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Investigation of Behaviors of Kerwin-Huelsman-Newcomb Filters Using Nichols Charts of Self-Loop Function

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Outline

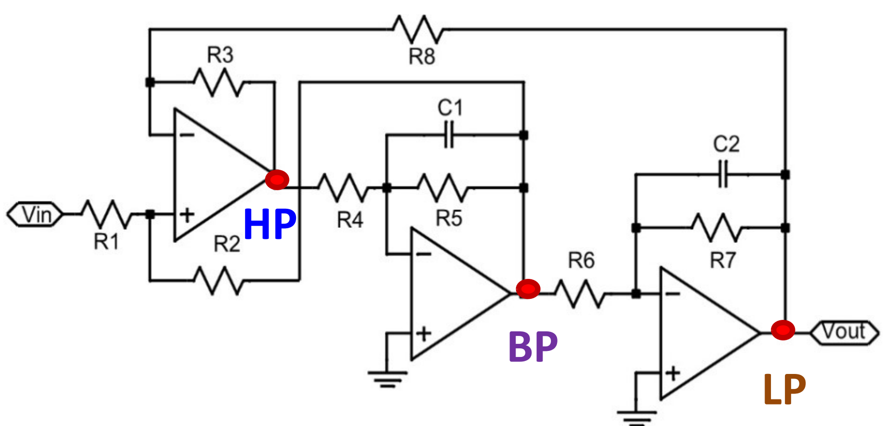
1. **Research Background**
   - Motivation, objectives and achievements
2. **Demerits of Conventional Stability Test Methods**
   - Reviews of loop gain in feedback systems
   - Limitations of Nyquist and Nichols charts of loop gain
3. **Behaviors of High-order Systems**
   - Self-loop function in a transfer function
   - Ringing test for 2^{nd} and 4^{th}-order systems
4. **Ringing Test for High-Order Low-Pass Filters**
   - Stability test for 2^{nd}-order Kerwin-Huelsman-Newcomb filters
5. **Conclusions**

1. Research Background

Study of Kerwin-Huelsman-Newcomb Topology

- Two most famous multiple output active filter circuits
  - Kerwin–Huelsman–Newcomb (KHN) bi-quadratic circuit
  - Tow–Thomas bi-quadratic circuit
- Both circuits are:
  - Included almost in all textbooks in active filters, and
  - Introduced in most universities to the undergraduate or graduate students.

Kerwin-Huelsman-Newcomb topology



Performance requirements

- Operating regions
- Overshoot phenomenon
- Stability test
- Phase margin

Not studied

1. Research Background

Motivation on Ringing Test

- High quality of the performance requirements for high-order electronic systems
- Operating regions of high-order multi-feedback systems are not introduced. (Kerwin-Huelsman-Newcomb filters)
- General ringing test for high-order electronic systems is not introduced.
- Limitations of loop gain, and conventional stability test using Nyquit plot are not pointed out.
- Nichols chart (magnitude-phase chart) is not widely applied for the stability test.

1. Research Background

Objectives of This Study

- **Investigation of some limitations of the conventional stability test methods (loop gain and Nyquist chart).**
- **Study of behaviors of various different high-order systems: 2^{nd}-order, 4^{th}-order systems, and multi-feedback systems**

→ Ringing test for high-order multi-feedback low-pass filters.

→ Observation of phase margin at unity gain on Nichols chart is used to determine operating regions of high-order systems

1. Research Background

Contributions of This Work

- Investigation of behaviours of high-order systems such as 2nd-order, 4th-order systems.
- Stability test for high-order systems using Nichols chart of self-loop function.
- Proposed ringing test for both the single-ended and the fully differential Kerwin-Huelsman-Newcomb low-pass filters.
- Proposal of stability test are verified by both laboratory simulations and practical experiments.

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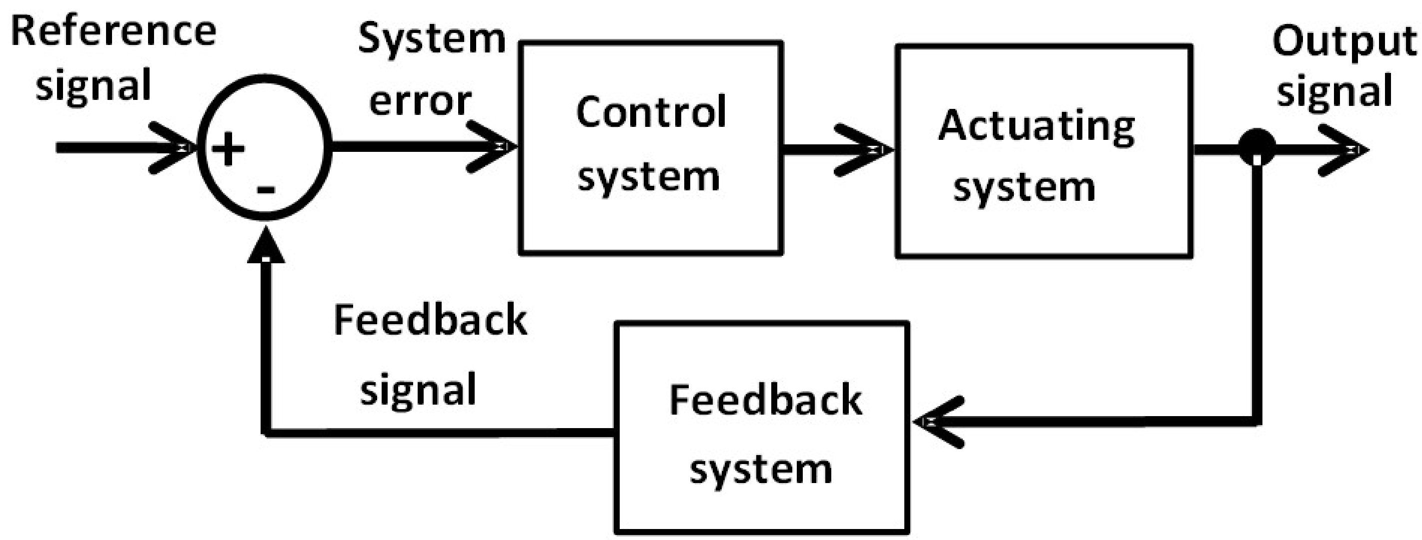
2. Demerits of Conventional Stability Test Methods

Review of Adaptive Feedback System

Block diagram of a typical adaptive feedback system



Adaptive feedback is used to control the output voltage along with the reference voltage.

Transfer function

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

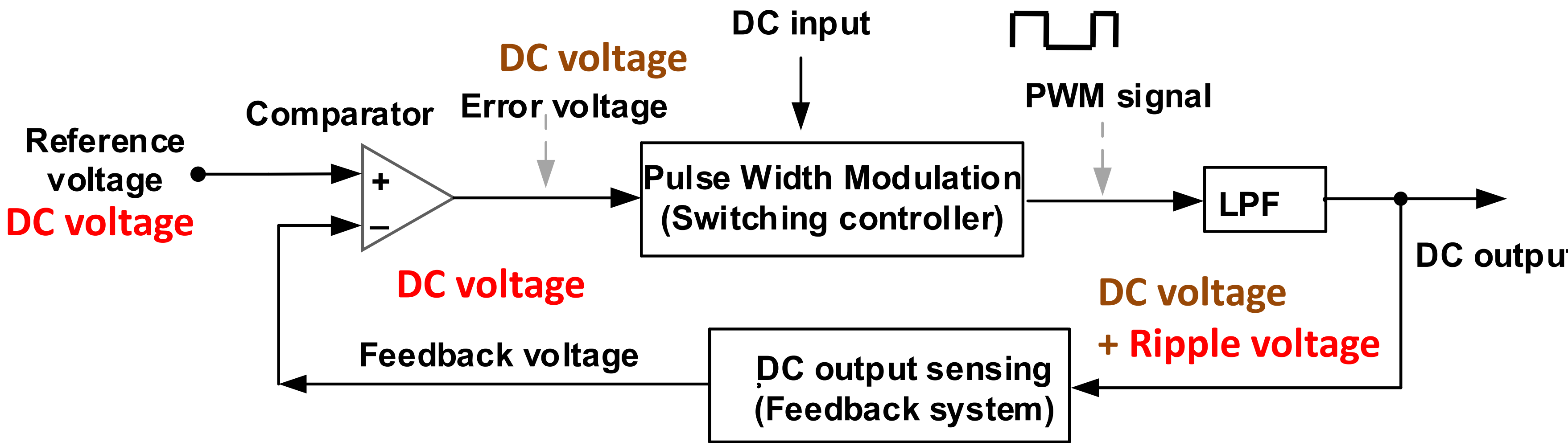
Aβ : loop gain

→ Loop gain is an approximation value.

2. Demerits of Conventional Stability Test Methods

Characteristics of Adaptive Feedback System

Block diagram of a DC-DC Buck converter



Adaptive feedback in a DC-DC Buck converter is used to control the output voltage along with the reference voltage.

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

2. Demerits of Conventional Stability Test Methods

Conventional Concepts of Loop Gain

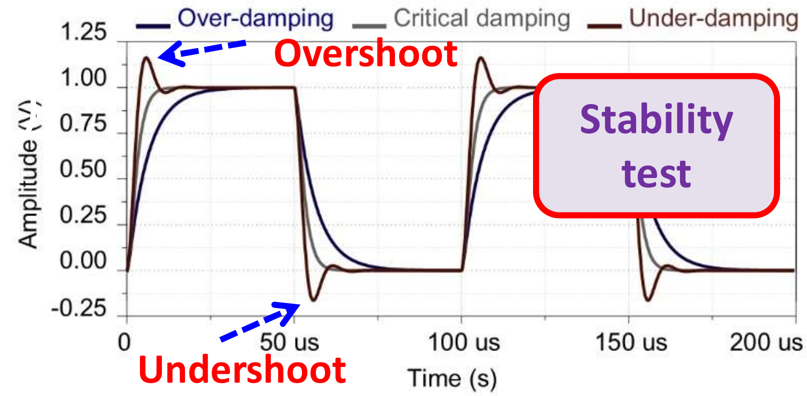
- Loop gain **cannot** be used to do the ringing test for negative feedback systems.

Transfer function

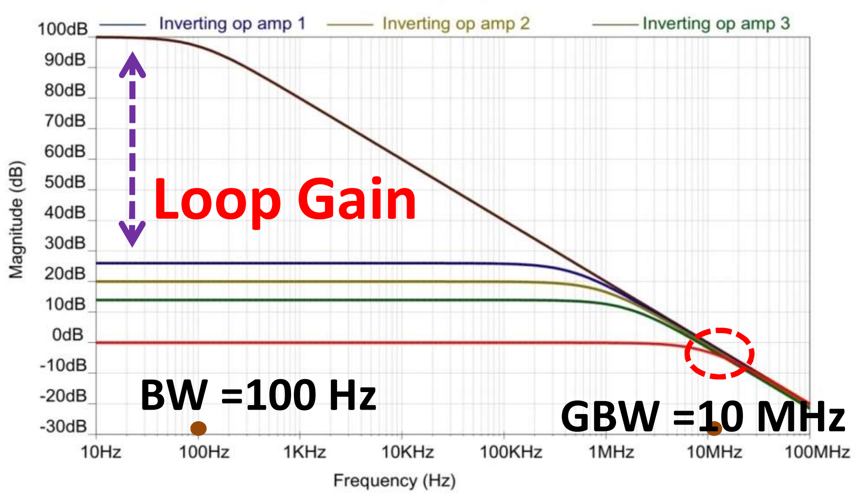
$$H = \frac{A}{1 + A\beta} \approx \frac{1}{\beta}$$

Aβ : loop gain

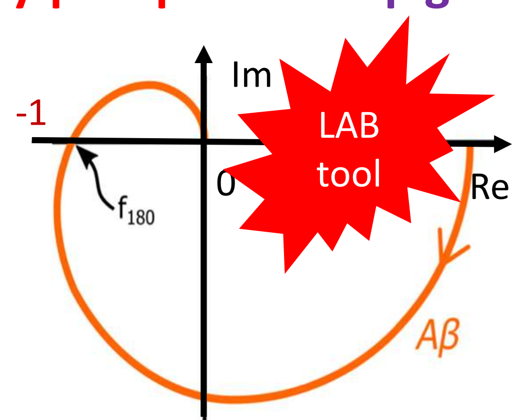
Ringing in electronic systems



Gain reduction in an inverting amplifier



Nyquist plot of loop gain

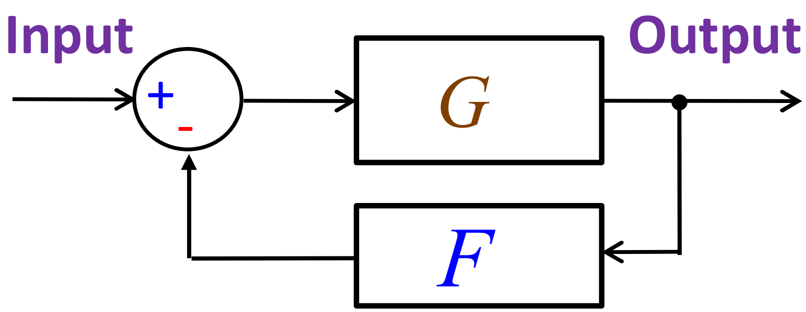


(Unclear operating region)

2. Demerits of Conventional Stability Test Methods

Conventional Concepts of Nichols Chart of Loop Gain

Adaptive feedback system

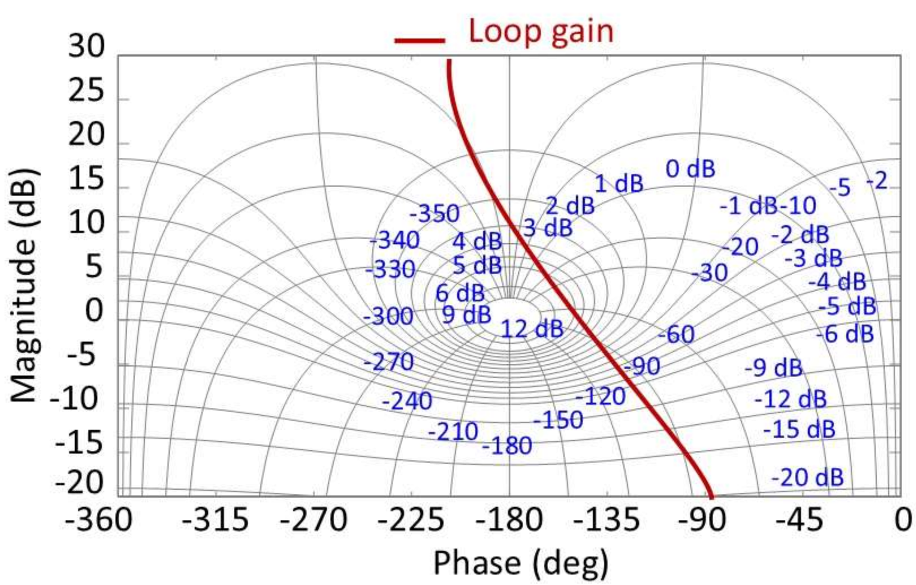


Transfer function

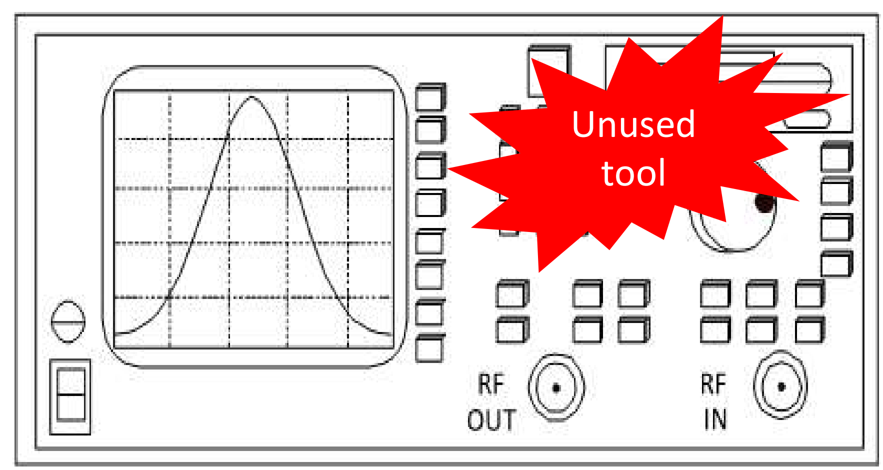
$$H = \frac{G}{1 + GF} \approx 1$$

GF : loop gain

Nichols plot of loop gain



Nichols chart in Network Analyzer?



(Technology limitations)

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3. Behaviors of High-order Systems

Self-loop Function in A Transfer Function

Motion model of a linear system

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

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

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

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

Simplified transfer function

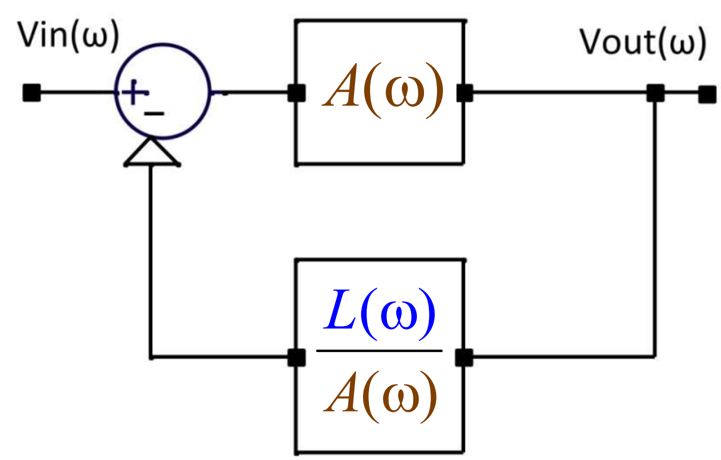
Variable: angular frequency (ω)

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

Graph signal of negative feedback system

Relationship between output and input

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



Negative feedback system

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

} **Bode plots**

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

3. Behaviors of High-order Systems

Characteristics of 2nd-order Self-loop Function

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

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

3. Behaviors of High-order Systems

Operating Regions of 2nd-Order System

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

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

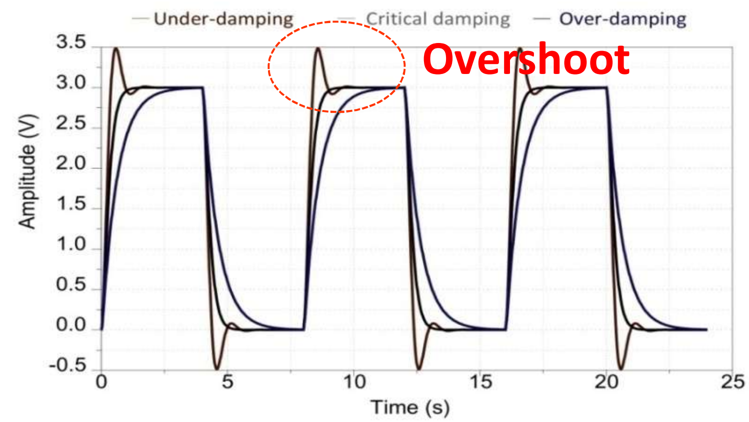
- **Critical damping:** $H_2(\omega) = \dfrac{1}{(j\omega)^2 + 2j\omega + 1};$

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

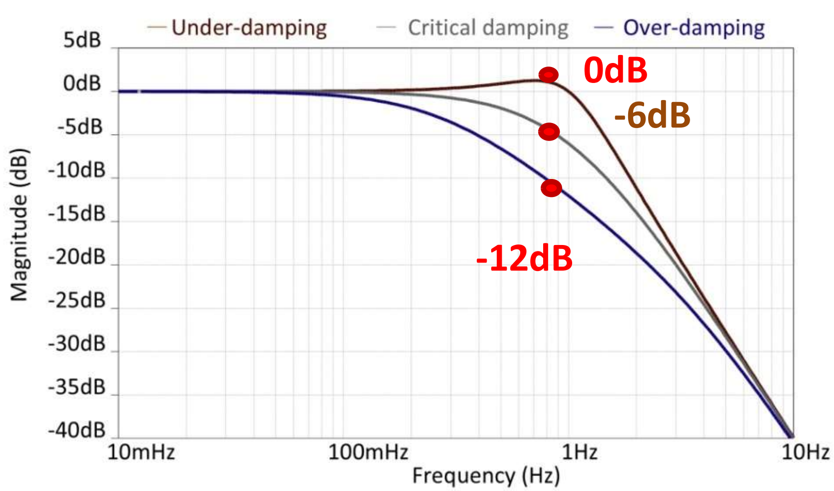
- **Over-damping:** $H_3(\omega) = \dfrac{1}{(j\omega)^2 + 3j\omega + 1};$

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

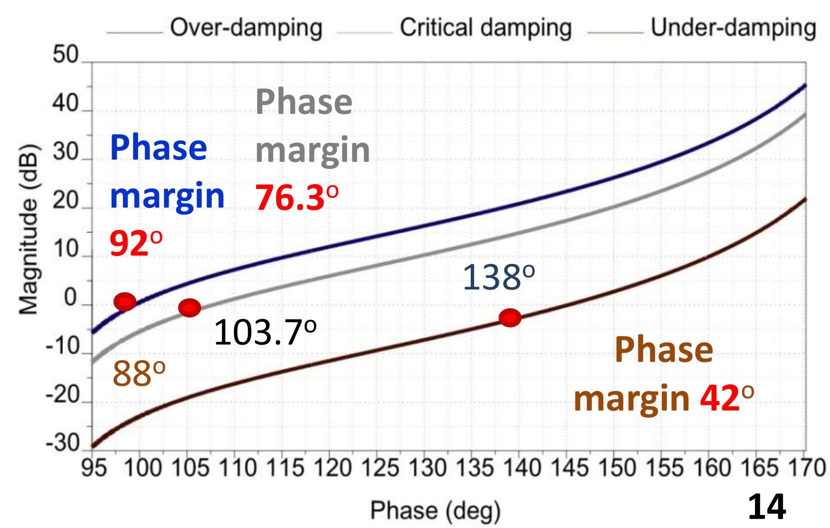
Transient response



Bode plot of transfer function



Nichols plot of self-loop function



3. Behaviors of High-order Systems

Operating Regions of 4th-Order System

Pascal's Triangle

n = 2	1 2 1
n = 3	1 3 3 1
n = 4	1 4 6 4 1
n = 5	1 5 10 10 5 1

- **Under-damping:** 1 : 2 : 3 : 2 : 1

$$H_1(\omega) = \frac{1}{(j\omega)^4 + 2(j\omega)^3 + 3(j\omega)^2 + 2j\omega + 1}$$

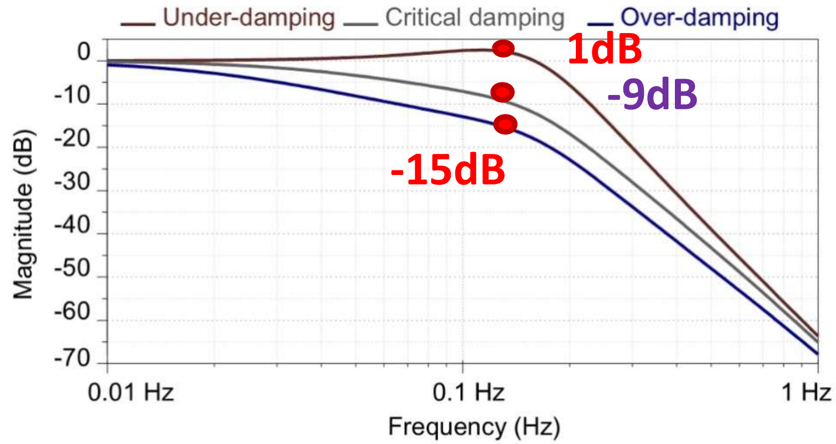
- **Critical damping:** 1 : 4 : 6 : 4 : 1

$$H_2(\omega) = \frac{1}{(j\omega)^4 + 4(j\omega)^3 + 6(j\omega)^2 + 4j\omega + 1}$$

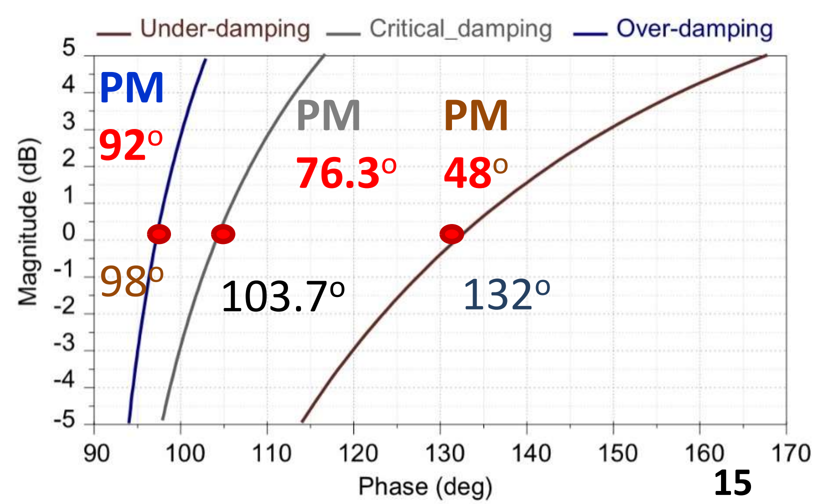
- **Over-damping:** 1 : 9 : 10 : 9 : 1

$$H_3(\omega) = \frac{1}{(j\omega)^4 + 9(j\omega)^3 + 10(j\omega)^2 + 9j\omega + 1}$$

Bode plot of transfer function



Nichols plot of self-loop function



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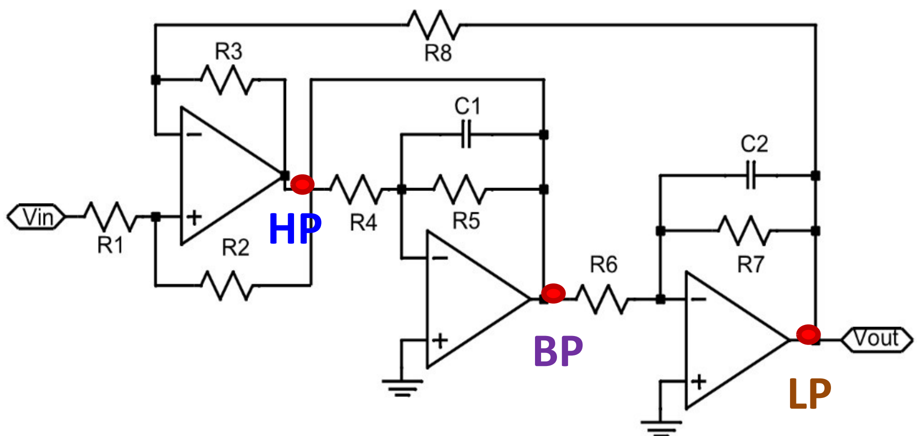
5. Conclusions

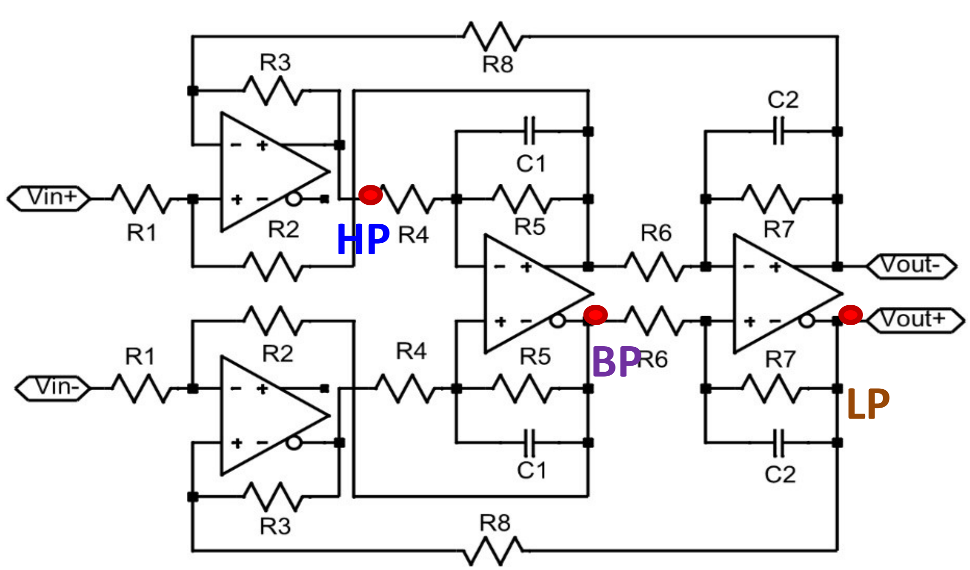
4. Ringing Test for High-Order Low-Pass Filters

Analysis of Kerwin-Huelsman-Newcomb LPF

Single-ended Kerwin-Huelsman-Newcomb LPF



Fully differential Kerwin-Huelsman-Newcomb 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, $b_0 = \frac{R_6}{R_1};$

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

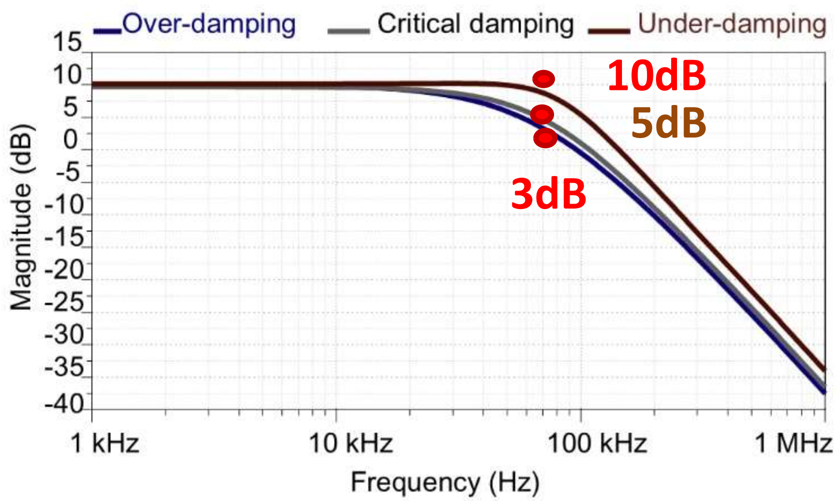
R1 = R3 = R4 = R6 = 1 kΩ, R5 = 5 kΩ, R7 = R8 = 10 kΩ, C1 = C2 = 1nF.

- **Over-damping (R2 = 1 kΩ),**
- **Critical damping (R2 = 1.2 kΩ), and**
- **Under-damping (R2 = 2.2 kΩ).**

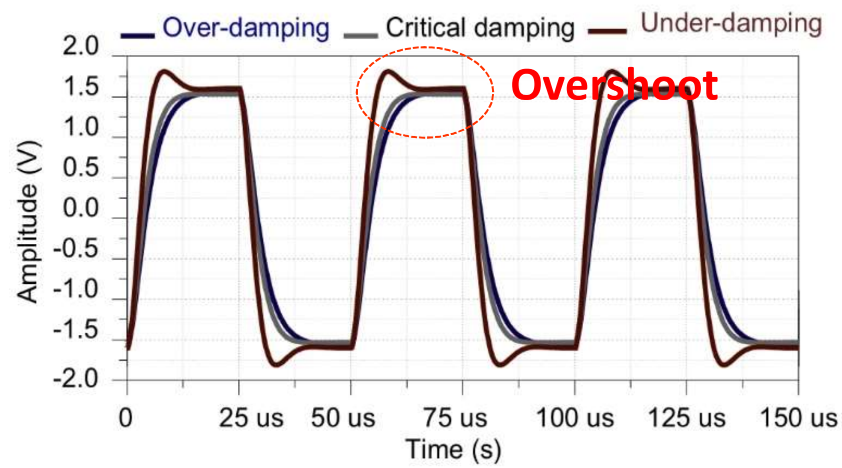
4. Ringing Test for High-Order Low-Pass Filters

Simulation Results of 2nd-Order KHN LPF

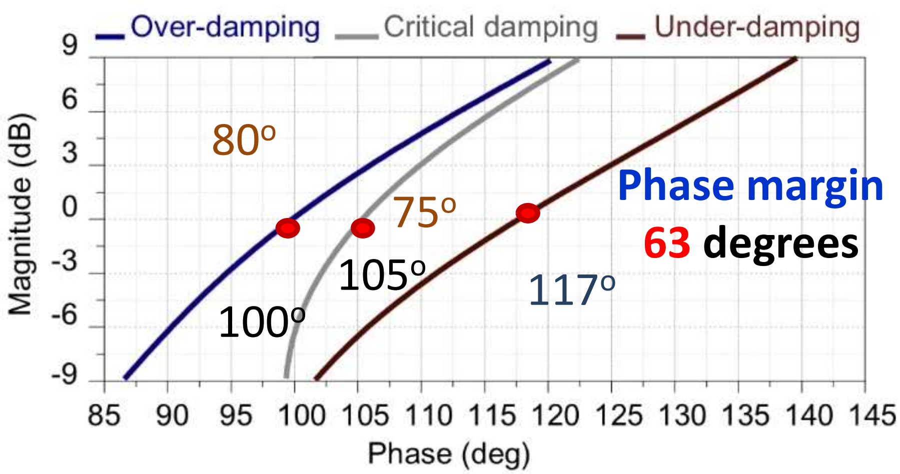
Bode plot of transfer function



Transient response



Nichols plot of self-loop function



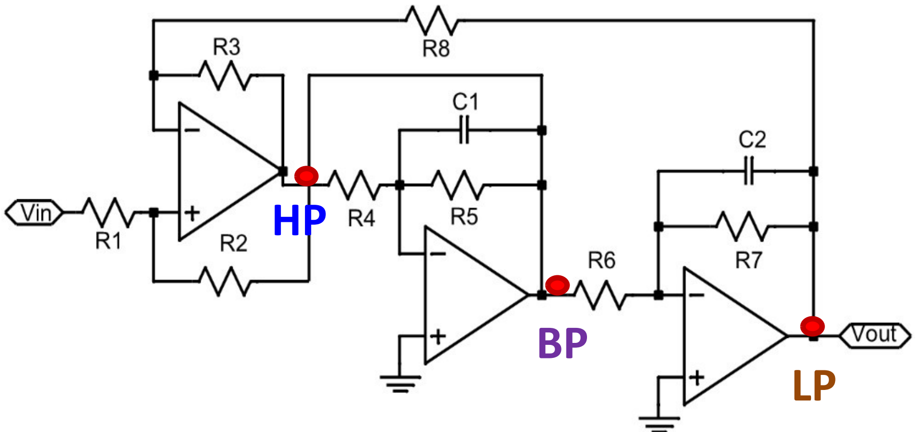
Summarized behaviors

	Magnitude (Transfer function)	Phase margin (Self-loop function)
Case 1 Over-damping	3 dB	80° (Observed at 100°)
Case 2 Critical damping	5 dB	75° (Observed at 105°)
Case 3 Under-damping	10 dB	63° (Observed at 117°)

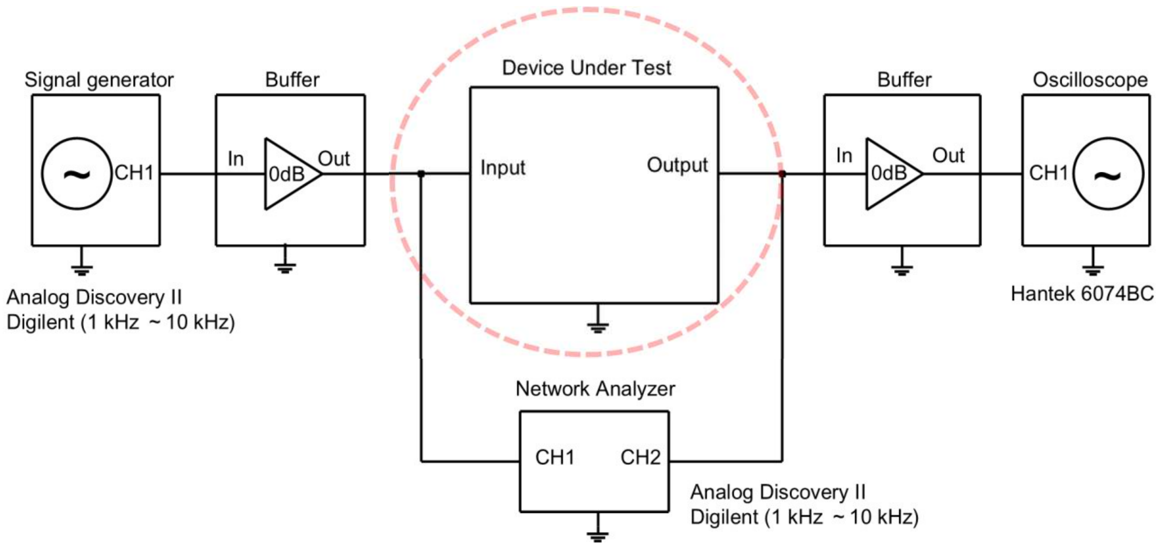
4. Ringing Test for High-Order Low-Pass Filters

Implemented Circuit of Kerwin-Huelsman-Newcomb LPF

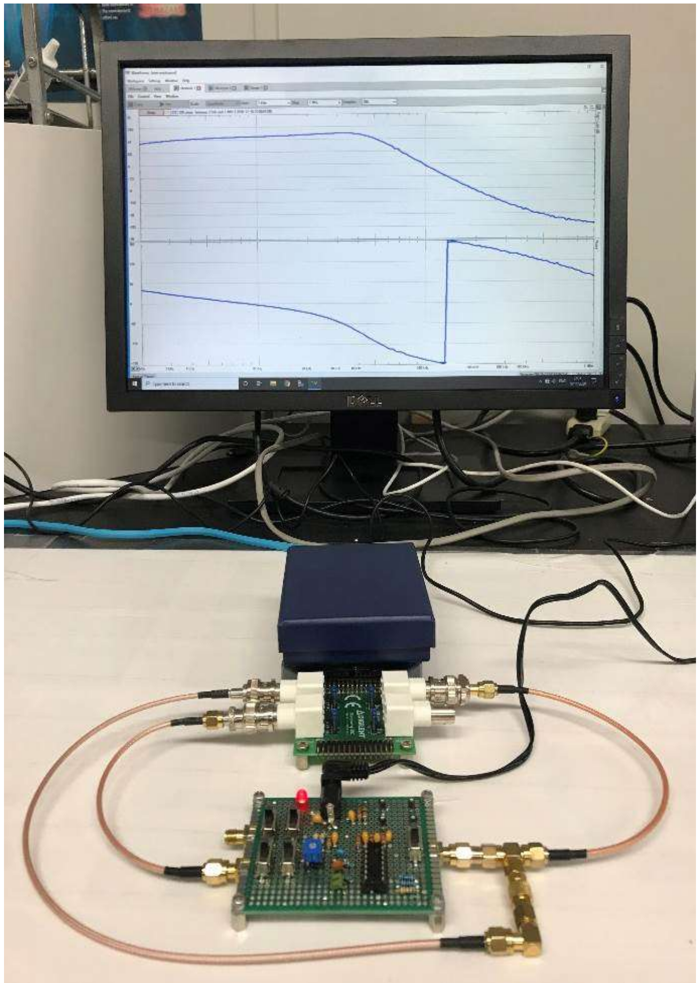
Schematic of Kerwin-Huelsman-Newcomb LPF



System Under Test



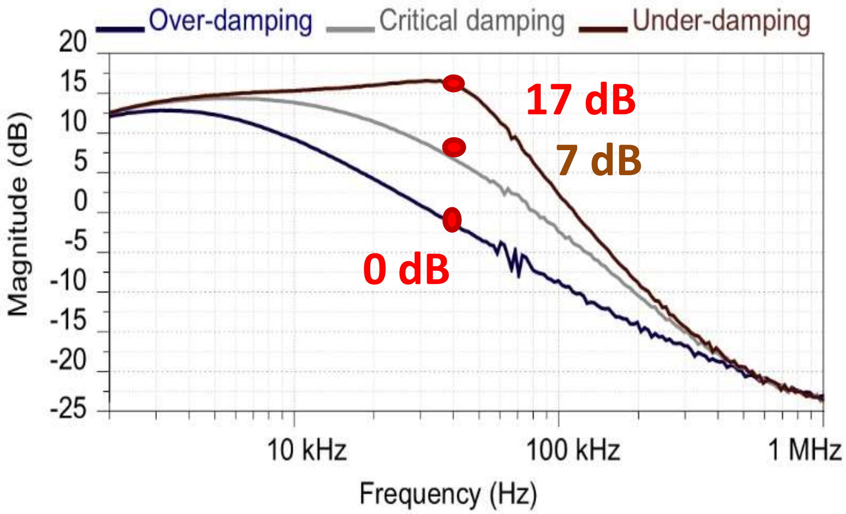
Measurement set up



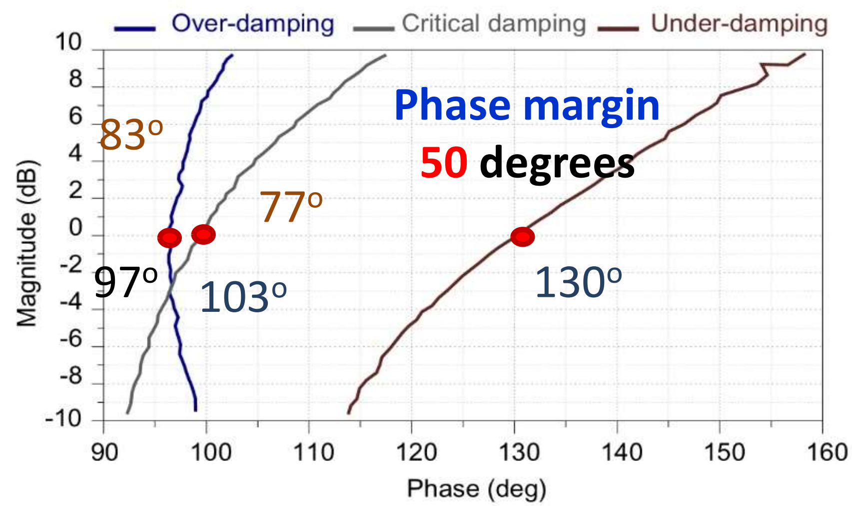
4. Ringing Test for High-Order Low-Pass Filters

Measurement Results of Kerwin-Huelsman-Newcomb LPF

Bode plot of transfer function



Nichols plot of self-loop function



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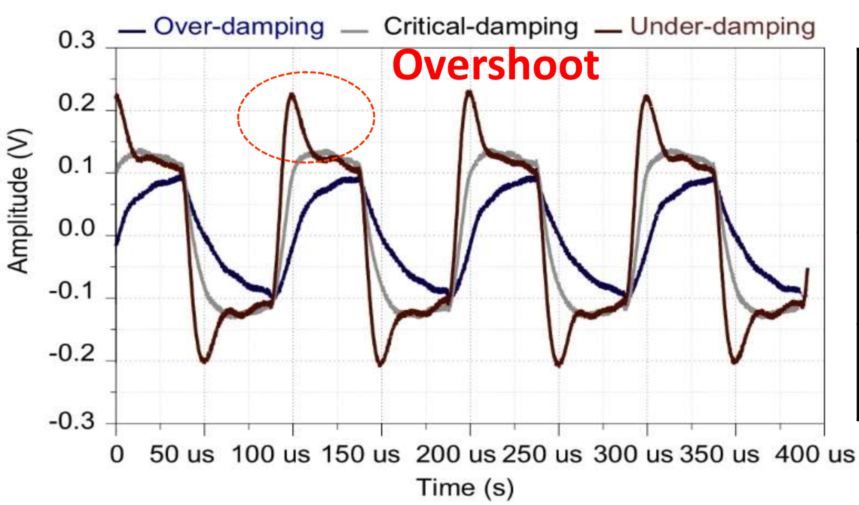

Summarized behaviors

	Magnitude (Transfer function)	Phase margin (Self-loop function)
Case 1 Over-damping	**0 dB**	**83° (Observed at 97°)**
Case 2 Critical damping	**7 dB**	**77° (Observed at 103°)**
Case 3 Under-damping	**17 dB**	**50° (Observed at 130°)**

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5. Comparison to existing methods

Features	Replica method	Middlebrook's method	Comparison measurement
Complex function	Loop gain	Loop gain	Self-loop function
Passive and active systems	No	No	Yes
Phase margin accuracy	No	No	Yes
Operating region accuracy	No	No	Yes
Disturbing feedback loop	Yes	Yes	No

5. Conclusions

This work:

- Investigation of limitations of loop gain and conventional stability test methods.
- Ringing test for high-order multi-feedback systems (Kerwin-Huelsman-Newcomb low-pass filters).

→ Observation of phase margin on the Nichols chart can help designers predict the overshoot phenomenon.

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

Future work:

- Stability test for transmission lines and other systems.

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Thank you very much!

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