Study of Behaviors of Electronic Amplifiers using Nichols Chart

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Outline

1. Research Background
   • Motivation, objectives and achievements
   • Self-loop function in a transfer function

2. Analysis of Behaviors of High-order Systems
   • Operating regions of high-order systems

3. Ringing Test for Feedback Amplifiers
   • Stability test for shunt-shunt feedback amplifiers
   • Stability test for unity-gain and inverting amplifiers

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

5. Conclusions
# 1. Research Background

## Noise in Electronic Systems

- **Ringing** does the following things:
  - Causes EMI noise,
  - Increases current flow,
  - Decreases the performance, and
  - Damages the devices.

### Performance of a system

| Signal to Noise Ratio: | SNR = Signal power \[ \frac{\text{Signal power}}{\text{Noise power}} \] |

### Performance of a device

| Figure of Merit: | \[ F = \frac{\text{Output SNR}}{\text{Input SNR}} \] |

### Common types of noise:

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

### STABILITY TEST

#### Unstable system

- **STABILITY TEST**
1. Research Background

Objectives of Study

- **Derivation of self-loop function** based on the proposed comparison measurement
- **Investigation of operating regions** of linear negative feedback networks
- **Observation of phase margin** at unity gain on the Nichols chart
  - **Over-damping** (high delay in rising time)
  - **Critical damping** (max power propagation)
  - **Under-damping** (overshoot and ringing)
1. Research Background
Achievements of Study

**Comparison measurement**
- Feedback amplifiers
- High-order low-pass filters

**Self-loop function**

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

**Alternating current conservation**

**Incident current**
- Balun transformer

**Transmitted current**
- AC source

**2\textsuperscript{nd}-order Deboo low-pass LPF**

Implementing circuit

![Implemented circuit diagram](image)
1. Research Background

Self-loop Function in A Transfer Function

**Linear system**

Input: $V_{in}(\omega)$  
Output: $V_{out}(\omega)$

**Transfer function**

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

- **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** $H(\omega)$, **Numerator function** $A(\omega)$, **Self-loop function** $L(\omega)$

- **Polar chart** $\rightarrow$ **Nyquist chart**
- **Magnitude-frequency plot**
- **Angular-frequency plot**
- **Magnitude-angular diagram $\rightarrow$ Nichols diagram**

**Variable:** angular frequency $(\omega)$

**Bode plots**
1. Research Background

Comparison Measurement

Sequence of steps:
(i) Measurement of numerator function $A(\omega)$,
(ii) Measurement of transfer function $H(\omega)$, and
(iii) Derivation of self-loop function.

Model of a linear system

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

Linear system

Input $V_{\text{in}}(\omega)$ \[ \rightarrow \] Output $V_{\text{out}}(\omega)$

Transfer function

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

Self-loop function

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

Alternating Current Conservation

Transfer function

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

\[ \Rightarrow L(\omega) = \frac{Z_{in}}{Z_{out}} \]

Self-loop function

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

Simplified linear system

Derivation of self-loop function

10 mH inductance

Incident current

Transmitted current

AC source
1. Research Background

Characteristics of Adaptive Feedback Network

Block diagram of a typical adaptive feedback system

Adaptive feedback is used to control the output source along with the decision source (DC-DC Buck converter).

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

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

Loop Gain in Feedback Systems

Adaptive feedback systems

Input +_ G F Output

Transfer function

GF : loop gain

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

Inverting amplifier

Vin +_ A Vout

Transfer function

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

Nichols plot of loop gain

Gain reduction

BW = 100 Hz

GBW = 10 MHz
1. Research Background
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5. Conclusions
2. Analysis of Behaviors of High-order Systems
Characteristics of 2nd-order Transfer Function

Second-order transfer function: \[ H(\omega) = \frac{1}{1 + a_0(j\omega)^2 + a_1j\omega} \]

<table>
<thead>
<tr>
<th>Case</th>
<th>Over-damping</th>
<th>Critical damping</th>
<th>Under-damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta ((\Delta))</td>
<td>(1 , a_0 &lt; \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^2 - 4a_0 &gt; 0)</td>
<td>(1 , a_0 = \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^2 - 4a_0 = 0)</td>
<td>(1 , a_0 &gt; \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^2 - 4a_0 &lt; 0)</td>
</tr>
<tr>
<td>Module (</td>
<td>H(\omega)</td>
<td>)</td>
<td>[1 , \frac{1}{a_0} \sqrt{\omega^2 + \left(\frac{a_1}{2a_0}\right)^2 - \omega^2 + \left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}]</td>
</tr>
<tr>
<td>Angular (\theta(\omega))</td>
<td>(-\arctan\left(\frac{\omega}{\frac{a_1}{2a_0}}\right) - \arctan\left(\frac{\omega}{\frac{a_1}{2a_0}}\right)) (-\arctan\left(\frac{\omega}{\frac{a_1}{2a_0}}\right))</td>
<td>(-2 \arctan\left(\frac{2a_0 \omega}{a_1}\right))</td>
<td>(-\arctan\left(\frac{a_1}{2a_0}\right) - \arctan\left(\frac{\omega}{\omega + \frac{a_1}{2a_0}}\right))</td>
</tr>
<tr>
<td>(\omega_{cut} = \frac{a_1}{2a_0})</td>
<td>(</td>
<td>H(\omega_{cut})</td>
<td>&lt; \frac{2a_0}{a_1}) (\theta(\omega_{cut}) &gt; -\frac{\pi}{2})</td>
</tr>
</tbody>
</table>
## 2. Analysis of Behaviors of High-order Systems

### Characteristics of 2\textsuperscript{nd}-order Self-loop Function

**Second-order self-loop function:**

\[ L(\omega) = j\omega \left[ a_0 j\omega + a_1 \right] \]

<table>
<thead>
<tr>
<th>Case</th>
<th>Over-damping</th>
<th>Critical damping</th>
<th>Under-damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta ((\Delta))</td>
<td>(\Delta = a_1^2 - 4a_0 &gt; 0)</td>
<td>(\Delta = a_1^2 - 4a_0 = 0)</td>
<td>(\Delta = a_1^2 - 4a_0 &lt; 0)</td>
</tr>
<tr>
<td>(</td>
<td>L(\omega)</td>
<td>)</td>
<td>(\omega \sqrt{(a_0\omega)^2 + a_1^2})</td>
</tr>
<tr>
<td>(\theta(\omega))</td>
<td>(\frac{\pi}{2} + \arctan \frac{a_0\omega}{a_1})</td>
<td>(\frac{\pi}{2} + \arctan \frac{a_0\omega}{a_1})</td>
<td>(\frac{\pi}{2} + \arctan \frac{a_0\omega}{a_1})</td>
</tr>
<tr>
<td>(\omega_1 = \frac{a_1}{2a_0} \sqrt{5} - 2)</td>
<td>(</td>
<td>L(\omega_1)</td>
<td>&gt; 1)</td>
</tr>
<tr>
<td>(\omega_2 = \frac{a_1}{2a_0})</td>
<td>(</td>
<td>L(\omega_2)</td>
<td>&gt; \sqrt{5})</td>
</tr>
<tr>
<td>(\omega_3 = \frac{a_1}{a_0})</td>
<td>(</td>
<td>L(\omega_3)</td>
<td>&gt; 4\sqrt{2})</td>
</tr>
</tbody>
</table>
2. Analysis of Behaviors of High-order Systems

Operating Regions of 2\textsuperscript{nd}-Order System

\begin{itemize}
    \item \textbf{Under-damping:} \\
        \(L_1(\omega) = (j\omega)^2 + j\omega;\)  \\
        \(H_1(\omega) = \frac{1}{(j\omega)^2 + j\omega + 1};\)
    \item \textbf{Critical damping:}  \\
        \(L_2(\omega) = (j\omega)^2 + 2j\omega;\)  \\
        \(H_2(\omega) = \frac{1}{(j\omega)^2 + 2j\omega + 1};\)
    \item \textbf{Over-damping:}  \\
        \(L_3(\omega) = (j\omega)^2 + 3j\omega;\)  \\
        \(H_3(\omega) = \frac{1}{(j\omega)^2 + 3j\omega + 1};\)
\end{itemize}

\textbf{Bode plot of transfer function}

\textbf{Nichols plot of self-loop function}

\textbf{Transient response}
## Outline

1. Research Background
   - Motivation, objectives and achievements
   - Self-loop function in a transfer function

2. Analysis of Behaviors of High-order Systems
   - Operating regions of high-order systems

3. Ringing Test for Feedback Amplifiers
   - Stability test for shunt-shunt feedback amplifiers
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5. Conclusions
3. Ringing Test for Feedback Amplifiers

Analysis of Shunt-Shunt Feedback Amplifier

BJT shunt-shunt feedback amplifier

Small signal model

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

$$V_\pi \left( \frac{1}{R_s} + \frac{1}{r_\pi} + \frac{1}{Z_{C\pi}} + \frac{1}{R_F} + \frac{1}{Z_{C\mu}} \right) = \frac{V_{in}}{R_s} + \frac{V_{out}}{Z_{C\mu}}; \quad V_{out} \left( \frac{1}{Z_{C\mu}} + \frac{1}{Z_{CCS}} + \frac{1}{R_C} + \frac{1}{r_o} \right) = V_\pi \left( \frac{1}{Z_{C\mu}} + \frac{1}{R_F} - g_m \right);$$

Transfer function and self-loop function

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

Where, $b_0 = R_L C_{GD1}; b_1 = -R_L g_{m1}; a_0 = R_S R_L \left( C_{GD1} C_{GS1} + C_{GD1} C_{DB1} + C_{DB1} C_{GS1} \right); \quad a_1 = R_L \left( C_{GD1} + C_{DB1} \right) + R_S \left( C_{GS1} + C_{GD1} \right) + R_S R_L g_{m1} C_{GD1};$
3. Ringing Test for Feedback Amplifiers

Characteristics of Shunt-Shunt Feedback Amplifier

BJT shunt-shunt feedback amplifier

\[ R_f = 1 \, \text{k}\Omega, \, R_C = 10 \, \text{k}\Omega, \, R_S = 950 \, \Omega. \]

Transient response

Bode plot of transfer function

- 17 dB

Nichols plot of self-loop function

- 94°
- 86 degrees
3. Ringing Test for Feedback Amplifiers

Analysis of Op Amp without Miller’s Capacitor

**Open-loop function**

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

**Self-loop function**

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

**Without frequency compensation**

**Small signal model of 2\textsuperscript{nd}-stage**

**Transfer function**

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

**Self-loop function**

\[
L(\omega) = a_0 (j\omega)^2 + a_1 j\omega
\]

Where, \( a_0 = R_D C_{GD}; a_1 = -R_D g_m; \)

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

\[
b_1 = \left[ R_D (C_{GD} + C_{DB}) + R_S (C_{GS} + C_{GD}) + R_D R_S g_m C_{GD} \right];
\]
3. Ringing Test for Feedback Amplifiers
Unity-Gain Amplifier without Miller’s Capacitor

Unity-Gain Amplifier

Bode plot of transfer function $H(\omega)$

Nichols plot of self-loop function $L(\omega)$

Transient response
3. Ringing Test for Feedback Amplifiers
Two-stage Op Amp with Frequency Compensation

**Open-loop function**

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

**Self-loop function**

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

With Miller’s capacitor and resistor

**Transfer function**

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

**Self-loop function**

\[
L(\omega) = a_0 (j\omega)^4 + a_1 (j\omega)^3 + a_2 (j\omega)^2 + a_3 j\omega
\]
3. Ringing Test for Feedback Amplifiers

Unity-Gain Amplifier with Miller’s Capacitor

Unity-gain amplifier with Miller’s capacitor

Simplified model

Transfer function and self-loop function

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

Under-damping:
R1 = 2 kΩ, C1 = 1 pF

Critical damping:
R1 = 3.5 kΩ, C1 = 0.2 pF

Over-damping:
R1 = 3.5 kΩ, C1 = 0.8 pF
3. Ringing Test for Feedback Amplifiers

Behaviors of Unity-Gain Amplifier

**Simplified model of unity gain amplifier**

**Simulated transient response**

**Bode plot of transfer function**

**Nichols plot of self-loop function**
3. Ringing Test for Feedback Amplifiers

Inverting Amplifier with Miller’s Capacitor

**Transfer function and self-loop function**

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

- **Under-damping:**
  \(R_z = 0 \, \text{k}\Omega, \, C_z = 0 \, \text{pF}\)

- **Critical damping:**
  \(R_z = 0.5 \, \text{k}\Omega, \, C_z = 0.5 \, \text{pF}\)

- **Over-damping:**
  \(R_z = 4 \, \text{k}\Omega, \, C_z = 0.5 \, \text{pF}\)
3. Ringing Test for Feedback Amplifiers

Behaviors of Inverting Amplifier

Simplified model of inverting amplifier

Simulated transient response

Bode plot of transfer function

Nichols plot of self-loop function
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5. Conclusions
4. Ringing Test for High-order Low-Pass Filters

Analysis of 2\textsuperscript{nd}-Order Passive RLC LPF

Passive RLC Low-pass Filter

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

Self-loop function

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

where, \(a_0 = LC; a_1 = RC;\)

Implemented circuit
4. Ringing Test for High-order Low-Pass Filters

Measurement Results for 2\textsuperscript{nd}-Order Passive RLC LPF

**Bode plot of transfer function**

![Bode plot]

**Nichols plot of self-loop function**

![Nichols plot]

**Transient responses**

![Transient responses]
4. Ringing Test for High-order Low-Pass Filters

Stability Test for 2\textsuperscript{nd}-Order Active Ladder LPF

Active ladder low-pass filter

\[
\begin{align*}
H(\omega) &= \frac{V_{out}}{V_{in}} = \frac{1}{a_0(j\omega)^2 + a_1j\omega + 1};
\end{align*}
\]

Bode plot of transfer function

Self-loop function

\[
L(\omega) = a_0(j\omega)^2 + a_1j\omega;
\]

Nichols plot of self-loop function

implemented circuit
4. Ringing Test for High-order Low-Pass Filters
Analysis of 2\textsuperscript{nd}-Order Deboo low-pass LPF

**Single ended Deboo low-pass LPF**

![Single ended Deboo low-pass LPF schematic](image)

**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,

\[
b_0 = \frac{R_2 R_4 R_7 (R_5 + R_6)}{R_1 \left[ R_2 R_4 (R_5 + R_6) + R_7 \left( R_4 R_5 - R_3 R_6 \right) \right]};
\]

\[
a_0 = \frac{R_2 R_3 R_4 R_5 R_7 C_1 C_2}{R_2 R_4 (R_5 + R_6) + R_7 \left( R_4 R_5 - R_3 R_6 \right)};
\]

\[
a_1 = \frac{R_2 R_7 C_1 \left( R_4 R_5 - R_3 R_6 \right) + R_3 R_4 R_5 R_7 C_2}{R_2 R_4 (R_5 + R_6) + R_7 \left( R_4 R_5 - R_3 R_6 \right)};
\]

\[
R_1 = R_3 = R_5 = 1 \text{ k\Omega}, \ R_2 = 10 \text{ k\Omega}, \ R_6 = R_7 = 5 \text{ k\Omega}, \ C_1 = 1 \text{ nF}, \ C_2 = 0.5 \text{ nF} \text{ at } f_0 = 10 \text{ kHz}.
\]

- **Over-damping** (R4 = 3 k\Omega),
- **Critical damping** (R4 = 6 k\Omega), and
- **Under-damping** (R4 = 10 k\Omega).
4. Ringing Test for High-order Low-Pass Filters

Implemented Circuit of Deboo low-pass LPF

Schematic of Deboo low-pass LPF

Implemented Circuit

System Under Test

Measurement set up
4. Ringing Test for High-order Low-Pass Filters

Measurement Results of Deboo low-pass LPF

**Bode plot of transfer function**

- **Over-damping:**
  - Frequency (Hz)
  - Magnitude (dB)
  - 7 dB
  - 0 dB
  - -7 dB

- **Critical damping:**
  - Frequency (Hz)
  - Magnitude (dB)
  - 81°

- **Under-damping:**
  - Frequency (Hz)
  - Magnitude (dB)
  - 62°

**Nichols plot of self-loop function**

- **Over-damping:**
  - Phase (deg)
  - 99°

- **Critical damping:**
  - Phase (deg)
  - 107°

- **Under-damping:**
  - Phase (deg)
  - 118°

**Transient response**

- **Over-damping:**
  - Time (s)
  - Amplitude (V)
  - Phase margin is 81 degrees.

- **Critical damping:**
  - Time (s)
  - Amplitude (V)
  - Phase margin is 73 degrees.

- **Under-damping:**
  - Time (s)
  - Amplitude (V)
  - Phase margin is 62 degrees.
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5. Conclusions
5. Limitations of Conventional Methods

- **Middlebrook’s measurement of loop gain**
  - Applying only in feedback systems (DC-DC converters).

- **Replica measurement of loop gain**
  - Using two identical networks (not real measurement).

- **Nyquist’s stability condition**
  - Theoretical analysis for feedback systems (Lab tool).

- **Nichols chart of loop gain**
  - Only used in feedback control theory (Lab tool).
## 5. Comparison

<table>
<thead>
<tr>
<th>Features</th>
<th>Comparison measurement</th>
<th>Alternating current conservation</th>
<th>Replica measurement</th>
<th>Middlebrook’s method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main objective</strong></td>
<td>Self-loop function</td>
<td>Self-loop function</td>
<td>Loop gain</td>
<td>Loop gain</td>
</tr>
<tr>
<td><strong>Transfer function accuracy</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Breaking feedback loop</strong></td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Operating region accuracy</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Phase margin accuracy</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Passive networks</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
5. Discussions

- Loop gain is independent of frequency variable.

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

Nichols chart is only used in MATLAB simulation.

Nichols chart isn’t used widely in practical measurements (only used in control theory).

https://www.mathworks.com/help/control/ref/nichols.html
5. Conclusions

This work:

- **Proposal of comparison measurement** for deriving **self-loop function** in a transfer function
  - **Observation** of self-loop function can help us optimize the behavior of a high-order system.
- **Implementation of circuit and measurements** of self-loop functions for high-order feedback amplifiers.
  - **Theoretical concepts** of stability test are verified by laboratory simulations and practical experiments.

Future of work:

- **Stability test** for **parasitic components** in transmission lines, printed circuit boards, physical layout layers
References


References


Thank you very much!
谢谢
Q&A