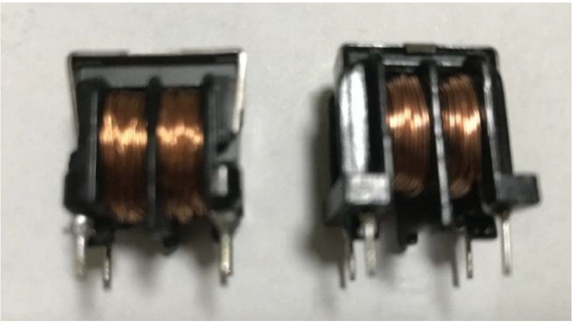
Approaching Methods

Passive RLC Low-pass Filter

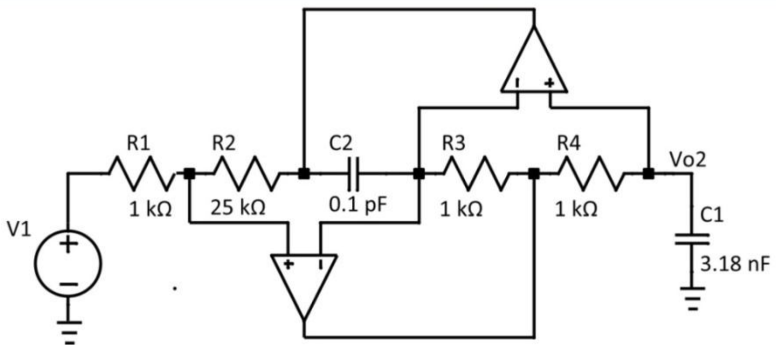




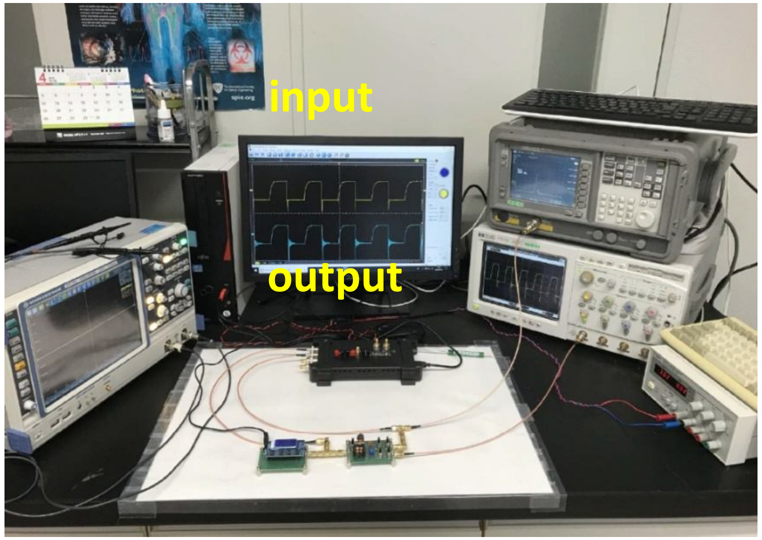
Balun transformer



Active RLC Low-pass Filter



Implementation of active RLC LPF



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

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

In spectrum domain

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

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

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

- **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

Linear system

Input $V_{in}(\omega) \longrightarrow \boxed{H(\omega)} \longrightarrow V_{out}(\omega)$ **Output**

$A(\omega)$ **: 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

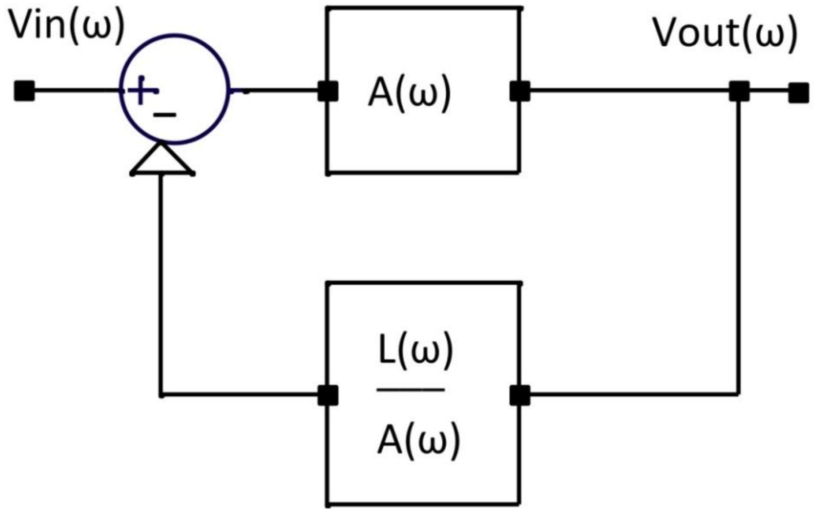
Transfer function

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

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.**

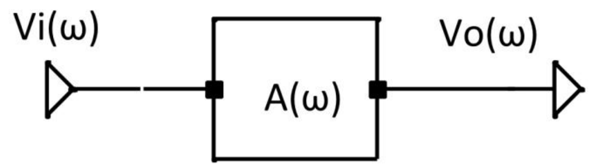
STABILITY TEST

1. Research Background

Proposed Comparison Measurement Technique

Step1: Open loop function

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

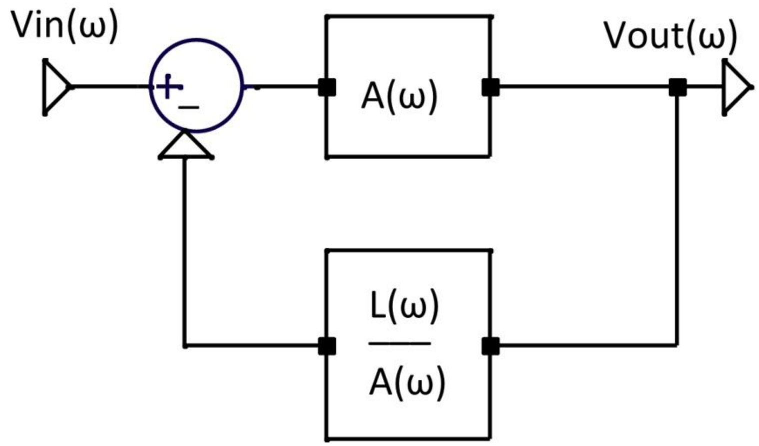


Step2: Transfer function

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

Step3: Self-loop function

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



Sequence of steps:

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

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

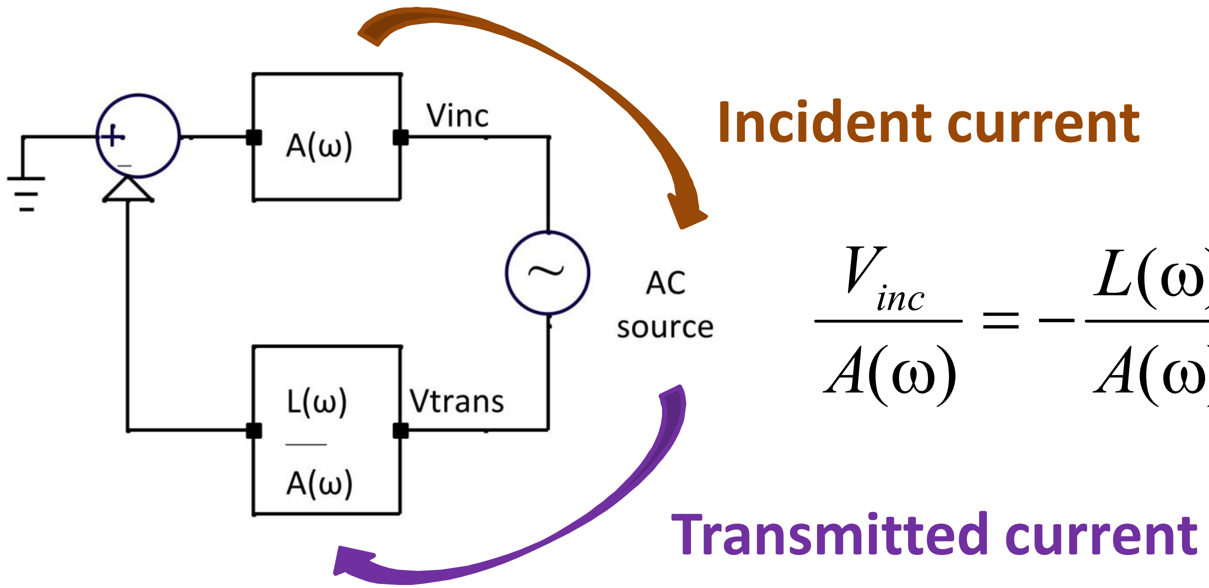
(iii) Derivation of self-loop function.

1. Research Background

Proposed Alternating Current Conservation (1)

Idea: **Alternating current is conserved.**

Incident current = Transmitted current

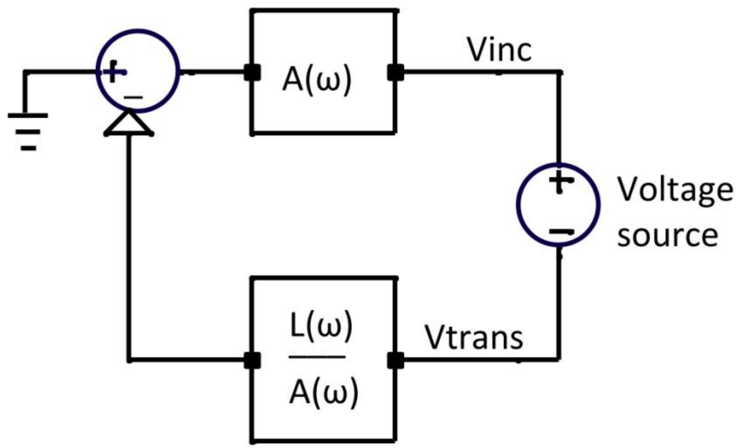


$$\frac{V_{inc}}{A(\omega)} = -\frac{L(\omega)}{A(\omega)} V_{trans}$$

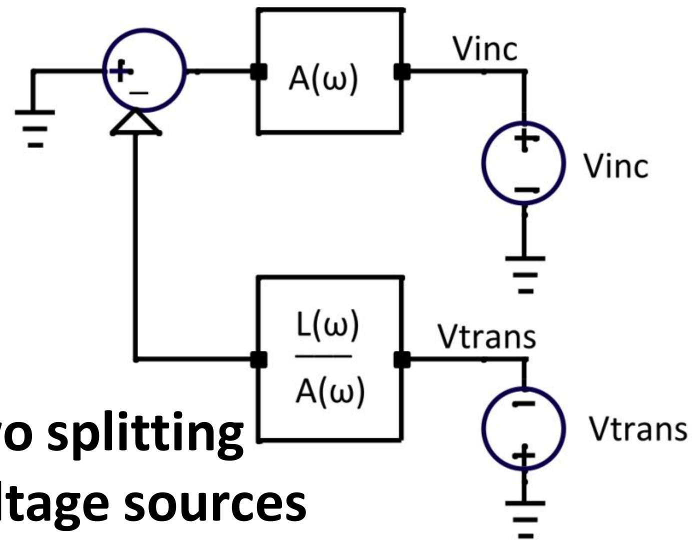
Self-loop function: $L(\omega) = -\frac{V_{inc}}{V_{trans}}$

1. Research Background

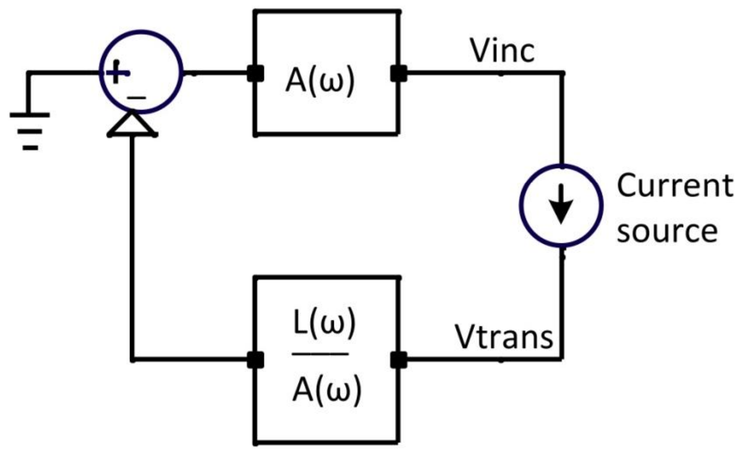
Proposed Alternating Current Conservation (2)



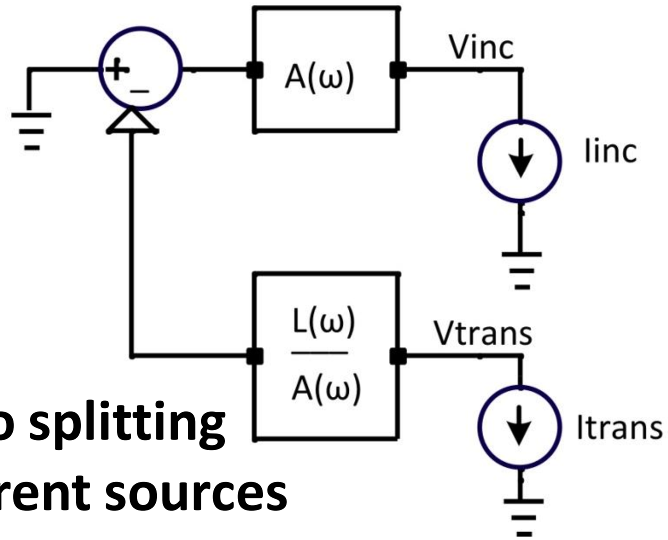
One voltage source



Two splitting voltage sources



One current source

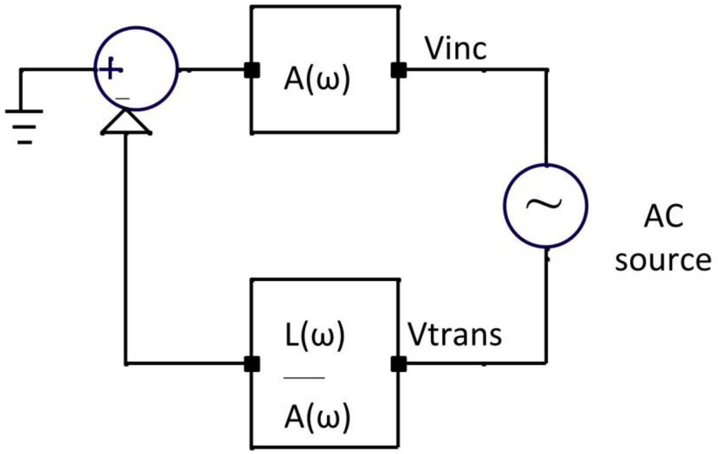


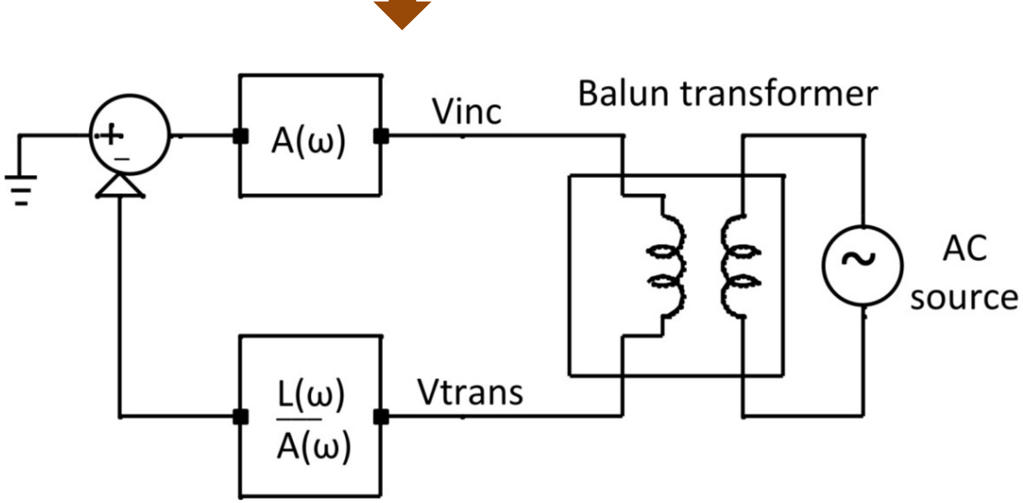
Two splitting current sources

1. Research Background

Proposed Alternating Current Conservation (3)

Alternating current conservation using balun transformer

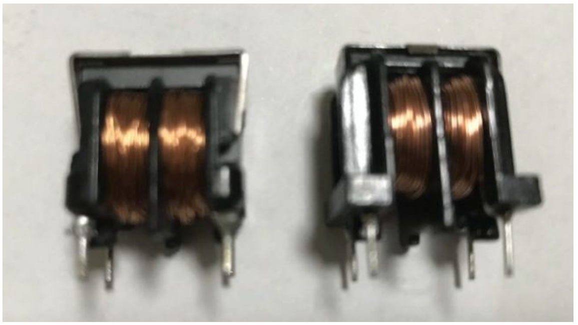




Self-loop function:

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

Balun transformer (10 mH inductance)



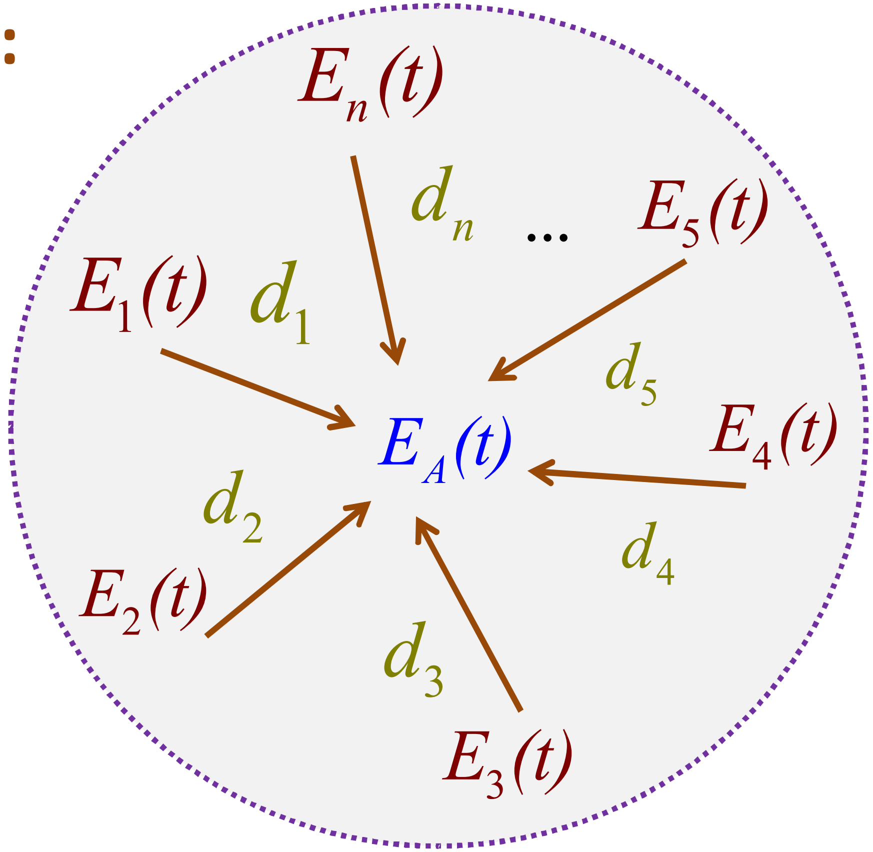
1. Research Background

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

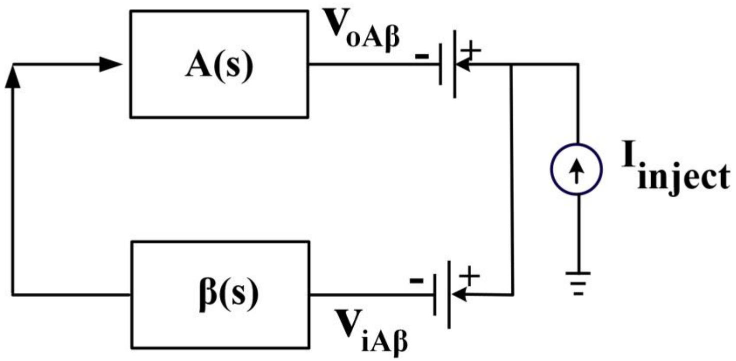
Limitations of Conventional Methods (1)

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

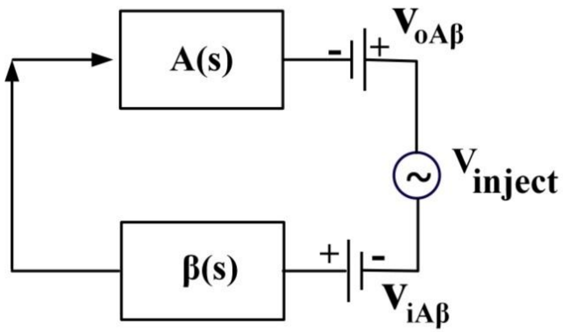
Measurement of loop gain

- ❖ Current injection
- ❖ Voltage injection

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



Current injection method



Voltage injection method

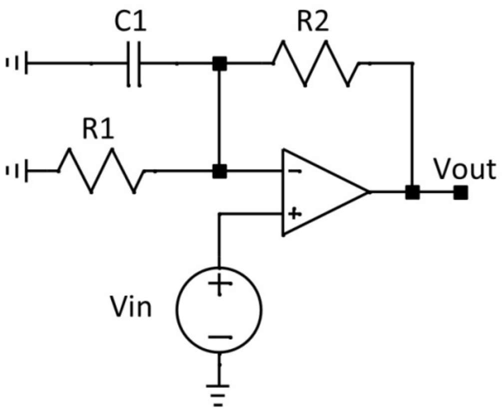
→**Difficult** to measure self-loop function in analog circuits

1. Research Background

Limitations of Conventional Methods (2)

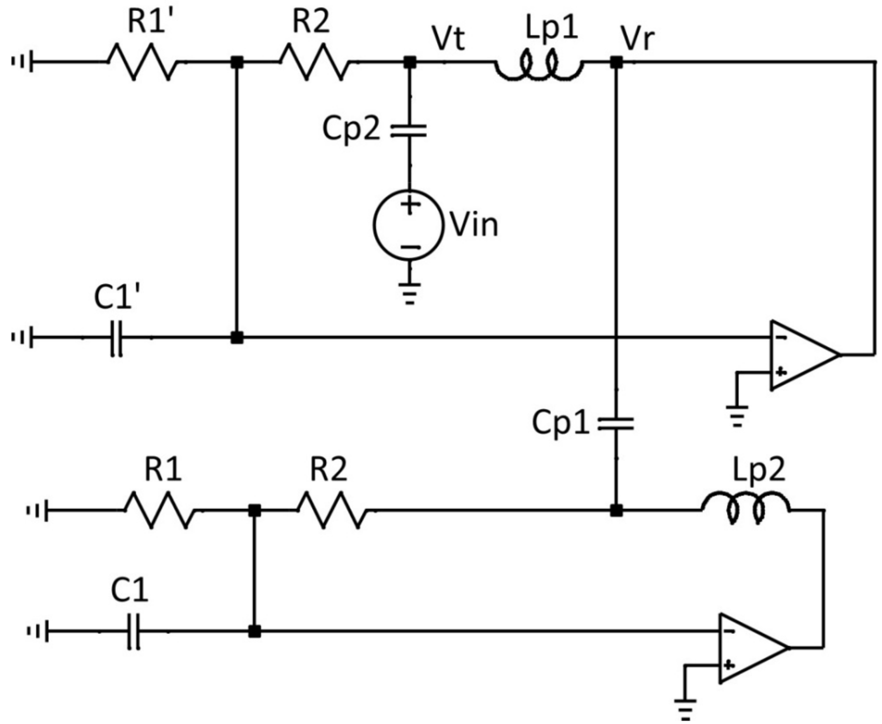
[9] A. S. Sedra and K. C. Smith, "Microelectronic Circuits," 6th ed. Oxford University Press, New York, 2010.

Measurement of loop gain



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

❖Replica measurement



→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**

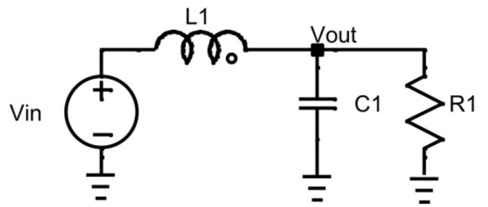
→ **Using in theoretical analysis for feedback systems (Lab simulation).**

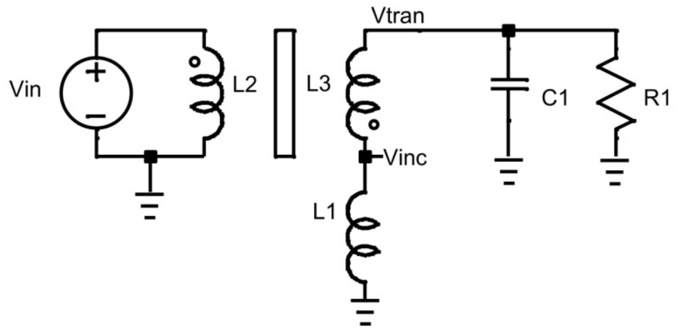
- **Conventional concepts, analysis and measurement of loop gain are not unique.**

2. Analysis of High-Order Transfer Functions

Second-order Parallel RLC Low-pass Filter

Parallel RLC low-pass filter





Apply superposition principle at Vout

$$V_{out}\left(\frac{1}{R}+\frac{1}{Z_C}+\frac{1}{Z_L}\right)=\frac{V_{in}}{Z_L};$$

Transfer function & self-loop function:

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

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

Where:

$$a_0=LC;\quad a_1=\frac{L}{R};$$

$$\omega_0=1\big/\sqrt{LC};$$

$$\left|Z_L\right|=\omega_0 L;\quad \left|Z_C\right|=1\big/\omega_0 C;$$

Operating regions

- **Over-damping:** $\frac{1}{LC}<\left(\frac{R}{2L}\right)^2 \Leftrightarrow \left|Z_L\right|=\left|Z_C\right|<R/2$
- **Critical damping:** $\frac{1}{LC}=\left(\frac{R}{2L}\right)^2 \Leftrightarrow \left|Z_L\right|=\left|Z_C\right|=R/2$
- **Under-damping:** $\frac{1}{LC}>\left(\frac{R}{2L}\right)^2 \Leftrightarrow \left|Z_L\right|=\left|Z_C\right|>R/2$

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">$\dfrac{\frac{1}{a_0}}{\sqrt{\omega^2 + \left(\frac{a_1}{2a_0} - \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}\right)^2}\sqrt{\omega^2 + \left(\frac{a_1}{2a_0} + \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}\right)^2}}$</td><td colspan="2">$\dfrac{\frac{1}{a_0}}{\left[\omega^2 + \left(\frac{a_1}{2a_0}\right)^2\right]}$</td><td colspan="2">$\dfrac{\frac{1}{a_0}}{\sqrt{\left(\omega - \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}\right)^2 + \left(\frac{a_1}{2a_0}\right)^2}\sqrt{\left(\omega + \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}\right)^2 + \left(\frac{a_1}{2a_0}\right)^2}}$</td></tr>
<tr><td>Angular $\theta(\omega)$</td><td colspan="2">$-\arctan\left(\dfrac{\omega}{\frac{a_1}{2a_0} - \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}}\right) - \arctan\left(\dfrac{\omega}{\frac{a_1}{2a_0} + \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}}\right)$</td><td colspan="2">$-2\arctan\left(\dfrac{2a_0\omega}{a_1}\right)$</td><td colspan="2">$-\arctan\left(\dfrac{\omega - \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}}{\frac{a_1}{2a_0}}\right) - \arctan\left(\dfrac{\omega + \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}}{\frac{a_1}{2a_0}}\right)$</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

Example of Second-order Transfer Function

Magnitude of transfer function

- **Under-damping:**

$$H_1(\omega) = \frac{1}{(j\omega)^2 + j\omega + 1} \Rightarrow |H_1(\omega)| = \frac{1}{\sqrt{\left(\omega - \frac{\sqrt{3}}{2}\right)^2 + \frac{1}{4}}\sqrt{\left(\omega + \frac{\sqrt{3}}{2}\right)^2 + \frac{1}{4}}}$$

$$\frac{\sqrt{3}-1}{2} < \omega < \frac{\sqrt{3}+1}{2} \Rightarrow |H_1(\omega)| > 1 \qquad \left(\omega_1 = \frac{\sqrt{3}-1}{2} < \omega_{cut} = 1\right)$$

- **Critical damping:**

$$H_2(\omega) = \frac{1}{(j\omega)^2 + 2j\omega + 1} \Rightarrow |H_2(\omega)| = \frac{1}{\omega^2 + 1} \qquad (\omega_{cut} = 1)$$

- **Over-damping:**

$$H_3(\omega) = \frac{1}{(j\omega)^2 + 3j\omega + 1} \Rightarrow |H_3(\omega)| = \frac{1}{\sqrt{\omega^2 + \left(\frac{3-\sqrt{5}}{2}\right)^2}\sqrt{\omega^2 + \left(\frac{3+\sqrt{5}}{2}\right)^2}}$$

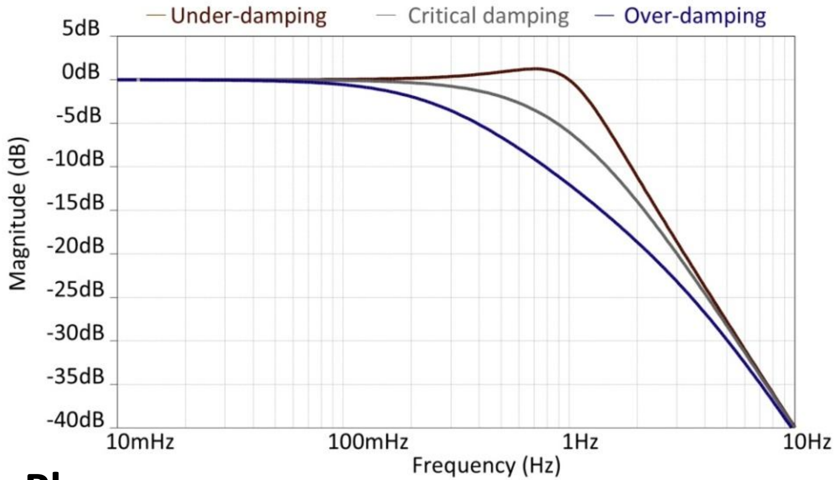
$$\frac{3-\sqrt{5}}{2} < \omega < \frac{3+\sqrt{5}}{2} \Rightarrow |H_3(\omega)| < 1 \qquad \left(\omega_1 = \frac{3-\sqrt{5}}{2} < \omega_{cut} = 1\right)$$

2. Analysis of High-Order Transfer Functions

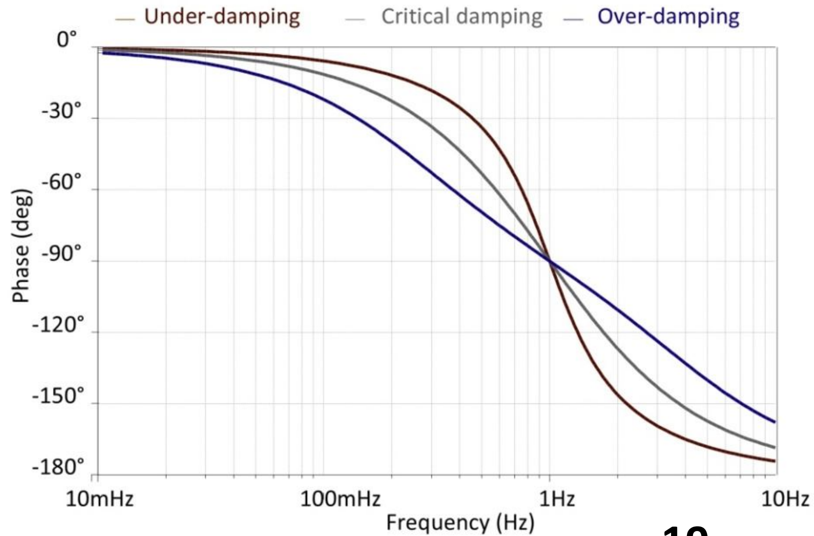
Simulations of Second-order Transfer Function

- **Under-damping:** $H_1(\omega) = \dfrac{1}{(j\omega)^2 + j\omega + 1};$
- **Critical damping:** $H_2(\omega) = \dfrac{1}{(j\omega)^2 + 2j\omega + 1};$
- **Over-damping:** $H_3(\omega) = \dfrac{1}{(j\omega)^2 + 3j\omega + 1};$

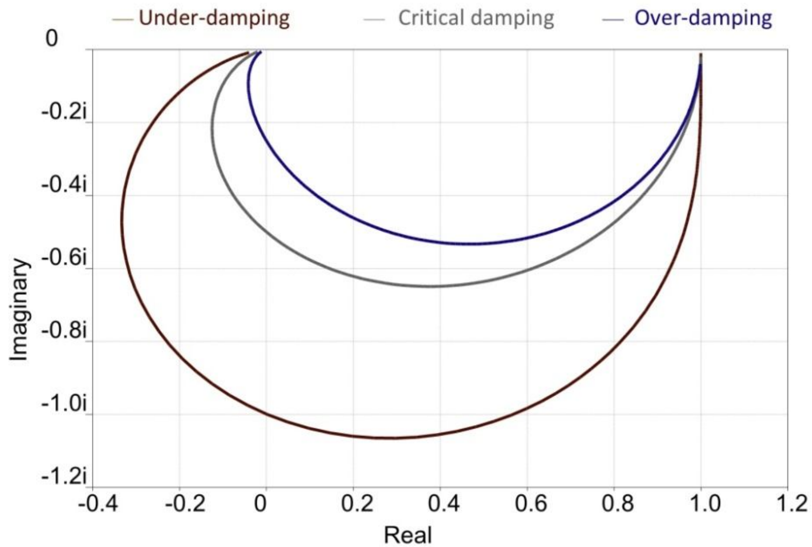
Magnitude response



Phase response



Polar chart of transfer function



Nyquist chart

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

2. Analysis of High-Order Transfer Functions

Behaviors of Second-order Self-loop Function

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

Unity gain of self-loop function $\left|L(\omega)\right| = \omega\sqrt{\left(a_0\omega\right)^2 + a_1^2} = 1$

Angular frequency at unity gain $\omega_1 = \frac{a_1}{2a_0}\sqrt{\sqrt{5} - 2}$

Phase margin at unity gain of self-loop function

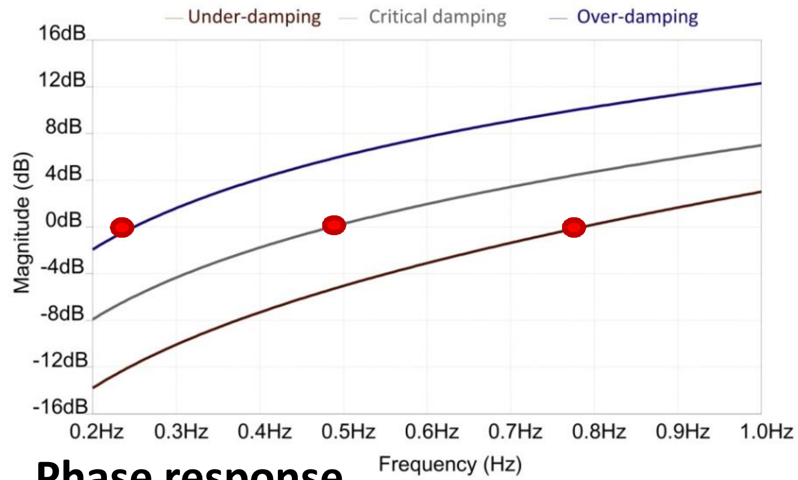
- **Under-damping:** $\text{Phase margin} = \pi - \theta(\omega_1) < 76.3^o$
- **Critical damping:** $\text{Phase margin} = \pi - \theta(\omega_1) = 76.3^o$
- **Over-damping:** $\text{Phase margin} = \pi - \theta(\omega_1) > 76.3^o$

2. Analysis of High-Order Transfer Functions

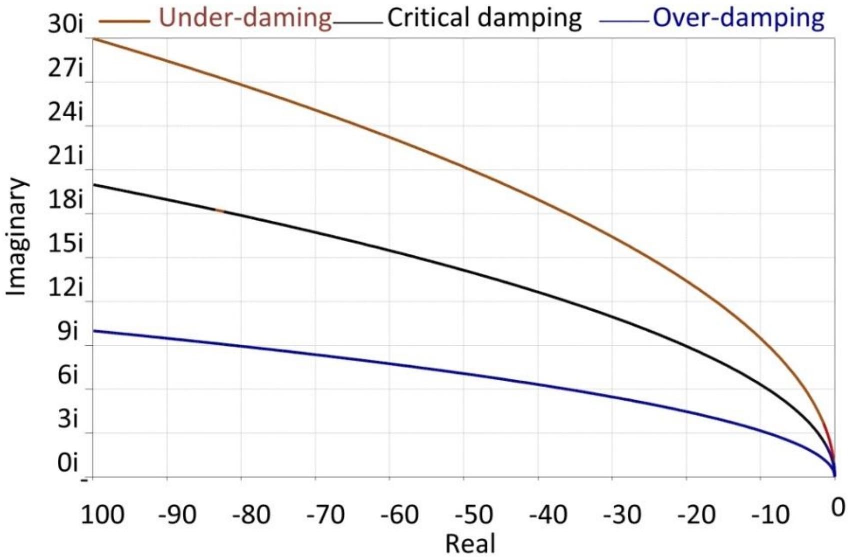
Simulations of Second-order Self-loop Function

- **Under-damping:** $L_1(\omega) = (j\omega)^2 + j\omega;$
- **Critical damping:** $L_2(\omega) = (j\omega)^2 + 2j\omega;$
- **Over-damping:** $L_3(\omega) = (j\omega)^2 + 3j\omega;$

Magnitude response

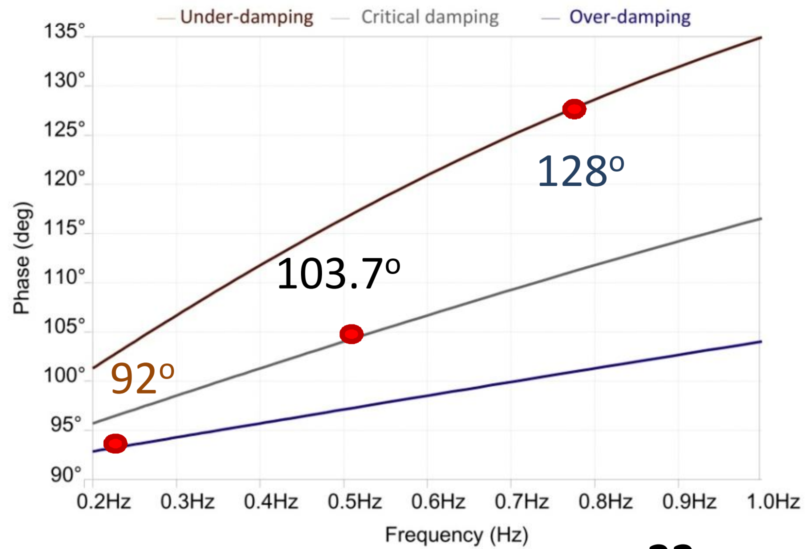


Polar chart of self-loop function



Nyquist chart

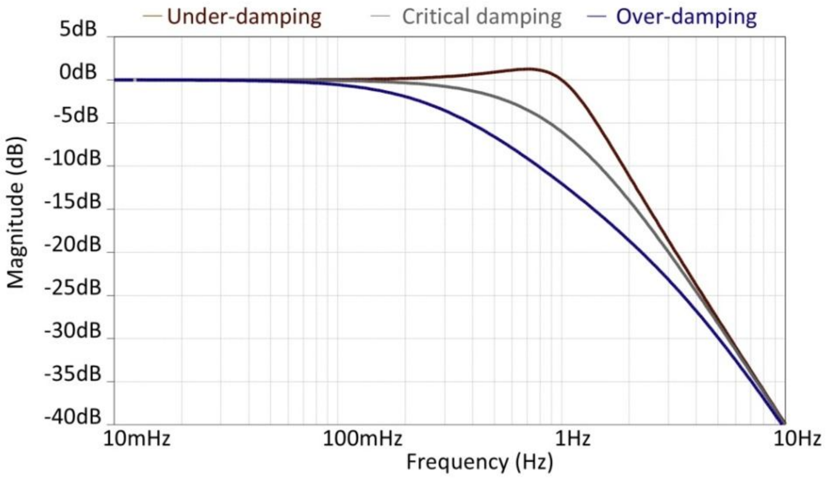
Phase response



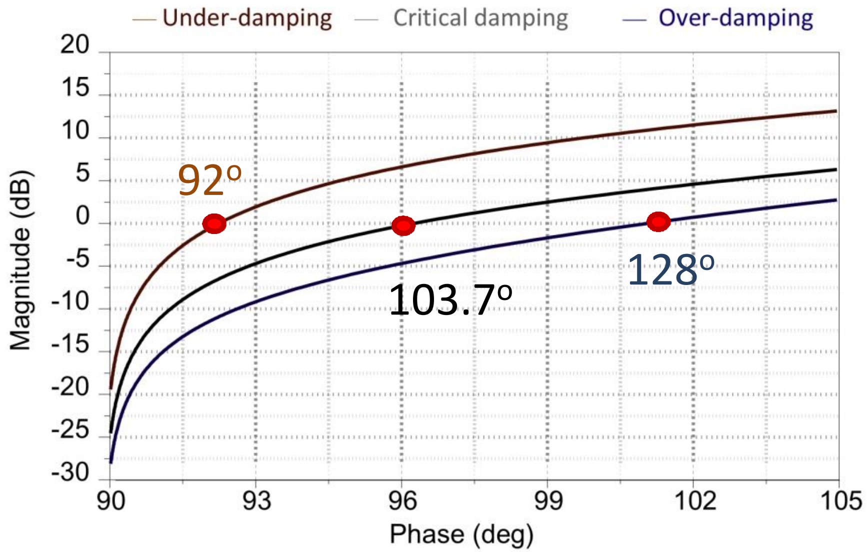
2. Analysis of High-Order Transfer Functions

Summary of Second-order System

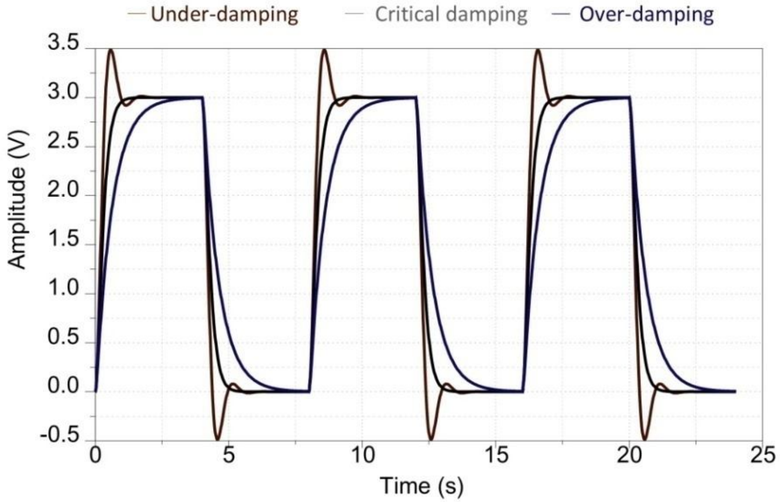
Magnitude response of transfer function



Magnitude-angular response of self-loop function



Transient response



Over-damping:

→Phase margin is 88 degrees.

Critical damping:

→Phase margin is 76.3 degrees.

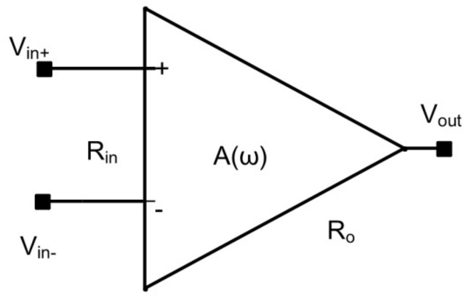
Under-damping:

→Phase margin is 52 degrees.

2. Analysis of High-Order Transfer Functions

Mathematical Model of Ideal Op Amp

Ideal op amp



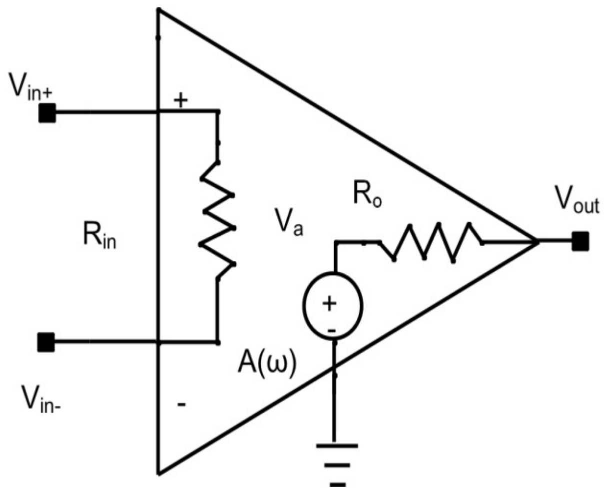
Open-loop function A(ω) of op amp

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

Gain-bandwidth (GBW), bandwidth fbw

Equivalent model of op amp

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



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

Open-loop function and self-loop function

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

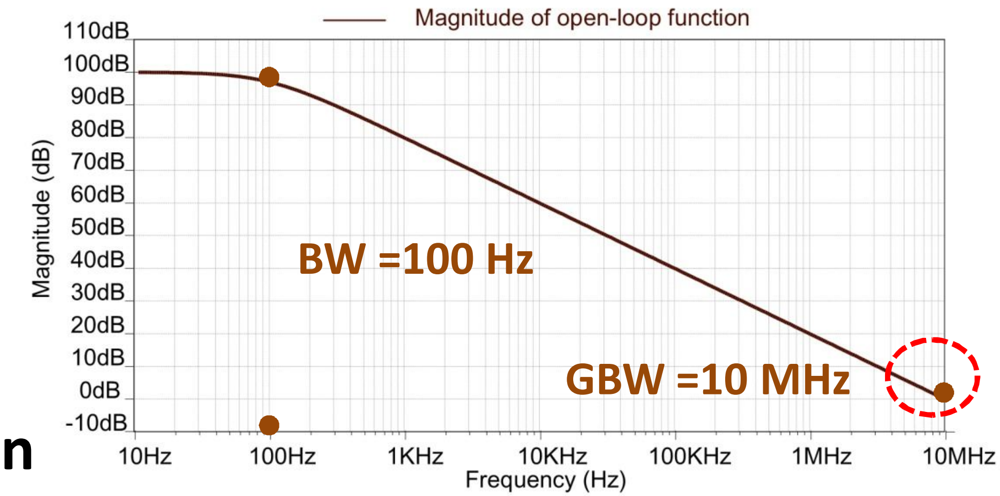
2. Analysis of High-Order Transfer Functions

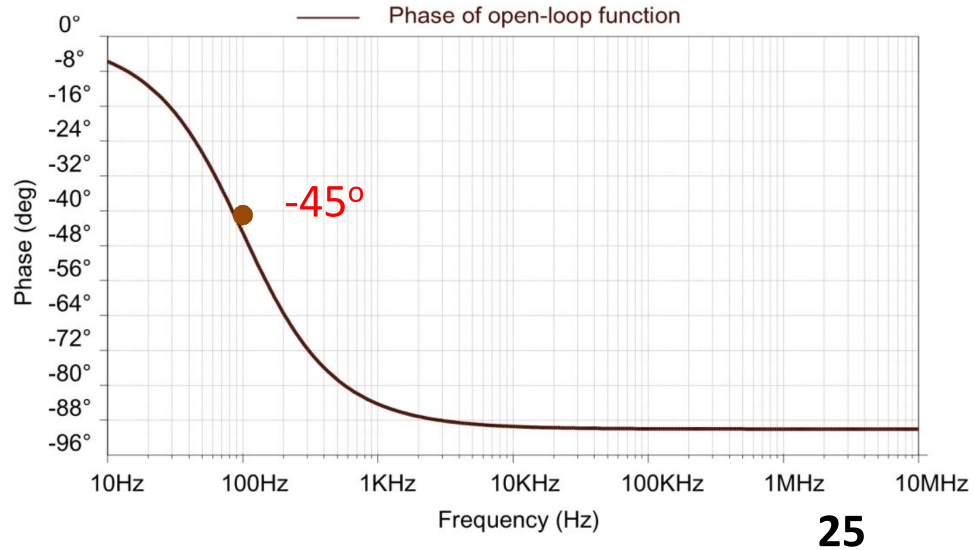
Behavior of Open-loop Function of Ideal Op Amp

Open-loop function A(ω)

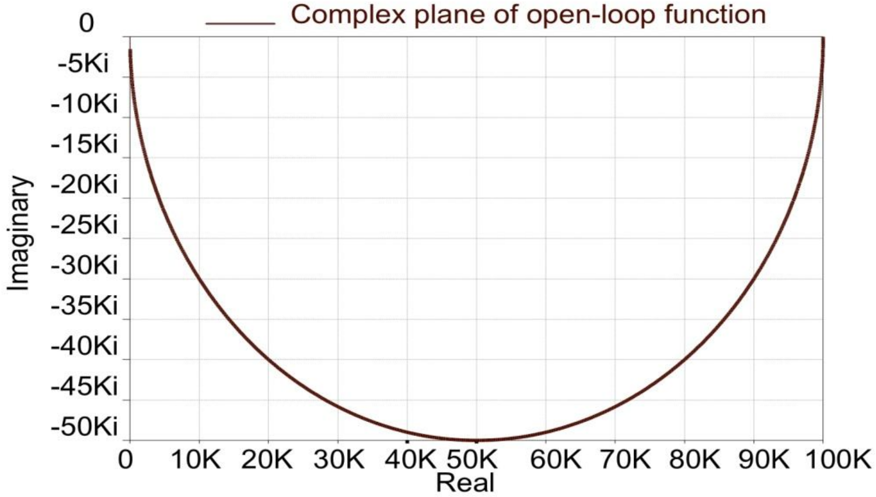
$$A(\omega) = \frac{10^5}{1 + j\dfrac{\omega}{200\pi}}$$

Bode plots of open-loop function





Nyquist plot of open-loop function



Nyquist chart

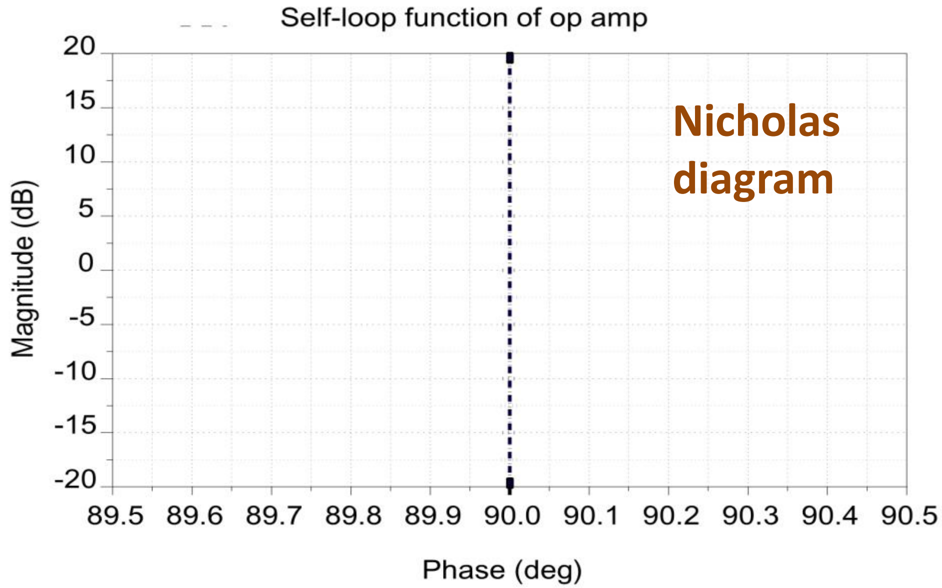
2. Analysis of High-Order Transfer Functions

Behavior of Self-loop Function of Ideal Op Amp

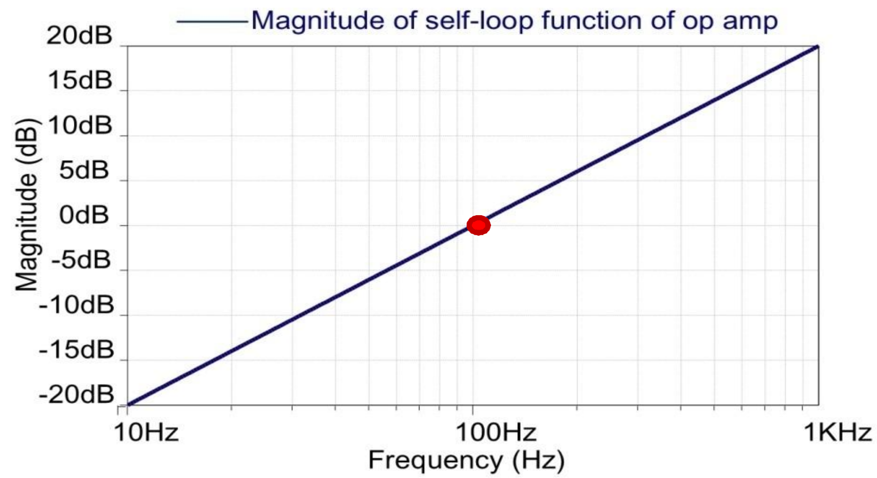
Self-loop function L(ω)

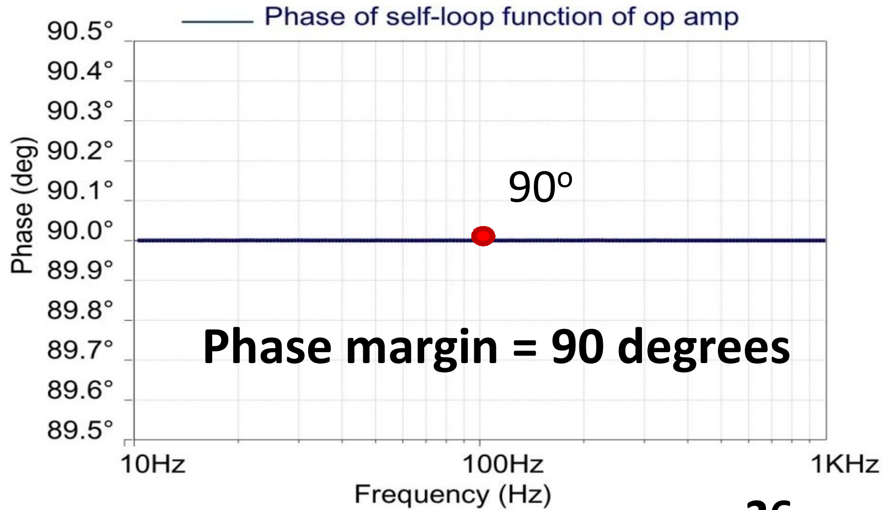
$$L(\omega) = j\frac{\omega}{200\pi} = 10^5\frac{V_{in}}{V_{out}} - 1$$

Magnitude-angular plot of self-loop function



Bode plots of self-loop functions

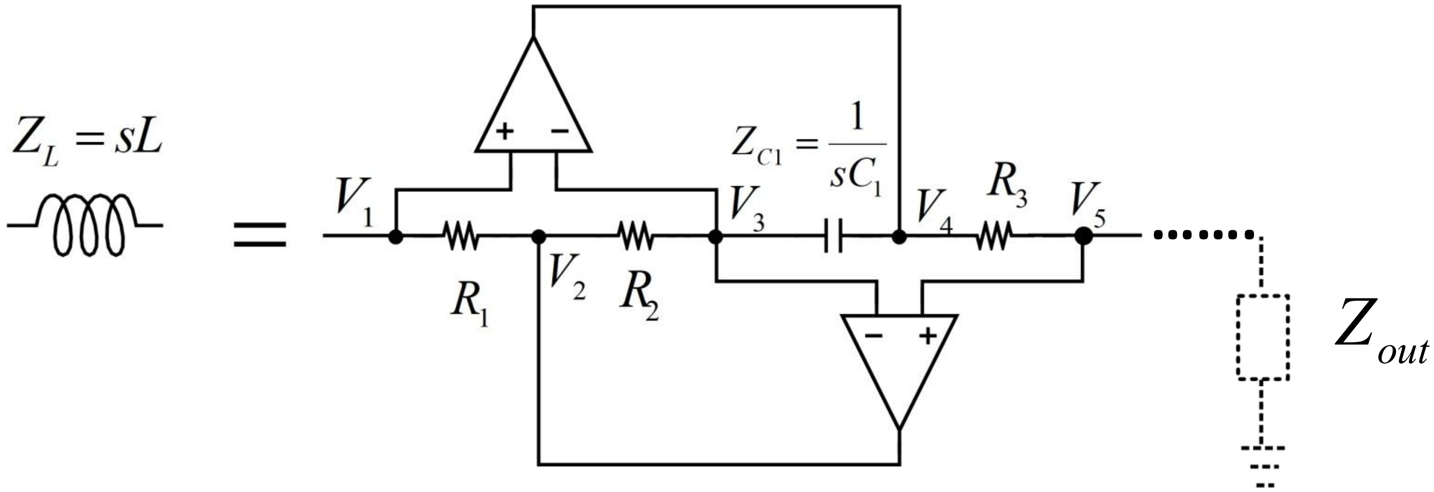




2. Analysis of High-Order Transfer Functions

Analysis of Active Inductor

General impedance converter



Apply superposition principle at V3

$$V_3\left(\frac{1}{R_2}+\frac{1}{Z_C}\right)=\frac{V_2}{R_2}+\frac{V_4}{Z_C}$$

Here, $V_1 = V_3 = V_5$

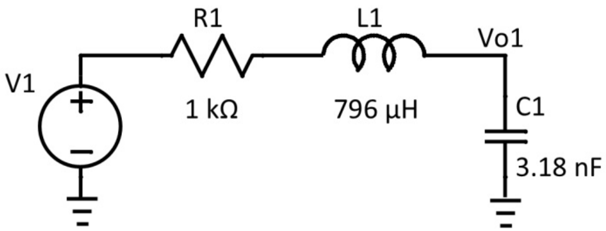
Approximated value of active inductor

$$Z_L = \frac{R_2}{R_1}\frac{R_3}{Z_C}Z_{out} = \frac{R_2 R_3}{R_1}sCZ_{out}$$

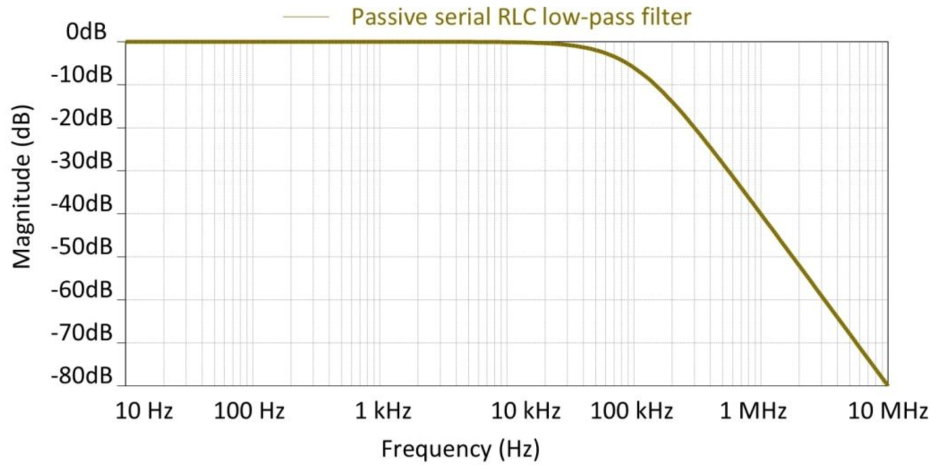
2. Analysis of High-Order Transfer Functions

Simulations of Passive & Active RLC Low-pass Filters

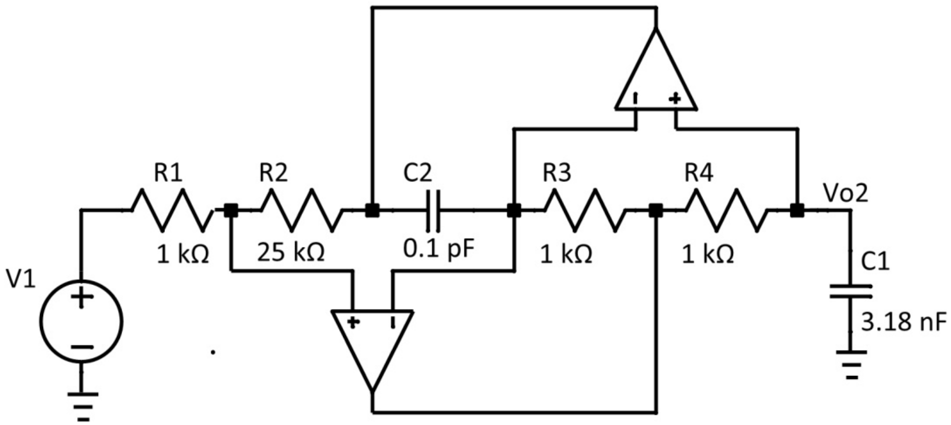
Passive serial RLC Low-pass Filter



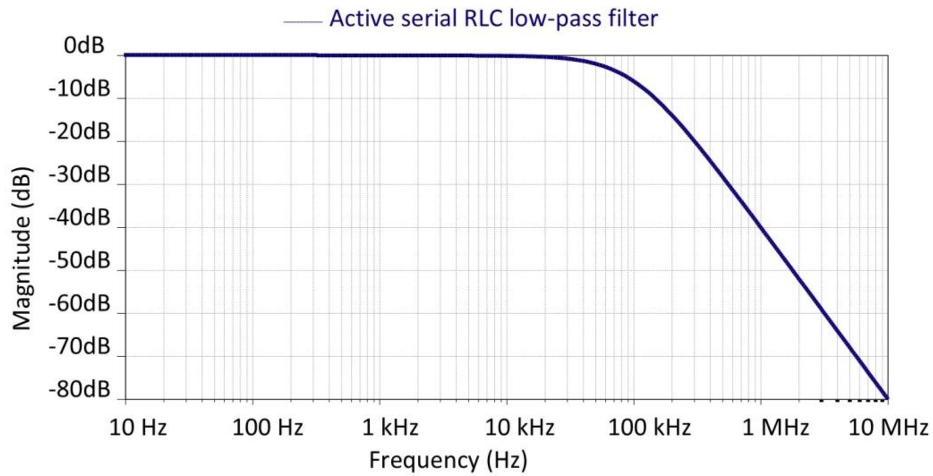
Magnitude response of transfer function



Active serial RLC Low-pass Filter



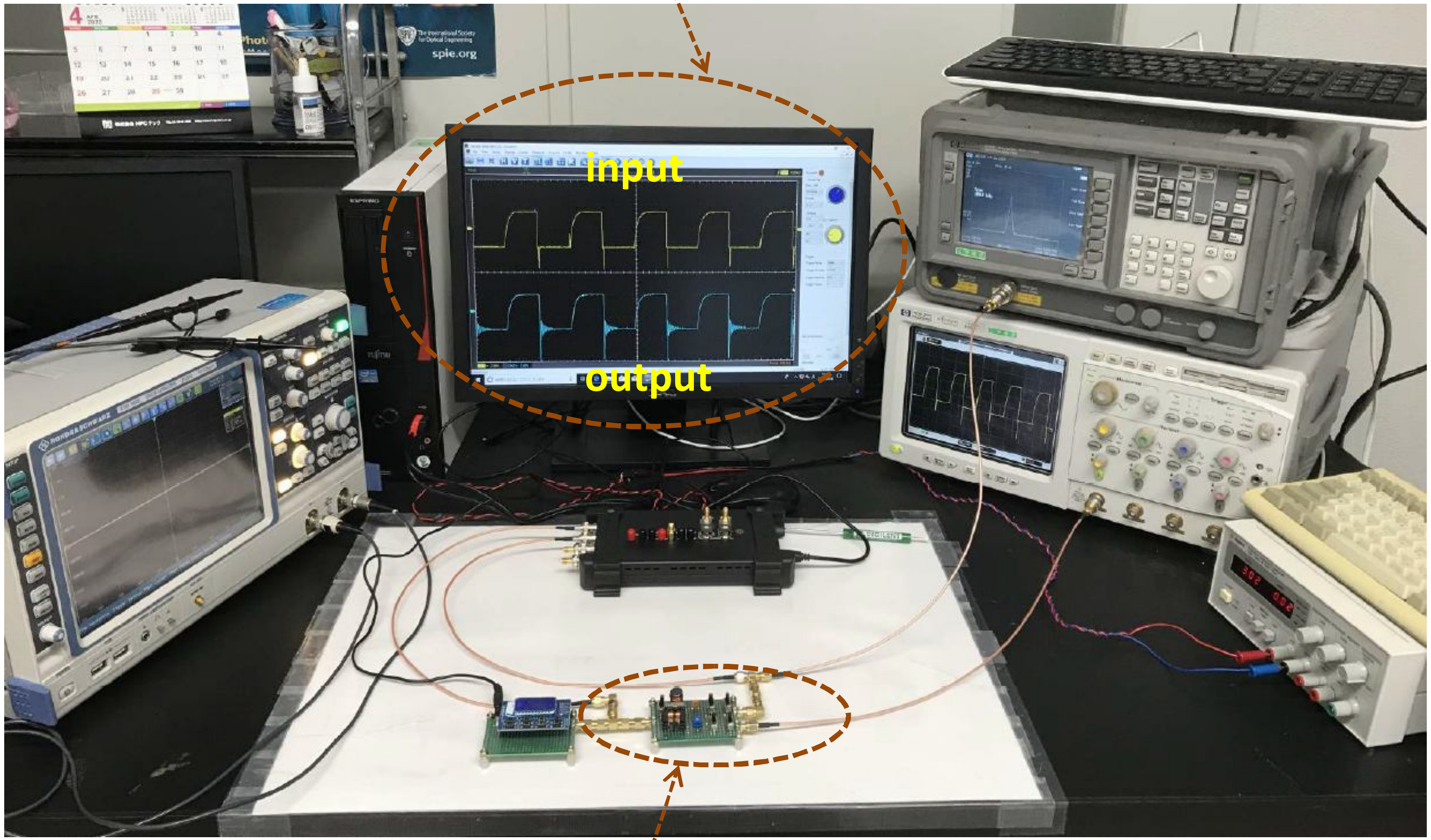
Magnitude response of transfer function



3. Proposed Designs and Experimental Results

Implementation of Second-order Serial RLC LPF

Under-shoot occurred at both input and output ports.

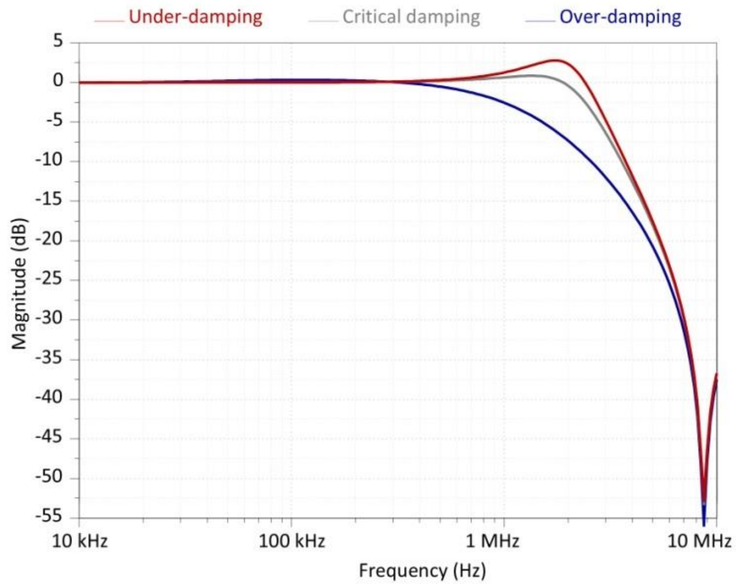


Device under test

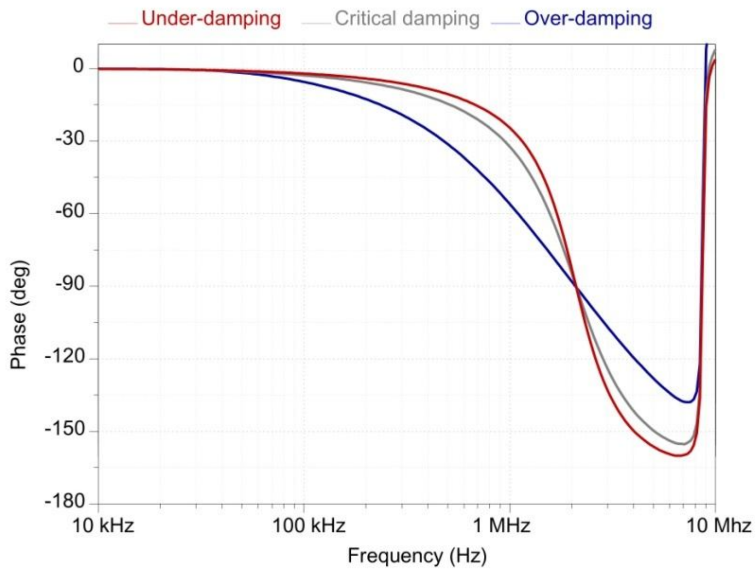
3. Proposed Designs and Experimental Results

Measured Transfer Function in Serial RLC LPF

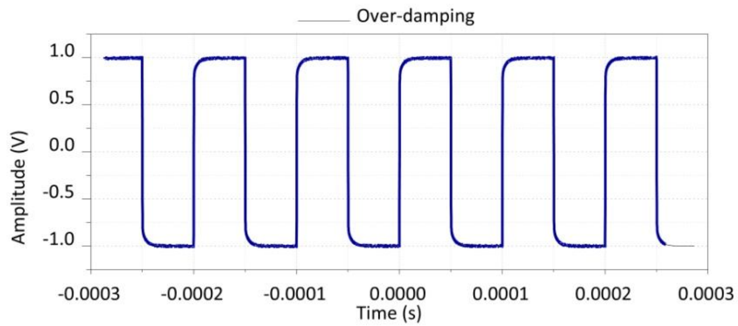
Magnitude response

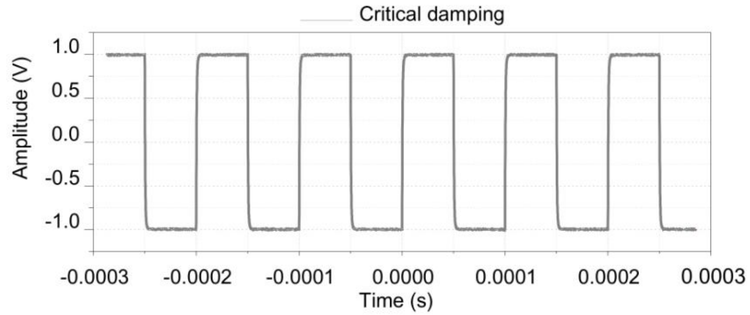


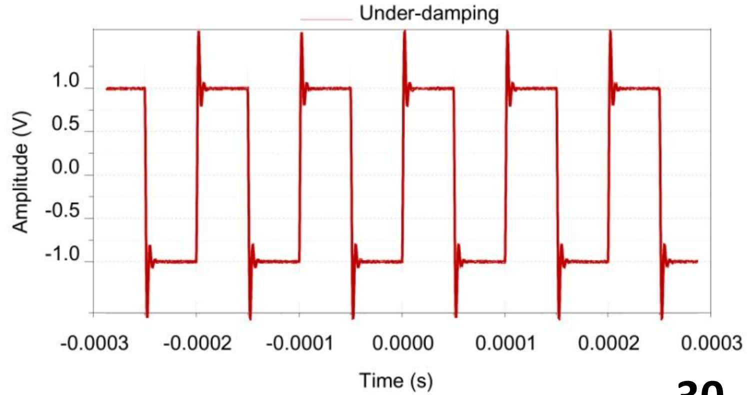
Phase response



Transient response



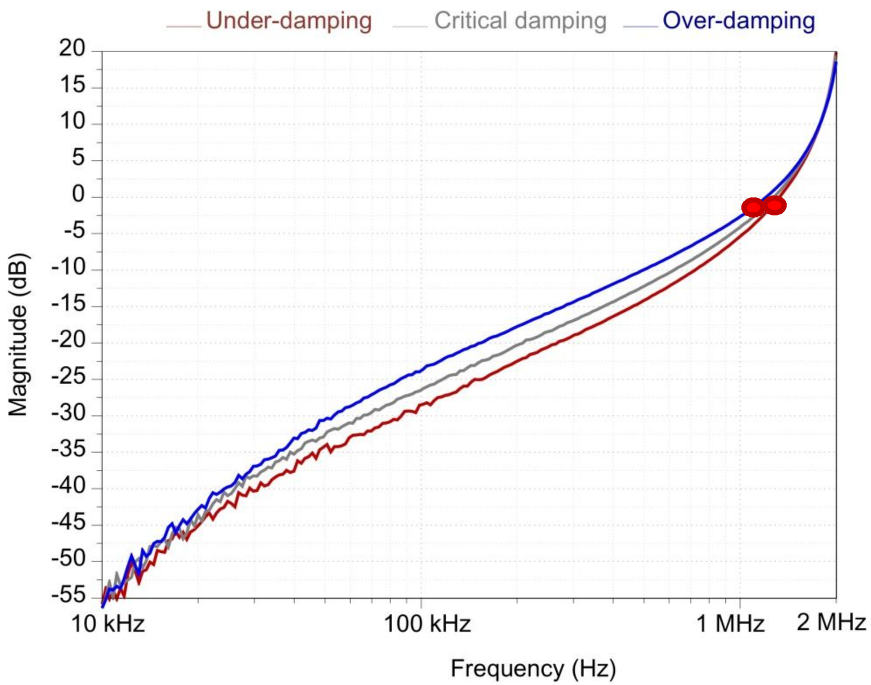




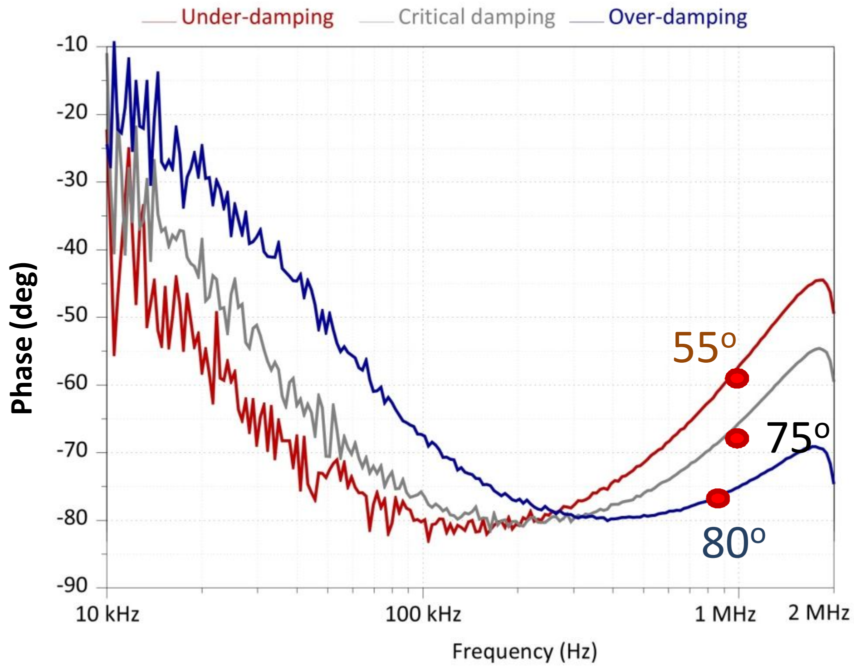
3. Proposed Designs and Experimental Results

Measured Self-loop Function in Serial RLC LPF

Magnitude response



Phase response



Over-damping: →Phase margin is 80 degrees.

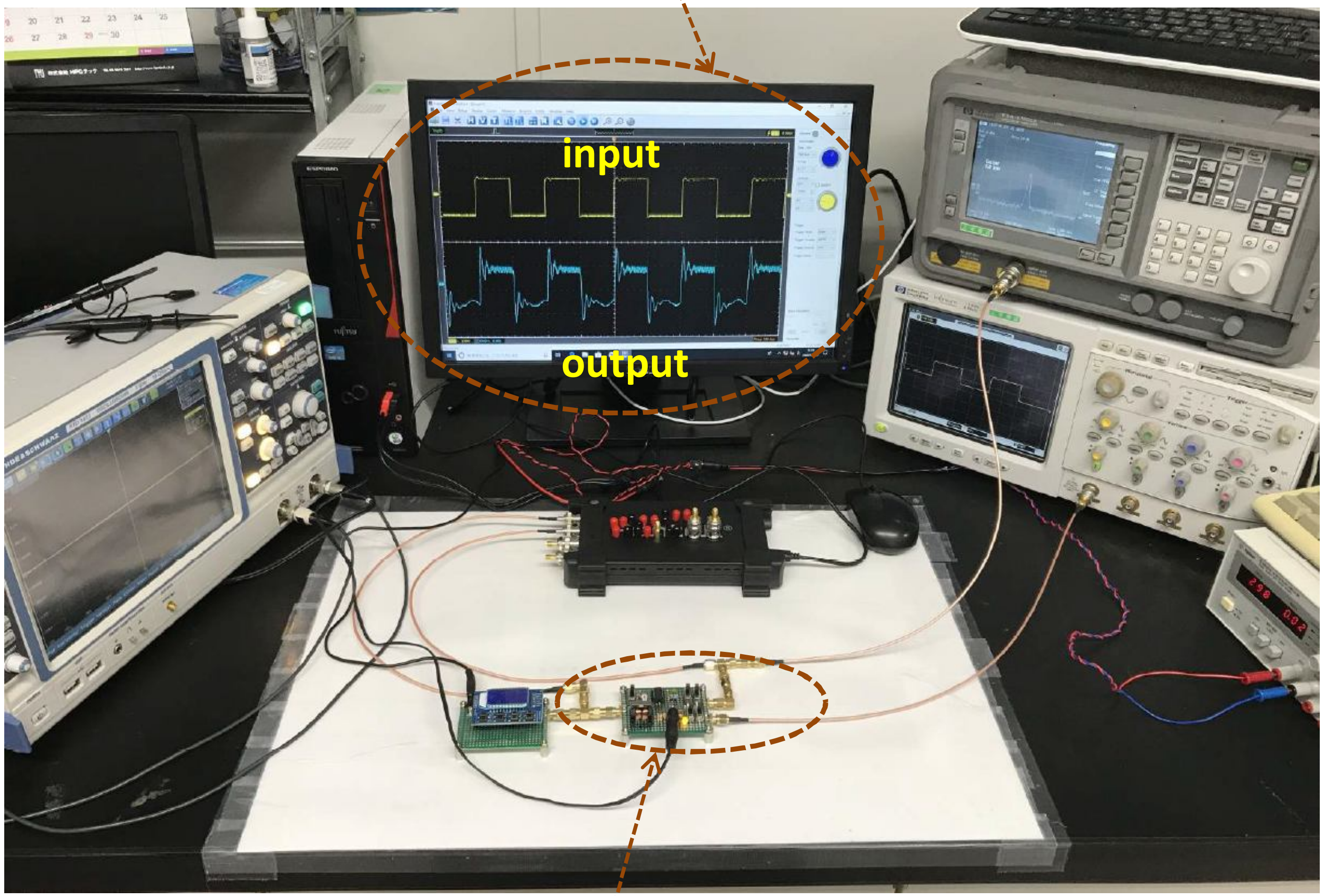
Nearly Critical damping: →Phase margin is 75 degrees.

Under-damping: →Phase margin is 55 degrees.

3. Proposed Designs and Experimental Results

Implementation of Active RLC Low-pass Filter

Over-shoot occurred at output port.

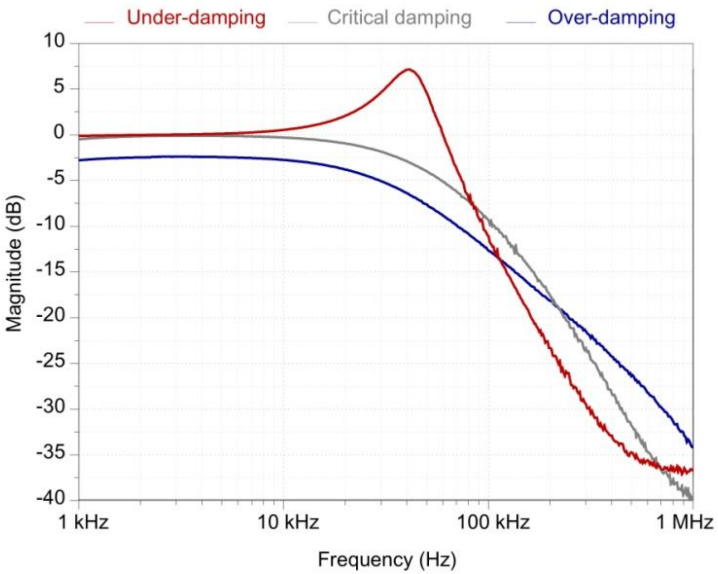


Device under test

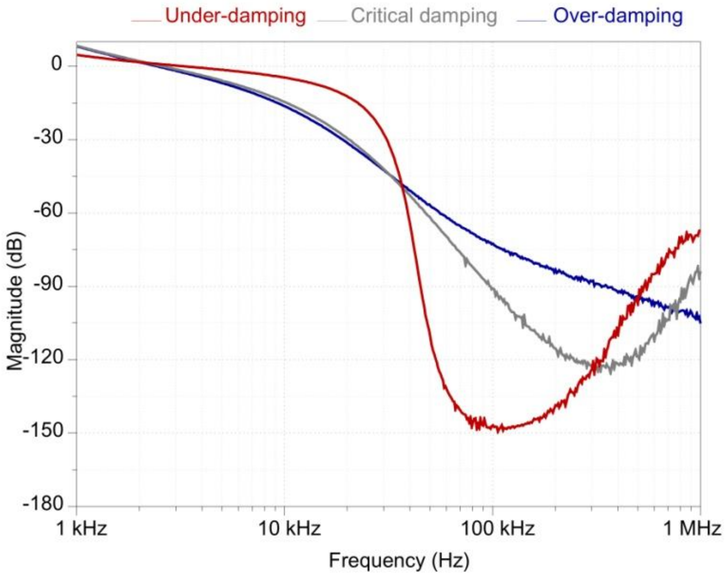
3. Proposed Designs and Experimental Results

Measured Transfer Function of Active RLC LPF

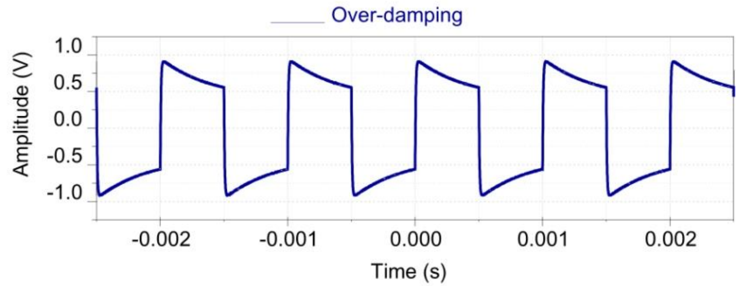
Magnitude response

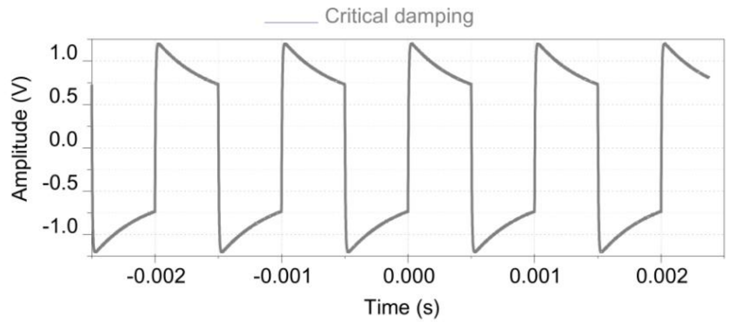


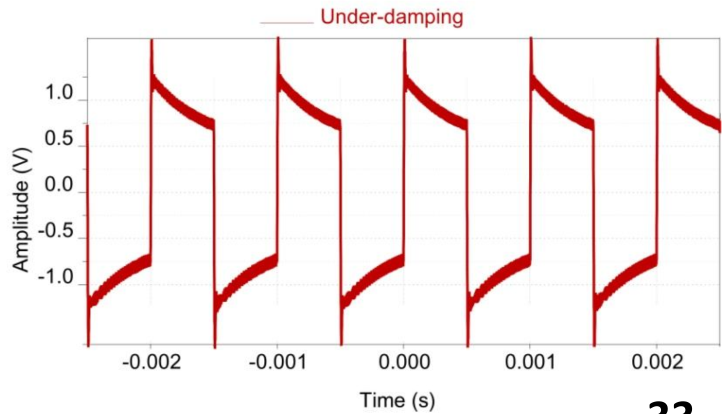
Phase response



Transient response



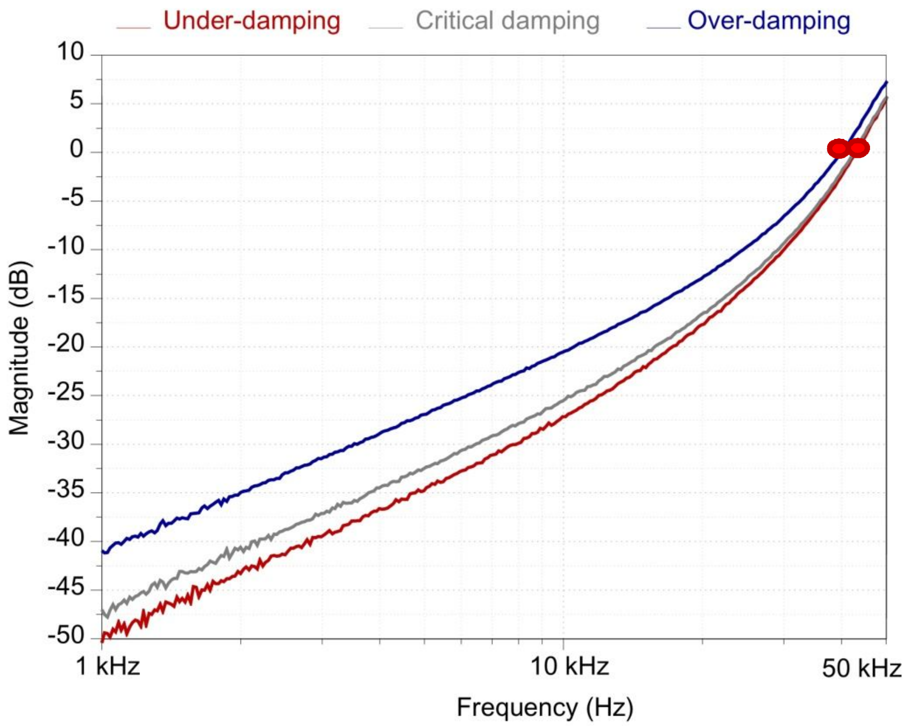




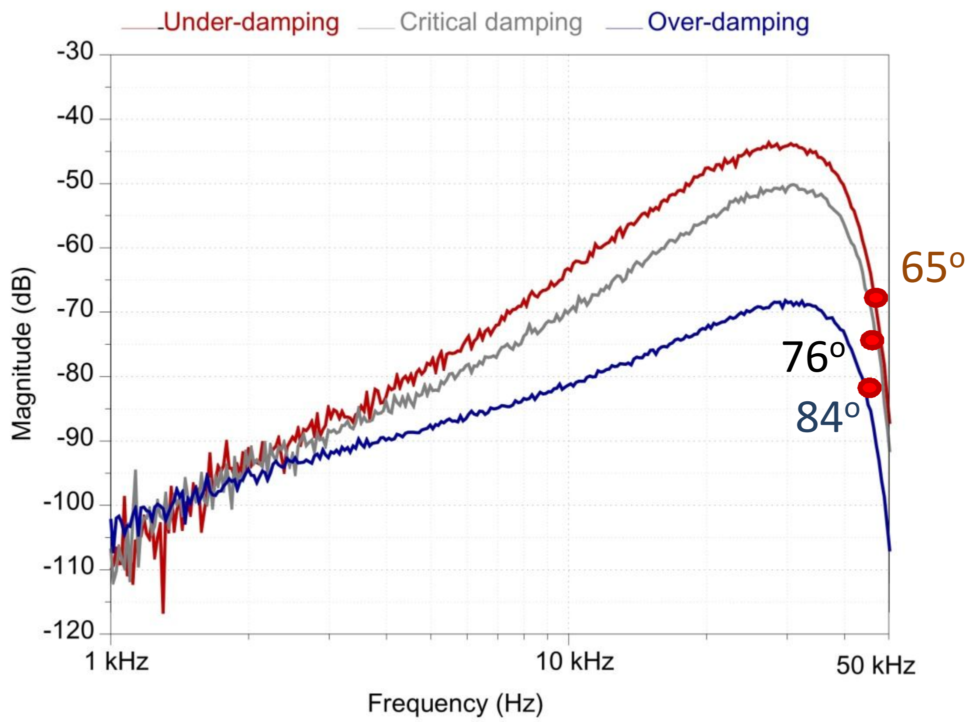
3. Proposed Designs and Experimental Results

Measured Self-loop Function of Active RLC LPF

Magnitude response



Phase response



Over-damping: →Phase margin is 84 degrees.

Nearly Critical damping: →Phase margin is 76 degrees.

Under-damping: →Phase margin is 65 degrees.

4. Conclusions

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This work:

- **Reviews of complex functions and stability test**
- **Proposed methods for derivation of transfer function and measurement of self-loop function**
- **Implementations and measurements of self-loop functions for passive and active second-order RLC low-pass filters**
- **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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