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# Limitations of Loop Gain in Motion Models of Physical Systems


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# Outline

1. Research Background
- Motivation, objectives and achievements
- Self-loop function in a transfer function
2. Limitations of Loop Gain
- Demerits of loop gain and Nyquist stability criterion
3. Behaviors of Feedback Amplifier Networks
- Stability test for high-order inverting amplifiers
4. Ringing Test for Adaptive Feedback Networks
- Phase margin of power-stage of DC-DC buck converter
5. Conclusions

# 1. Research Background

## Motivation on Limitations of Loop Gain

### ① Research papers and commercial devices

**Op amp ADA4870**

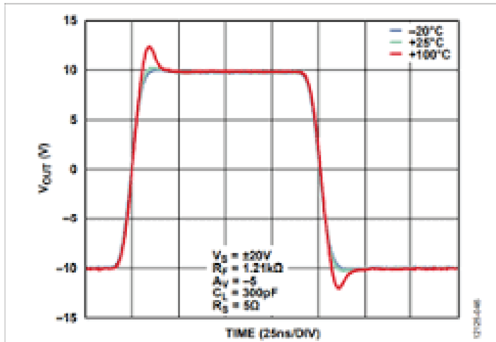
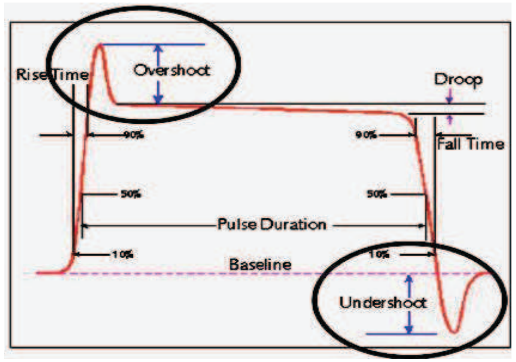
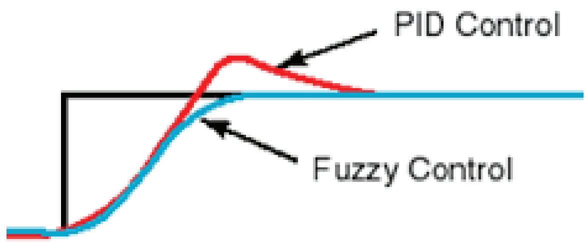



*Figure 26. Large Signal Pulse Response vs. Case Temperature, $A_V = -5$, $V_S = \pm 20$ V, $V_{OUT} = 20$ V p-p, $R_F = 1.21$ kΩ, $C_L = 300$ pF, $R_S = 5$ Ω*

**Feedback systems**




**Control systems**




### ② Theoretical analysis for adaptive feedback systems

- Steady-state oscillations → Barkhausen theorem
- Nyquist criterion → Left side of complex s plain (-1, 0)
- Routh–Hurwitz, Jury stability criterion, …
- Loop gain of adaptive feedback systems,
- Middlebrook's measurement of loop gain,

# 1. Research Background

## Objectives of This Study

- Study of limitations of loop gain in motion models of mechatronic systems
- Mechanical systems and electronic circuits are usually expressed by complex functions.

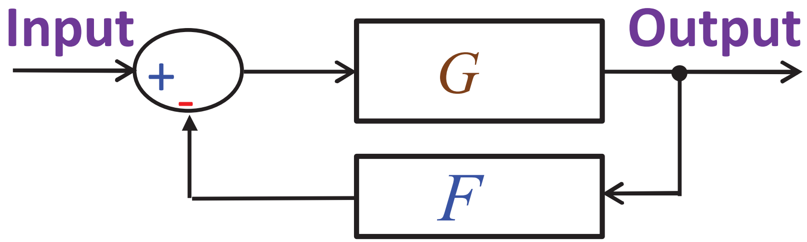
→ The properties of transfer function and self-loop function in these systems are the same.

→ Investigation of phase margin at unity gain to determine operating regions of high-order systems

- Measurement of phase margin in an adaptive feedback system (power-stage of DC-DC converter)

# 1. Research Background
## Conventional Concepts of Loop Gain

### Adaptive feedback system

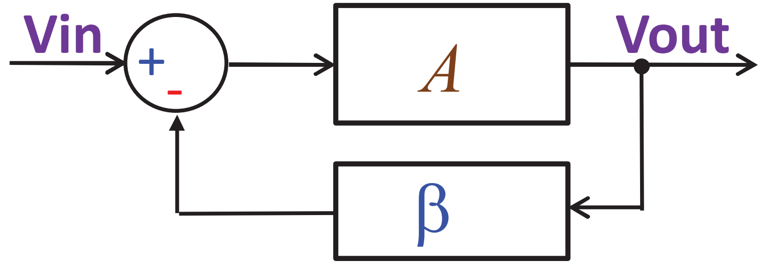



**Transfer function**

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

**GF : loop gain**

### Inverting amplifier

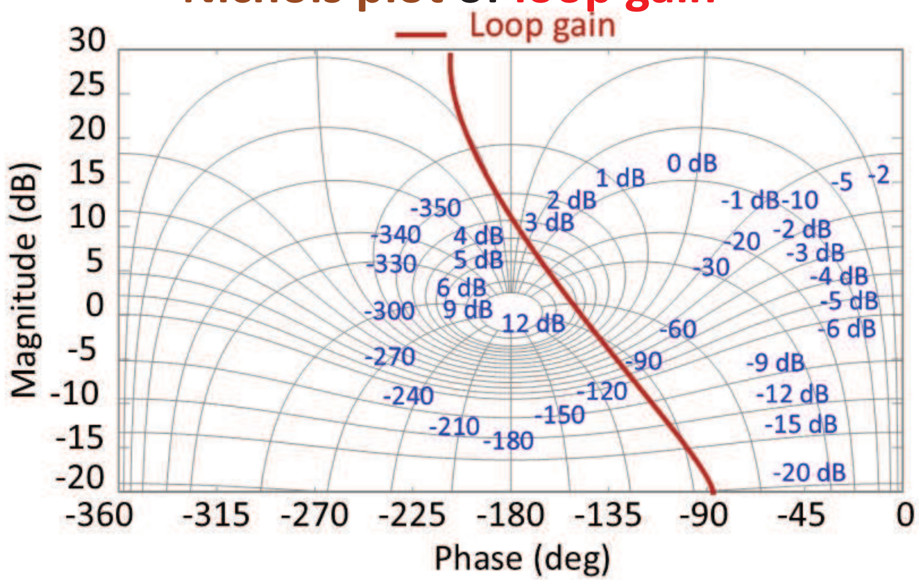



**Transfer function**

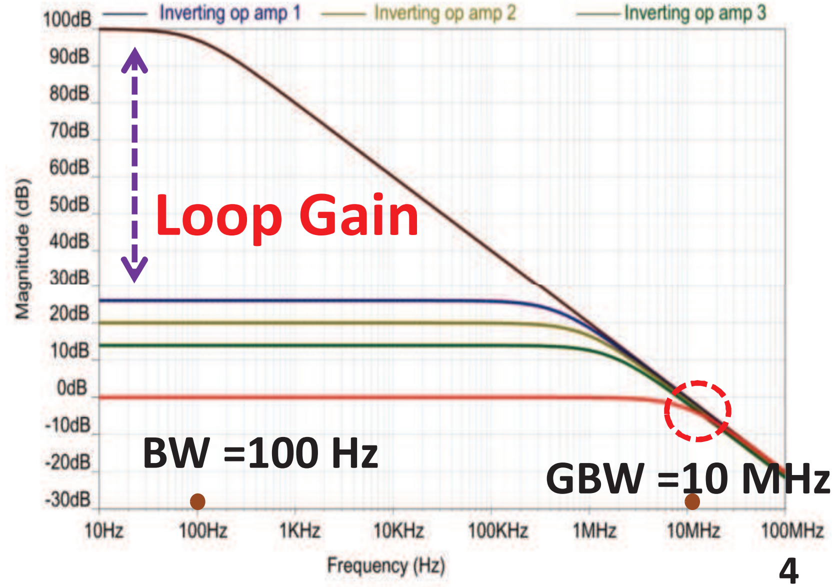
$$H = \frac{A}{1+A\beta} \approx \frac{1}{\beta}$$

**Aβ : loop gain**

### Nichols plot of loop gain




### Gain reduction

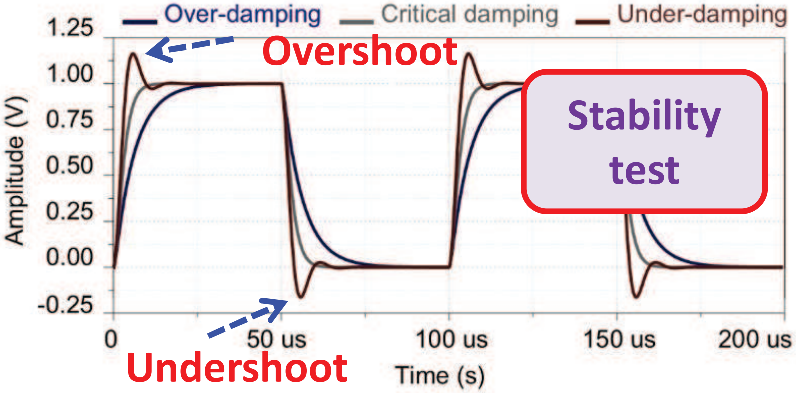


# 1. Research Background

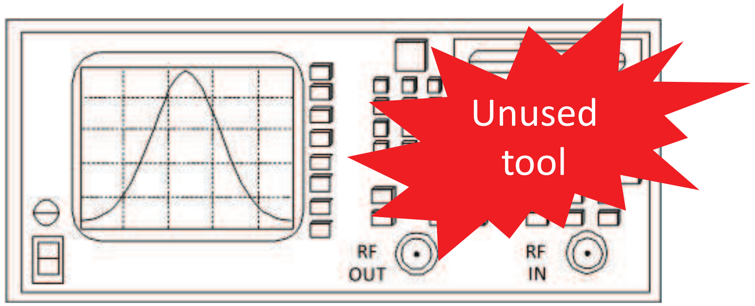
## Stability Test for Mechatronic Systems

→ Loop gain **cannot** be used to perform the **ringing test**.

Ringing in electronic systems

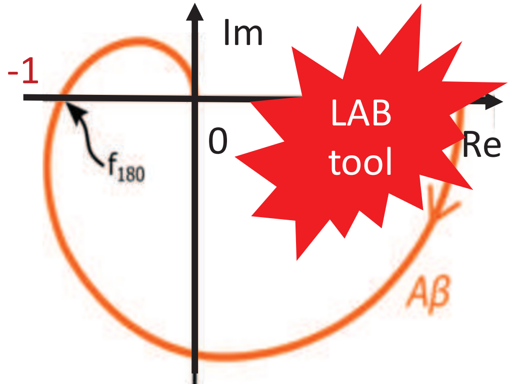



Nichols chart in Network Analyzer?



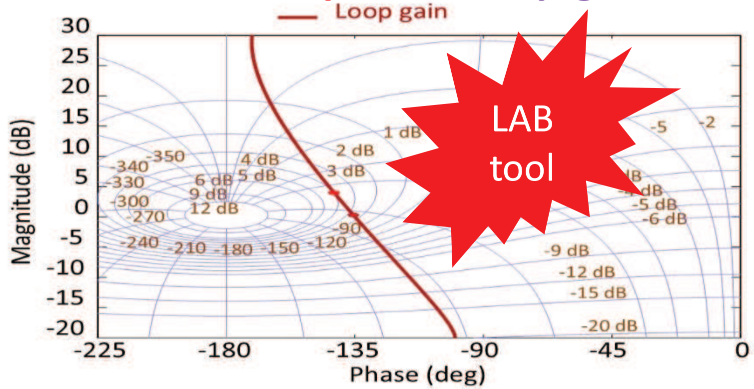

(Technology limitations)

Nyquist plot of loop gain




(Unclear operating region)

Nichols plot of loop gain




(Very complicated)

# 1. Research Background

## Self-loop Function in A Transfer Function

### Linear system


### Motion model of a linear system

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

### 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 ($\omega$)

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

} Bode plots

- ○ Magnitude-angular diagram → Nichols diagram

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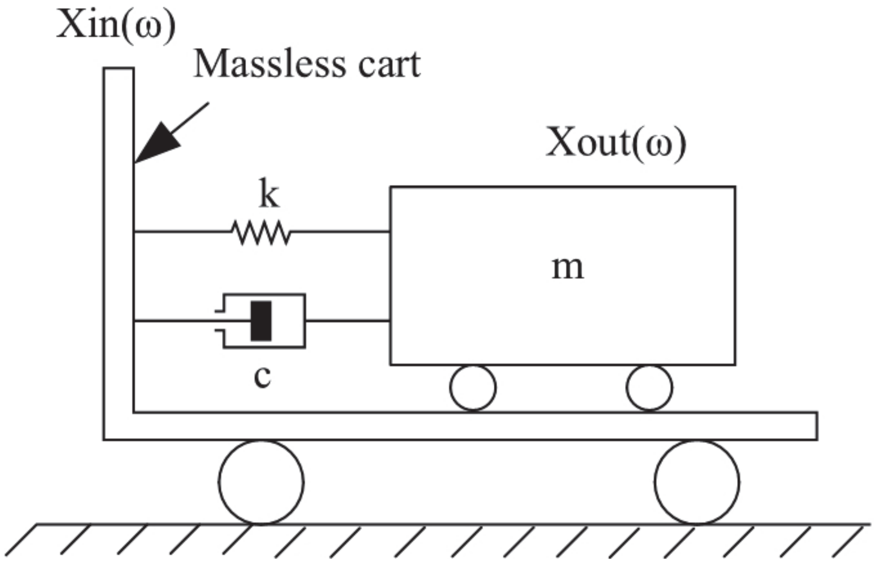
   - **Demerits of loop gain and Nyquist stability criterion**
3. Behaviors of Feedback Amplifier Networks
   - Stability test for high-order inverting amplifiers
4. Ringing Test for Adaptive Feedback Networks
   - Phase margin of power-stage of DC-DC buck converter
5. Conclusions

# 2. Limitations of Loop Gain

## Behaviors of a 2nd -Order Mechanical System

**Model of spring-damper-mass system**




**Transfer function and self-loop function**

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

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

**Loop gain cannot be applied for a 2nd-order mechanical system**

**Apply superposition at the node $X_{out}$, we have**

$$\left[ j\omega m + c + \frac{k}{j\omega} \right] X_{out}(\omega) = \left[ c + \frac{k}{j\omega} \right] X_{in}(\omega);$$

**Where,**

$$b_0 = \frac{c}{k}; a_0 = \frac{m}{k}; a_1 = \frac{c}{k}$$

# 2. Limitations of Loop Gain

## 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. Limitations of Loop Gain

## Operating Regions of 2nd-Order System

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

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

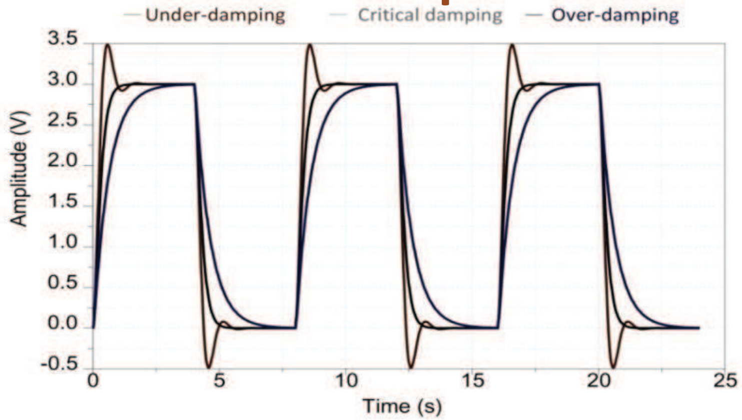
- **Critical damping:** $H_2(\omega) = \dfrac{1}{(j\omega)^2 + 2j\omega + 1};$

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

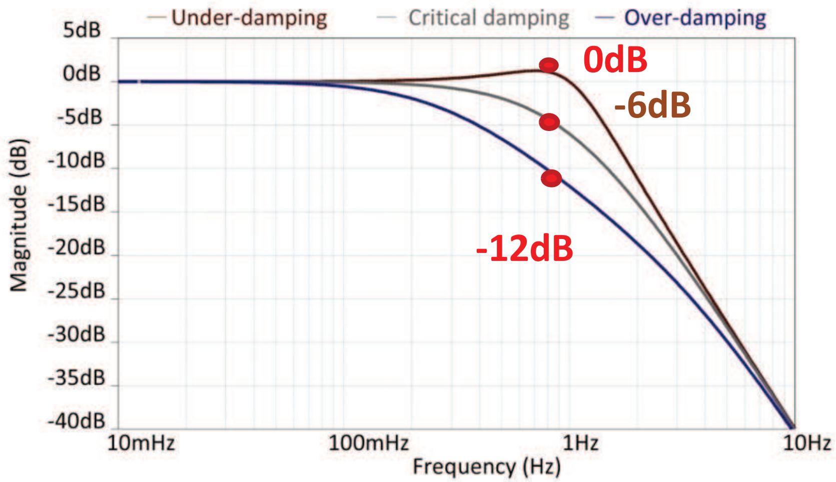
- **Over-damping:** $H_3(\omega) = \dfrac{1}{(j\omega)^2 + 3j\omega + 1};$

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

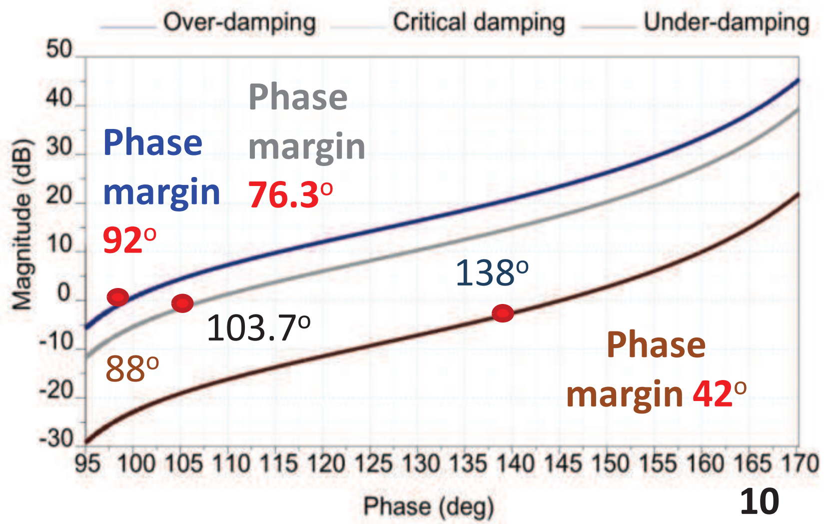
### Transient response




### Bode plot of transfer function




### Nichols plot of self-loop function

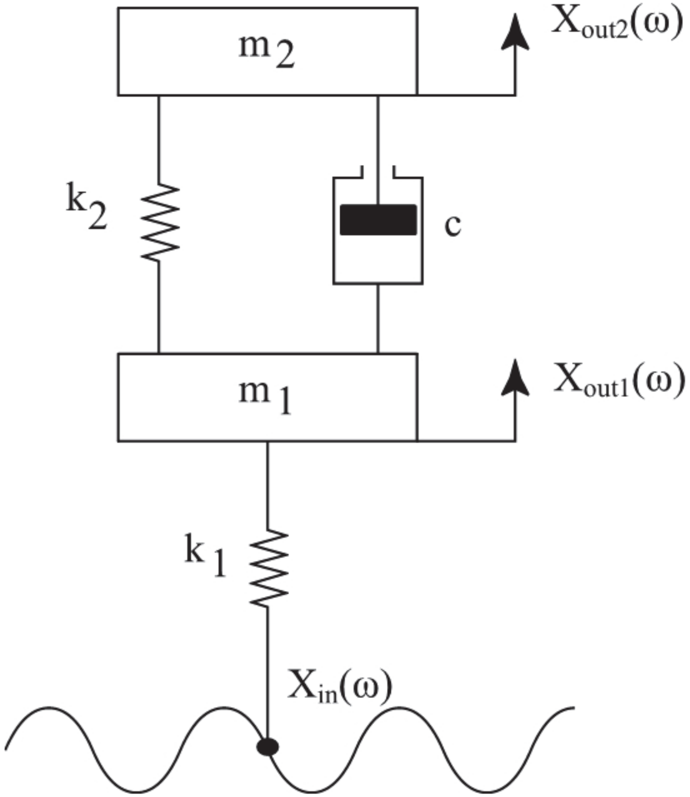


# 2. Limitations of Loop Gain

## Behaviors of a 4th -Order Mechanical System

**Loop gain cannot be applied for a 4th-order mechanical system**

**Model of 4th-order spring-damper-mass system**




**Apply superposition at the nodes $X_{out1}$ and $X_{out2}$, we have**

$$\left(\frac{k_1}{j\omega}+m_1 j\omega+c+\frac{k_2}{j\omega}\right)X_1(\omega)=\left(c+\frac{k_2}{j\omega}\right)X_2(\omega)+\frac{k_1}{j\omega}X_{in}(\omega);$$

$$\left(m_2 j\omega+c+\frac{k_2}{j\omega}\right)X_2(\omega)=\left(c+\frac{k_2}{j\omega}\right)X_1(\omega);$$

**Transfer function and self-loop function**

$$H_1(\omega)=\frac{X_1(\omega)}{X_{in}(\omega)}=\frac{b_0(j\omega)^2+b_1 j\omega+1}{a_0(j\omega)^4+a_1(j\omega)^3+a_2(j\omega)^2+a_3 j\omega+1};$$

$$H_2(\omega)=\frac{X_2(\omega)}{X_{in}(\omega)}=\frac{b_1 j\omega+1}{a_0(j\omega)^4+a_1(j\omega)^3+a_2(j\omega)^2+a_3 j\omega+1};$$

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

# 2. Limitations of Loop Gain

## Operating Regions of 4$^{th}$-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

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

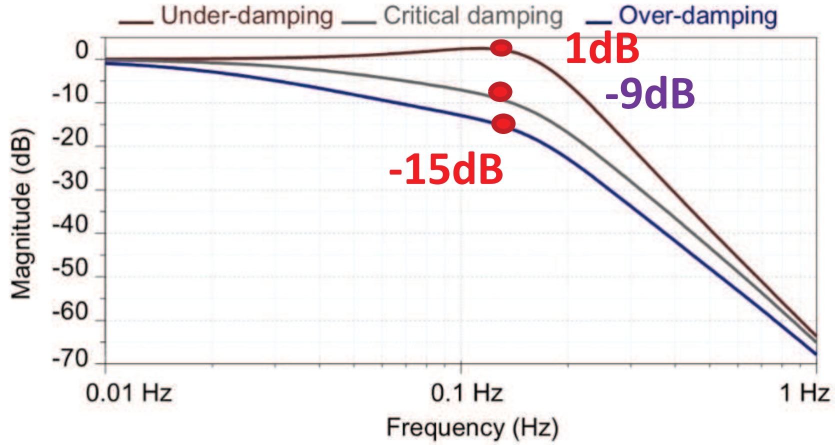
- **Critical damping:** 1 : 4 : 6 : 4 : 1

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

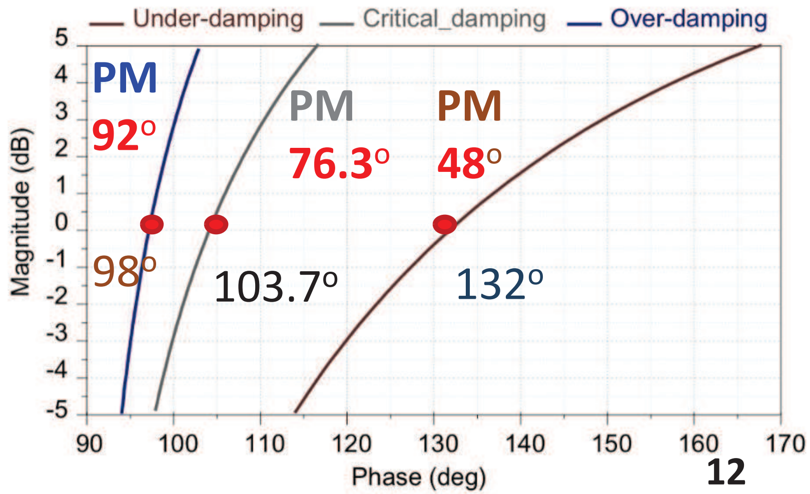
- **Over-damping:** 1 : 9 : 10 : 9 : 1

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

**Bode plot of transfer function**




**Nichols plot of self-loop function**



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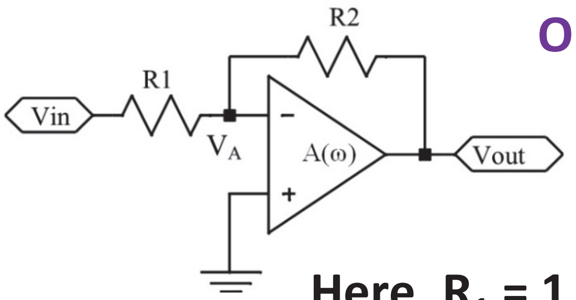
# 3. Behaviors of Feedback Amplifier Networks

## Self-loop Function of Inverting Amplifiers

### Single-ended inverting amplifier

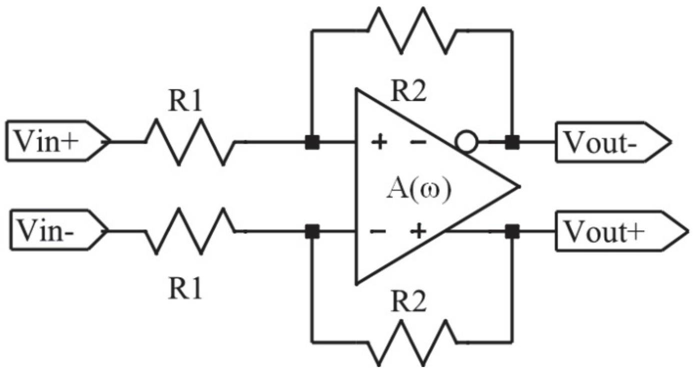



**Open-loop function**

$$A(\omega) = \frac{10^5}{1 + j\dfrac{\omega}{2*10^2\pi}};$$

**Here, $R_1$ = 1 kΩ and $R_2$ = 10 kΩ**

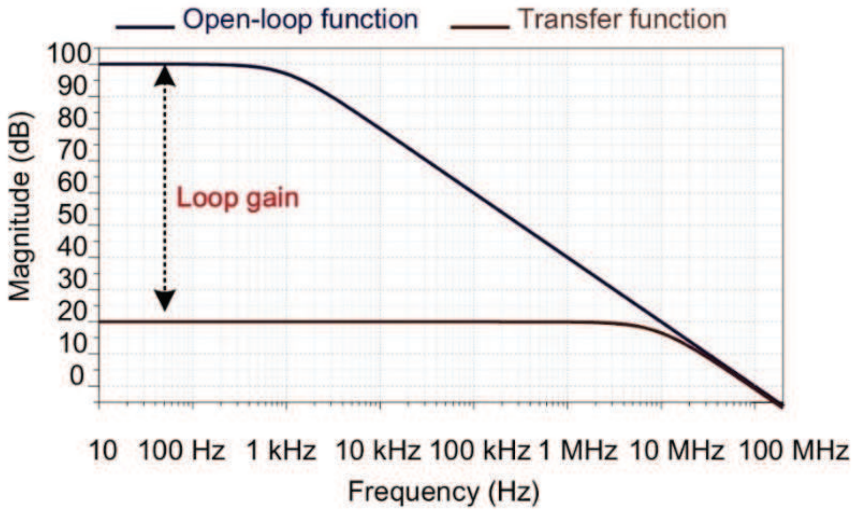
### Fully differential inverting amplifier



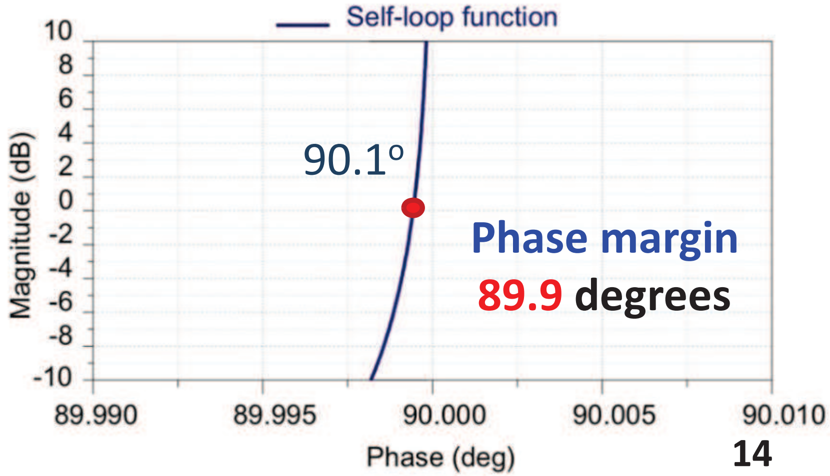

### Transfer function and self-loop function

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

### Bode plot of transfer function



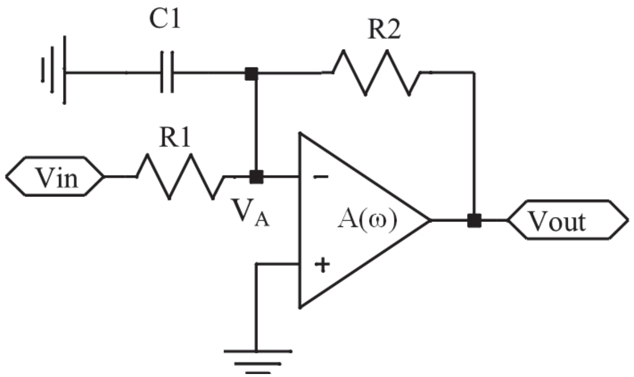

### Nichols plot of self-loop function



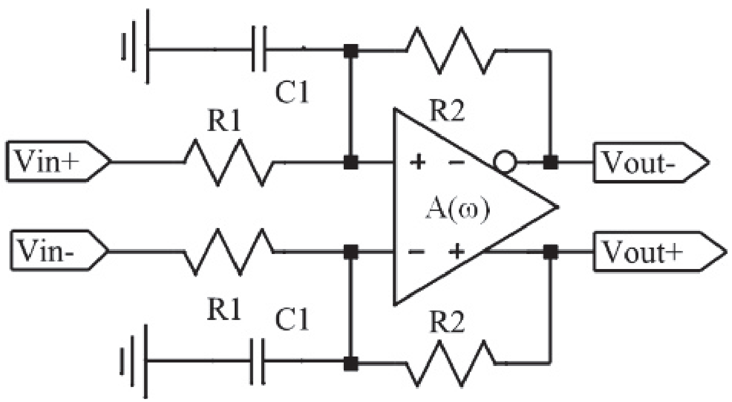
# 3. Behaviors of Feedback Amplifier Networks

## Analysis of Inverting Amplifier with Parasitic Capacitor

**Single-ended inverting amplifier with parasitic capacitor**




**Fully-differential inverting amplifier with parasitic capacitors**




**Apply superposition at the node $V_A$, we have**

$$V_A\left(\frac{1}{R_1}+\frac{1}{R_2}+j\omega C_1\right)=\frac{V_{out}}{R_2};\ V_{out}=A(\omega)\left(V_{in}-V_A\right);$$

**Transfer function and self-loop function**

$$H(\omega)=\frac{V_{out}(\omega)}{V_{in}(\omega)}=\frac{b_0 j\omega+b_1}{a_0\left(j\omega\right)^2+a_1 j\omega+a_2+1};$$

$$L(\omega)=a_0\left(j\omega\right)^2+a_1 j\omega+a_2;$$

**Where,**

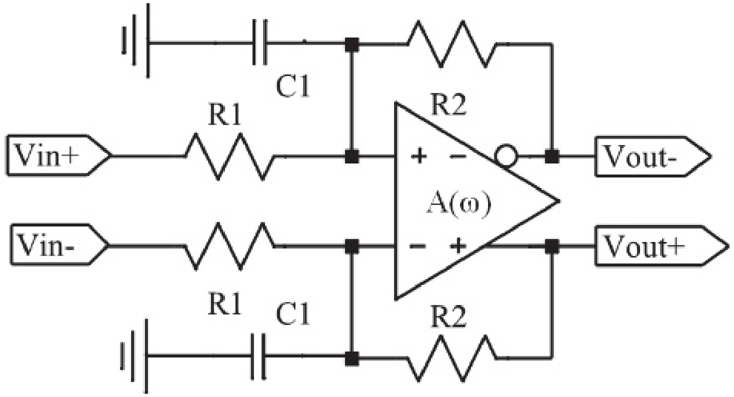
$$b_0=\frac{R_2}{R_1};a_1=\frac{1}{10^5}\left[R_2C_1+\frac{1}{2*10^2\pi}\left(1+\frac{R_2}{R_1}\right)\right];$$

$$a_0=\frac{R_2C_1}{2*10^7\pi};a_2=\frac{1}{10^5}\left(1+\frac{R_2}{R_1}\right);$$

# 3. Behaviors of Feedback Amplifier Networks

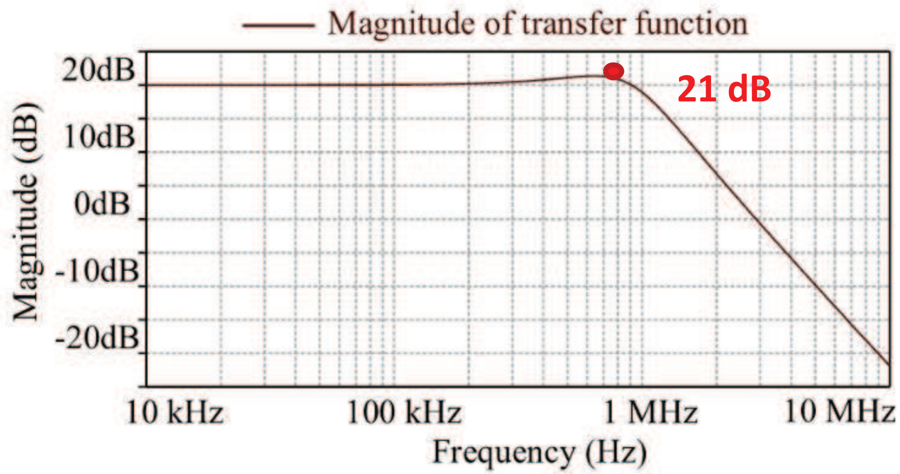
## Self-loop Function of A 2nd - Order Inverting Amplifier

**Inverting amplifier with parasitic capacitors**

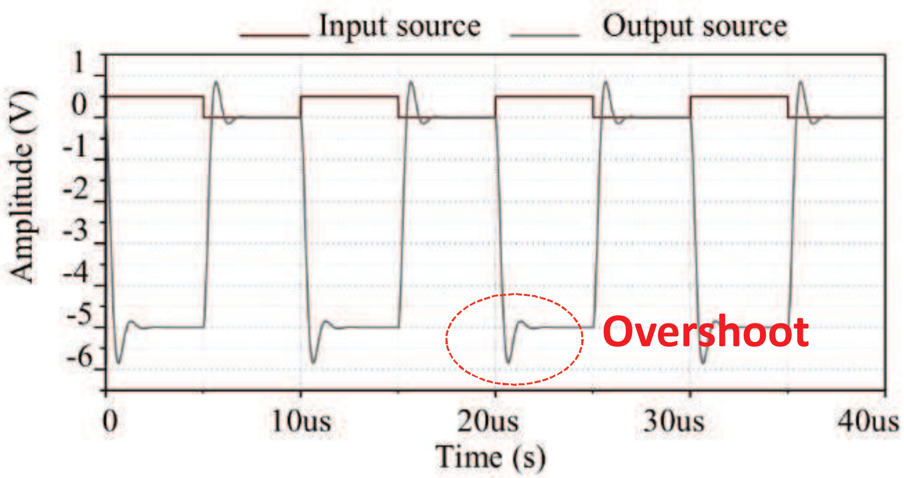



**Here, $R_1$ = 1 kΩ and $R_2$ = 10 kΩ**

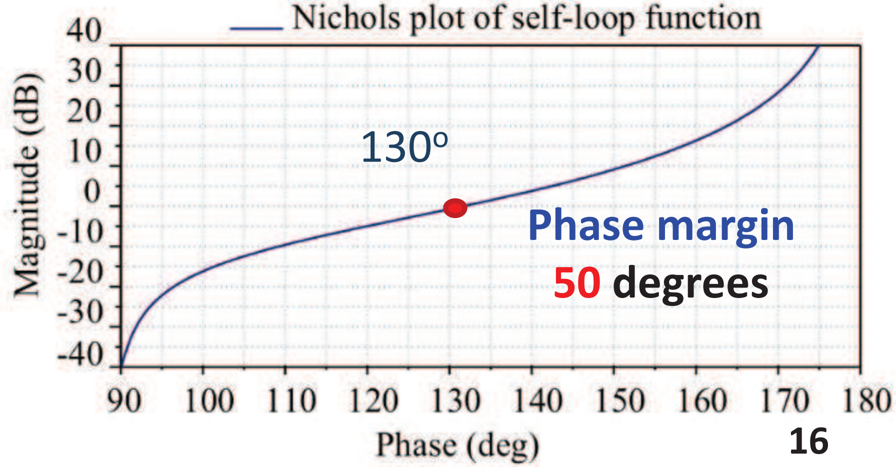
**Bode plot of transfer function**




**Simulated transient response**



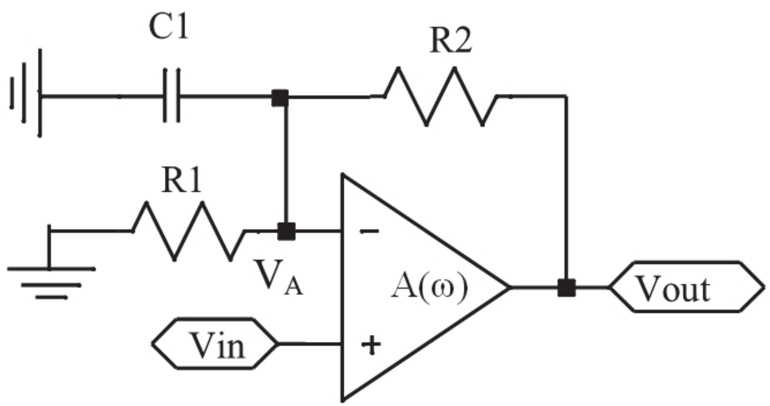

**Nichols plot of self-loop function**



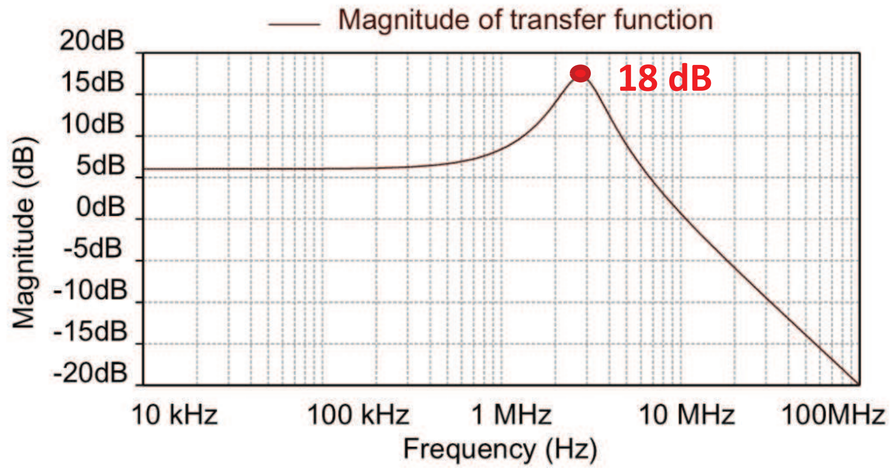
# 3. Behaviors of Feedback Amplifier Networks

## Self-loop Function of 2nd-Order Non-Inverting Amplifier

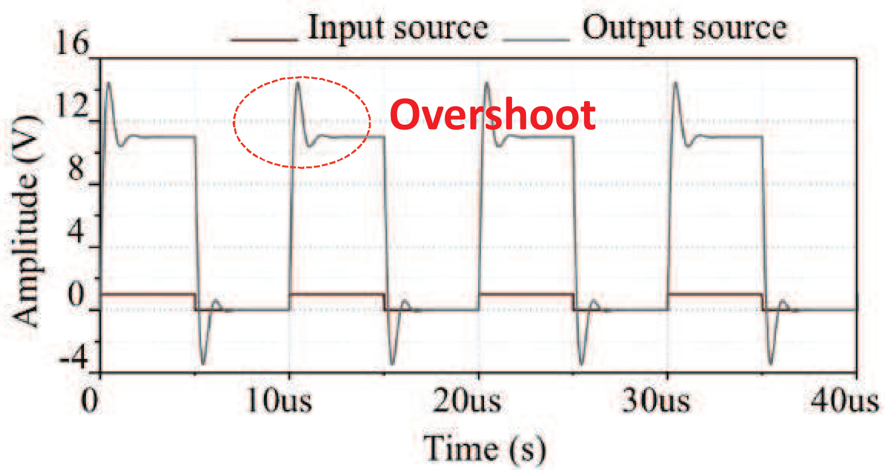
### Non-inverting amplifier with a parasitic capacitor



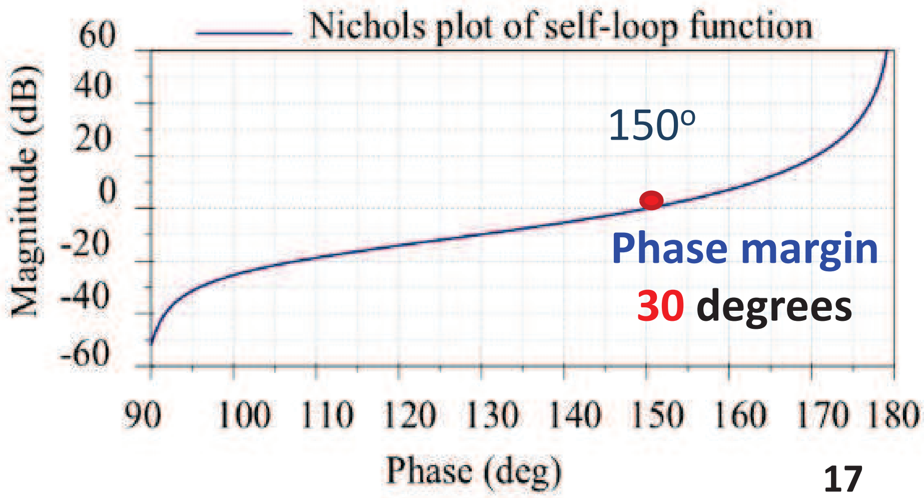

### Bode plot of transfer function




### Simulated transient response



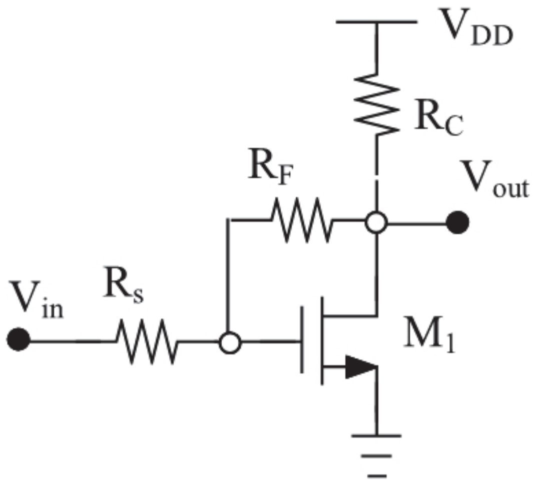

### Nichols plot of self-loop function



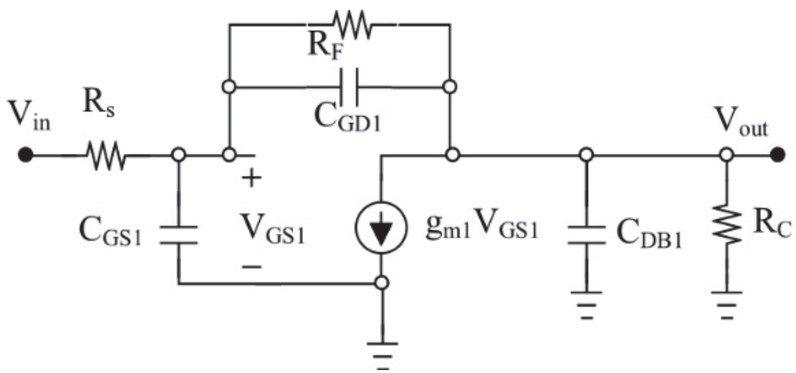
# 3. Behaviors of Feedback Amplifier Networks

## Analysis of Shunt-Shunt CMOS Feedback Amplifier

**Shunt-shunt MOS feedback amplifier**




**Small signal model**




**Apply superposition at the nodes $V_\pi$ and $V_{out}$, we have**

$$V_{GS1}\left(\frac{1}{R_s}+\frac{1}{Z_{CGS1}}+\frac{1}{R_F}+\frac{1}{Z_{CGD1}}\right)=\frac{V_{in}}{R_s}+V_{out}\left(\frac{1}{R_F}+\frac{1}{Z_{CGD1}}\right);$$

$$V_{out}\left(\frac{1}{Z_{CGD1}}+\frac{1}{Z_{CDB1}}+\frac{1}{R_F}+\frac{1}{R_C}\right)=V_{GS1}\left(\frac{1}{R_F}+\frac{1}{Z_{CGD1}}-g_{m1}\right);$$

**Transfer function and self-loop function**

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

**Where,**

$$b_0=R_F R_C C_{GD1};\ b_1=R_C-R_F R_C g_{m1};$$

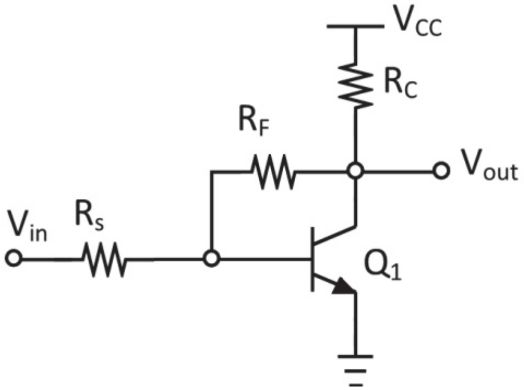
$$a_0=R_S R_F R_C\left(C_{GD1}C_{GS1}+C_{GD1}C_{DB1}+C_{DB1}C_{GS1}\right);$$

$$a_1=\left(R_C R_F^2+R_S R_C R_F g_{m1}+R_S R_F^2\right)C_{GD1}$$
$$+R_C R_F\left(R_S+R_F\right)C_{DB1}+R_S R_F\left(R_C+R_F\right)C_{GS1};$$

# 3. Behaviors of Feedback Amplifier Networks

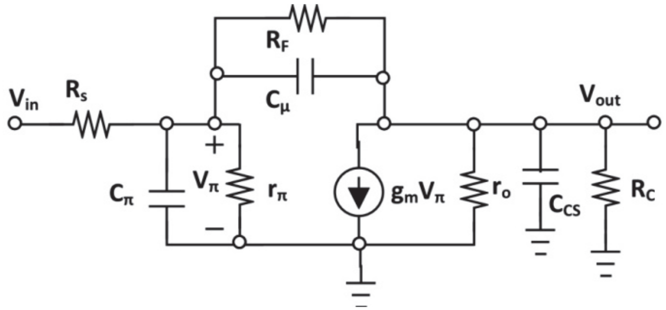
## Behaviors of Shunt-Shunt BJT Feedback Amplifier

### Shunt-shunt BJT feedback amplifier




Here, Rf = 1 kΩ, RC = 10 kΩ, RS = 950 Ω.

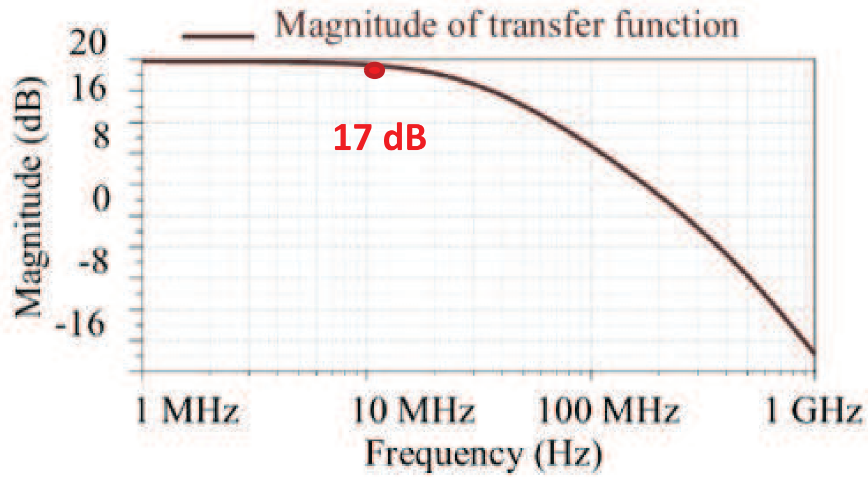
### Small signal model



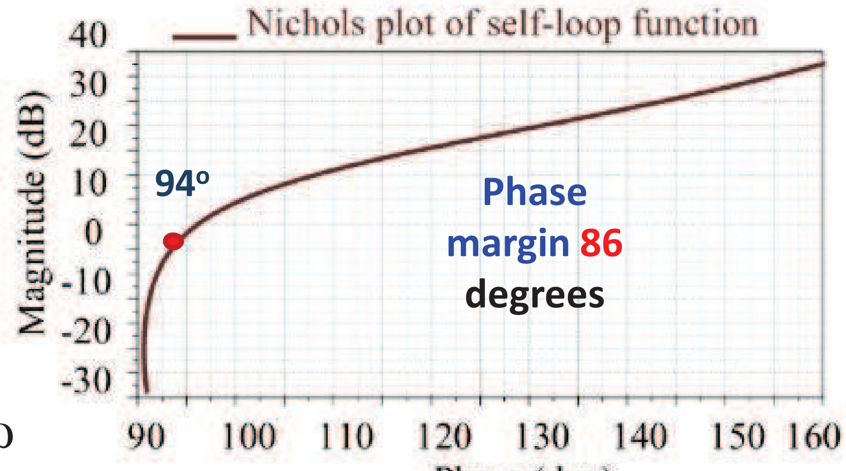

### Transfer function and self-loop function

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

### Bode plot of transfer function




### Nichols plot of self-loop function



# Outline

1. Research Background
   - Motivation, objectives and achievements
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   - Demerits of loop gain and Nyquist stability criterion
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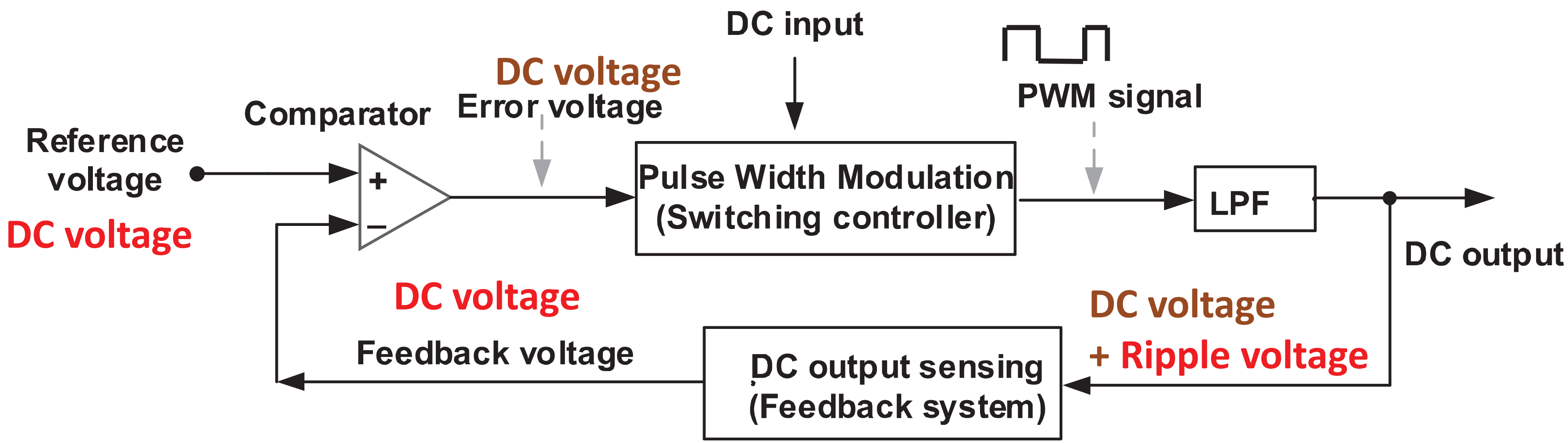
   - Stability test for high-order inverting amplifiers
4. Ringing Test for Adaptive Feedback Networks
   - **Phase margin of power-stage of DC-DC buck converter**
5. Conclusions

# 4. Ringing Test for Adaptive Feedback Networks

## Characteristics 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 (DC-DC Buck converter).**

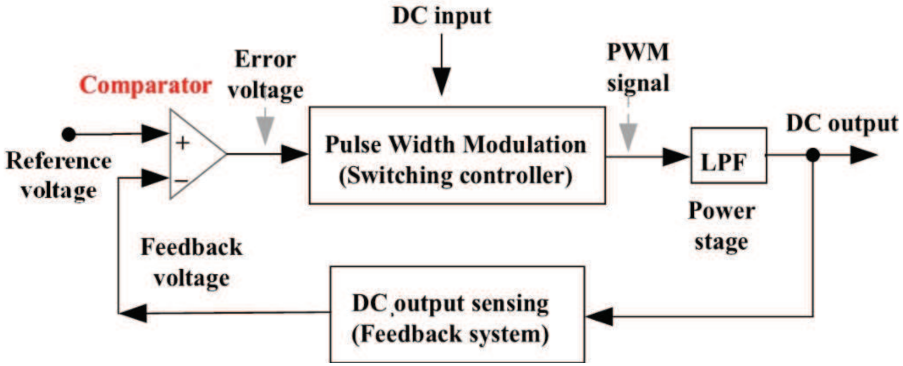
**→ Loop gain is independent of frequency variable (referent voltage, feedback voltage, and error voltage are DC voltages).**

**→ Loop gain is an approximation value.**

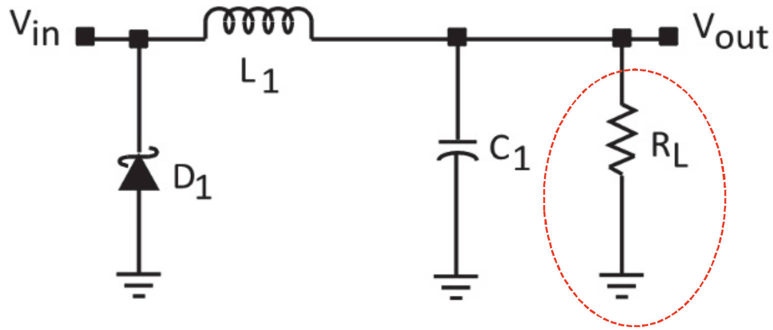
# 4. Ringing Test for Adaptive Feedback Networks

## Behaviors of Power-Stage of DC-DC Converter

**Block diagram of DC-DC Converter**




**Simplified power-stage**




**Transfer function and self-loop function**

$$H(\omega)=\frac{1}{a_0(j\omega)^2+a_1 j\omega+1};L(\omega)=a_0(j\omega)^2+a_1 j\omega;\ a_0=L_1C_1;a_1=\frac{L_1}{R_L};$$

**Operating regions**

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

**Max power propagation condition**

$$|Z_L|=|Z_C|=2R$$

**Balanced charging-discharging time condition**

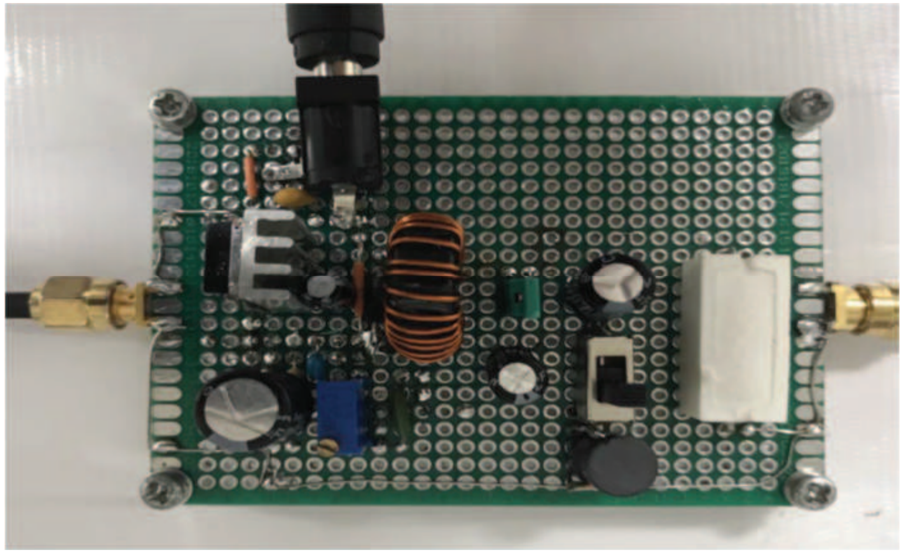
# 4. Ringing Test for Adaptive Feedback Networks

## Implemented Circuit for DC-DC Buck Converter

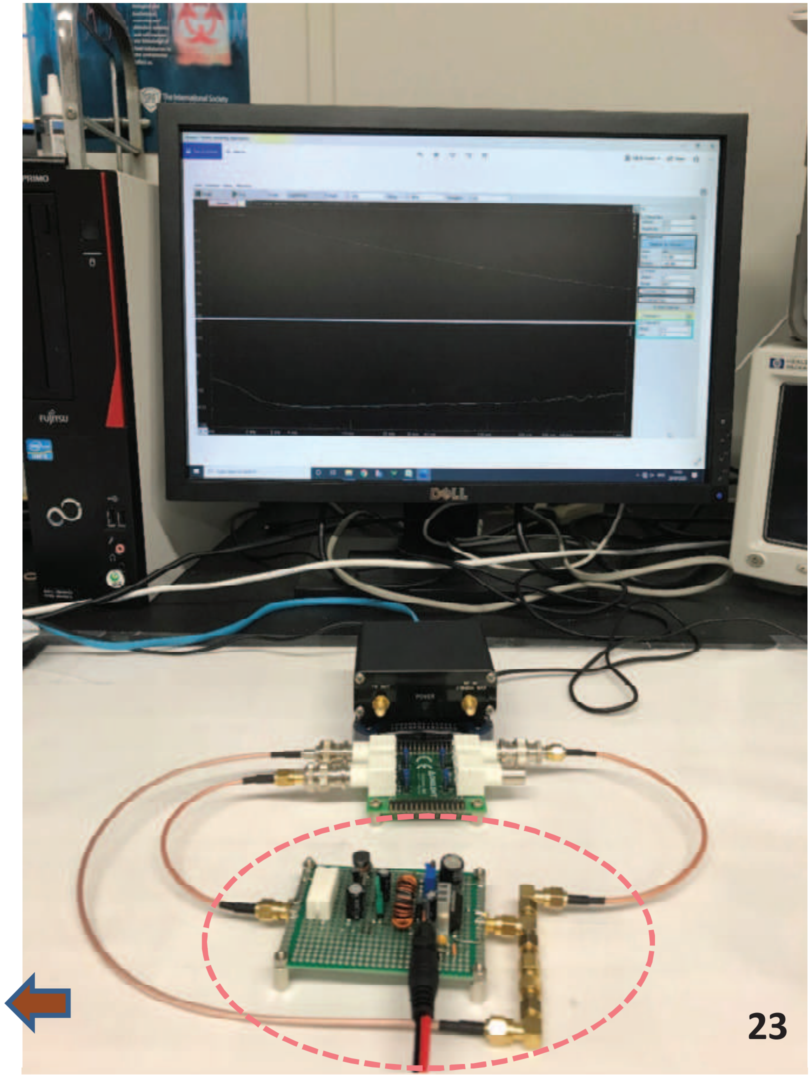
### Design parameters

| | |
|---|---|
| Input voltage (Vin) | 12 V |
| Output voltage (Vo) | 5.0 V |
| Output current (Io) | 1 A |
| Clock frequency (Fck) | 180 kHz |
| Output ripple | < 10 mVpp |

### Implemented circuit



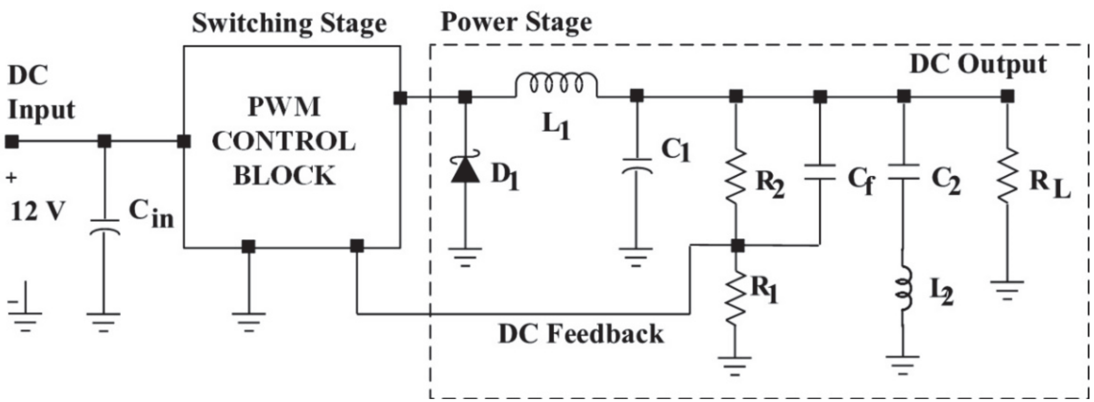
### Measurement set up



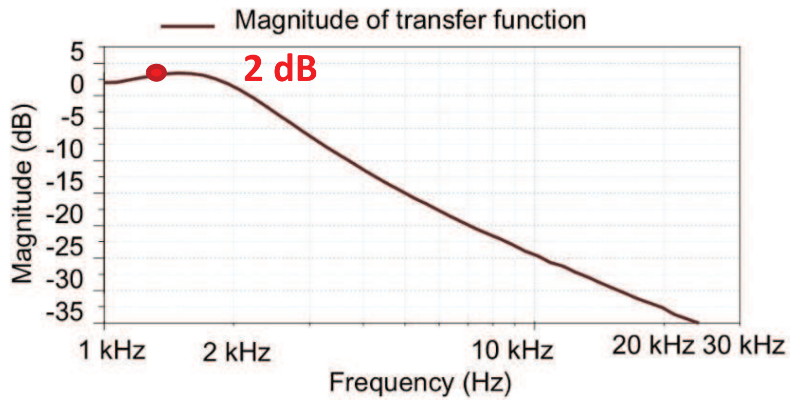
# 4. Ringing Test for Adaptive Feedback Networks

## Phase Margin of Power-Stage of DC-DC Converter

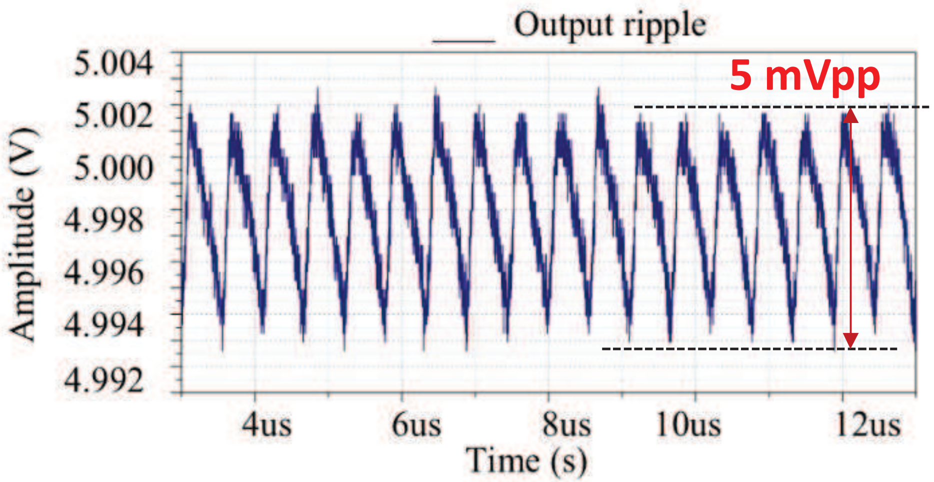
### Schematic diagram of DC-DC converter



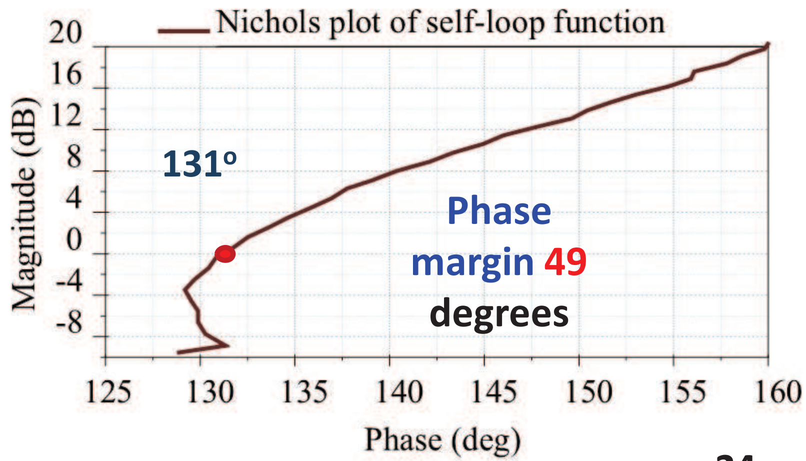

### Bode plot of transfer function




### Measured transient response




### Nichols plot of self-loop function



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# 5. Conclusions

## This work:

- Study of some limitations of loop gain in motion models of mechatronic systems such as spring-damper-mass systems, inverting amplifier, and power-stage of DC-DC buck converter.

→ Observation of self-loop function can help us optimize the behaviors of high-order mechatronic systems easily.

- Implementation of circuit and measurements of self-loop functions for adaptive feedback systems.

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

## Future work:

- Stability test for dynamic load systems and other mechatronic systems.

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# Thank you very much!


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