Ringing Test for Negative Feedback Amplifiers

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## Outline

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

2. **Ringing Test for Feedback Amplifiers**
   - Stability test for shunt-shunt feedback amplifiers

3. **Ringing Test for Op Amps with Feedback Loops**
   - Stability test for unity-gain and inverting amplifiers

4. **Ringing Test for High-Order Low-Pass Filters**
   - Stability test for 2\textsuperscript{nd}-order Åkerberg-Mossberg filters

5. **Conclusions**
1. Research Background
Noise in Electronic Systems

**Common types of noise:**
- Electronic noise
- Thermal noise,
- Intermodulation noise,
- Cross-talk,
- Impulse noise,
- Shot noise, and
- Transit-time noise.

**Device noise:**
- Flicker noise,
- Thermal noise,
- White noise.

**Linear networks**
- Overshoot,
- Ringing
- Oscillation noise

**Performance of a system**

\[
\text{SNR} = \frac{\text{Signal power}}{\text{Noise power}}
\]

**Performance of a device**

\[
F = \frac{\text{Output SNR}}{\text{Input SNR}}
\]
1. Research Background

Effects of Ringing on Electronic Systems

Ringing represents a distortion of a signal. Ringing is overshoot/undershoot voltage or current when it’s seen on time domain.

Ringing does the following things:

• Causes EMI noise,
• Increases current flow,
• Consumes the power,
• Decreases the performance, and
• Damages the devices.
1. Research Background

Objectives of Study

- Derivation of transfer function in electronic systems using superposition theorem
  - Investigation of operating regions of linear negative feedback networks
    - Over-damping (high delay in rising time)
    - Critical damping (max power propagation)
    - Under-damping (overshoot and ringing)
- Ringing test for linear negative feedback amplifiers based on comparison measurement
1. Research Background

Achievements of Study

Superposition formula for multi-source networks

\[
V_O(t)\sum_{i=1}^{n} \frac{1}{Z_i} + V_O(t)\sum_{i=1}^{n} \frac{1}{Z_{si}} + \sum_{i=1}^{n} \left( \frac{V_i(t)}{Z_i} + I_{ai}(t) - I_{gi}(t) \right) = \sum_{k=1}^{n} \frac{1}{Z_{pik}}
\]

Transfer function

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

Self-loop function

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

Derivation of self-loop function using comparison measurement

- Shunt-shunt feedback amplifiers
- Inverting amplifiers
- Unity-gain amplifiers
- 2nd-order low-pass filters
1. Research Background

Approaching Methods

Shunt-shunt feedback amplifier

\[ V_{\text{in}} \rightarrow R_s \rightarrow Q_1 \rightarrow V_{\text{out}} \]

2\textsuperscript{nd}-order Åkerberg-Mossberg LPF

\[ \begin{align*}
C_1 & \rightarrow R_6 \\
C_2 & \rightarrow R_4 \rightarrow R_5 \\
C_1 & \rightarrow R_3 \\
C_2 & \rightarrow R_2 \rightarrow R_3 \\
V_{\text{in}} & \rightarrow A(u) \\
\text{Implemented circuit} & \rightarrow \text{input} \\
V_{\text{out}} & \rightarrow \text{output}
\end{align*} \]
1. Research Background

Superposition Theorem for Multi-Source Systems

Superposition formula:

\[
V_O(t) \sum_{i=1}^{n} \frac{1}{Z_i} + V_O(t) \sum_{i=1}^{n} \frac{1}{Z_{si}} + \sum_{k=1}^{n} \frac{1}{Z_{pik}} \\
= \sum_{i=1}^{n} \left( \frac{V_i(t)}{Z_i} + I_{ai}(t) - I_{gi}(t) \right)
\]

- \( V_O(t) \): Voltage at one node
- \( V_i(t) \): Input voltage sources
- \( I_{ai}(t) \): Ahead-toward current sources
- \( I_{gi}(t) \): Ground-toward current sources
- \( Z_{i, si, pi, k}(t) \): Impedances at each branch

- Multi-source systems, feedback networks (op amps, amplifiers), polyphase filters, complex filters...
1. Research Background

Analysis of 2\textsuperscript{nd}–Order Polyphase Filter

Transfer function for \textit{positive} polyphase signal

\[ H_F(\omega) = \frac{V_{out}}{V_{in}} = \frac{1 + (j)^3 b_1 j\omega}{a_0 (j\omega)^2 + a_1 j\omega + 1} \times \frac{1 + (j)^3 b_2 j\omega}{a_0 (j\omega)^2 + a_1 j\omega + 1}; \]

Transfer function for \textit{negative} polyphase signal

\[ H_N(\omega) = \frac{V_{out}}{V_{in}} = \frac{1 + (j)^3 b_1 j\omega}{a_0 (j\omega)^2 + a_1 j\omega + 1} \times \frac{1 + (j)^3 b_2 j\omega}{a_0 (j\omega)^2 + a_1 j\omega + 1}; \]

Here: \[ b_0 = R_1 C_1; b_1 = R_2 C_2; a_0 = b_0 b_1; a_1 = b_0 + b_1 + 2 R_2 C_1; \]

Image rejection ratio (IRR)

\[ IRR(\omega) = \left| \frac{H_F(\omega)}{H_N(\omega)} \right| = \left| \frac{(1 + b_1 \omega)(1 + b_2 \omega)}{(1 - b_1 \omega)(1 - b_2 \omega)} \right|; \]
1. Research Background

Behaviors of 2\textsuperscript{nd}–Order Polyphase Filter

2-order RC polyphase filter

Transfer function in all frequency domain

\[ |H(\omega)| = \frac{(1 + b_1 \omega)(1 + b_2 \omega)}{\sqrt{(1 - a_0 \omega^2)^2 + (a_1 \omega)^2}}; \quad \omega \in R \]

Here, \( R_1 = 1 \, \text{k}\Omega, \, C_1 = 227 \, \text{pF}, \, R_2 = 1 \, \text{k}\Omega, \, C_2 = 114 \, \text{pF}, \) at \( f_1 = 700 \, \text{kHz}, \, f_2 = 1.4 \, \text{MHz}, \)

Bode plot of transfer function in all frequency domain

IRR = 32 dB
1. Research Background

Behavior of 4\textsuperscript{th}-order Complex Filter

Transfer function for positive polyphase signals

\[
H_p(\omega) = \frac{R_{21}}{R_{11}} \left[1 + j \left(\frac{\omega}{\omega_{cut1}} + \frac{R_{21}}{R_{31}}\right)\right] \frac{R_{22}}{R_{12}} \left[1 + j \left(\frac{\omega}{\omega_{cut2}} + \frac{R_{22}}{R_{32}}\right)\right] \frac{R_{23}}{R_{13}} \left[1 + j \left(\frac{\omega}{\omega_{cut3}} + \frac{R_{23}}{R_{33}}\right)\right] \frac{R_{24}}{R_{14}} \left[1 + j \left(\frac{\omega}{\omega_{cut4}} + \frac{R_{24}}{R_{34}}\right)\right],
\]

Transfer function for negative polyphase signals

\[
H_n(\omega) = \frac{R_{21}}{R_{11}} \left[1 + j \left(\frac{\omega}{\omega_{cut1}} - \frac{R_{21}}{R_{31}}\right)\right] \frac{R_{22}}{R_{12}} \left[1 + j \left(\frac{\omega}{\omega_{cut2}} - \frac{R_{22}}{R_{32}}\right)\right] \frac{R_{23}}{R_{13}} \left[1 + j \left(\frac{\omega}{\omega_{cut3}} - \frac{R_{23}}{R_{33}}\right)\right] \frac{R_{24}}{R_{14}} \left[1 + j \left(\frac{\omega}{\omega_{cut4}} - \frac{R_{24}}{R_{34}}\right)\right],
\]

4\textsuperscript{th}-order complex filter

Bode plot of transfer function

Gain Ripple = 0.7 dB

Gain = 10 dB

\(\text{BW} = 6\text{MHz}\)

IRR = 43 dB
1. Research Background

Self-loop Function in A Transfer Function

Linera system

\[ H(\omega) \]

Input \( V_{in}(\omega) \)  \rightarrow \ Output \( V_{out}(\omega) \)

Transfer function

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

- Polar chart \( \rightarrow \) Nyquist chart
- Magnitude-frequency plot
- Angular-frequency plot

Model of a linear system

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

- \( A(\omega) \) : Open loop function
- \( H(\omega) \) : Transfer function
- \( L(\omega) \) : Self-loop function

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

Bode plots

- Magnitude- angular diagram \( \rightarrow \) Nichols diagram
1. Research Background

Characteristics of Adaptive Feedback Network

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
Comparison Measurement

Transfer function

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

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

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

Self-loop function

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

- **Conventional superposition**
  → Solving for every source (**several times**).
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   • Stability test for shunt-shunt feedback amplifiers

3. Ringing Test for Op Amps with Feedback Loops
   • Stability test for unity-gain and inverting amplifiers

4. Ringing Test for High-Order Low-Pass Filters
   • Stability test for 2\textsuperscript{nd}-order Åkerberg-Mossberg filters

5. Conclusions
2. Ringing Test for Feedback Amplifiers

Characteristics of 2\textsuperscript{nd}-order Transfer Function

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

<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>(\frac{1}{a_0} &lt; \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^2 - 4a_0 &gt; 0)</td>
<td>(\frac{1}{a_0} = \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^2 - 4a_0 = 0)</td>
<td>(\frac{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>(</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))</td>
<td>(-2\arctan\left(\frac{2a_0\omega}{a_1}\right))</td>
<td>(-\arctan\left(\frac{\omega - \frac{a_1}{2a_0}}{\frac{a_1}{2a_0}}\right)) (-\arctan\left(\frac{\omega + \frac{a_1}{2a_0}}{\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. Ringing Test for Feedback Amplifiers

### Characteristics of $2^{nd}$-order Self-loop Function

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

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

<table>
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<th>Critical damping</th>
<th>Under-damping</th>
</tr>
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<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>$</td>
<td>L(\omega_1)</td>
<td>&gt; 1, \pi - \theta(\omega_1) &gt; 76.3^\circ$</td>
</tr>
<tr>
<td>$\omega_2 = \frac{a_1}{2a_0}$</td>
<td>$</td>
<td>L(\omega_2)</td>
<td>&gt; \sqrt{5}, \pi - \theta(\omega_2) &gt; 63.4^\circ$</td>
</tr>
<tr>
<td>$\omega_3 = \frac{a_1}{a_0}$</td>
<td>$</td>
<td>L(\omega_3)</td>
<td>&gt; 4\sqrt{2}, \pi - \theta(\omega_3) &gt; 45^\circ$</td>
</tr>
</tbody>
</table>
2. Ringing Test for Feedback Amplifiers
Operating Regions of 2\textsuperscript{nd}-Order System

- **Under-damping:** 
  \[ L_1(\omega) = (j\omega)^2 + j\omega; \]
  \[ H_1(\omega) = \frac{1}{(j\omega)^2 + j\omega + 1}; \]

- **Critical damping:** 
  \[ L_2(\omega) = (j\omega)^2 + 2j\omega; \]
  \[ H_2(\omega) = \frac{1}{(j\omega)^2 + 2j\omega + 1}; \]

- **Over-damping:** 
  \[ L_3(\omega) = (j\omega)^2 + 3j\omega; \]
  \[ H_3(\omega) = \frac{1}{(j\omega)^2 + 3j\omega + 1}; \]

**Nichols plot of self-loop function**

**Bode plot of transfer function**

**Transient response**

- Phase margin: 
  - Under-damping: 92°
  - Critical damping: 76.3°
  - Over-damping: 52°
2. 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 $V_{\text{out}}$, we have

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

Transfer function $H(\omega)$ and self-loop function $L(\omega)$

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

Where,

\[ b_0 = R_L C_{GD1}; \quad b_1 = -R_L g_m; \quad a_0 = R_S R_L \left( C_{GD1} C_{GS1} + C_{GD1} C_{DB1} + C_{DB1} C_{GS1} \right) \]

\[ a_1 = R_L \left( C_{GD1} + C_{DB1} \right) + R_S \left( C_{GS1} + C_{GD1} \right) + R_S R_L g_m C_{GD1}; \]
2. Ringing Test for Feedback Amplifiers

Characteristics of Shunt-Shunt Feedback Amplifier

BJT shunt-shunt feedback amplifier

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

Transients response

Bode plot of transfer function

- Magnitude of transfer function
  - 17 dB

Nichols plot of self-loop function

- Phase margin
  - 94°
  - 86 degrees
Outline

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

2. Ringing Test for Feedback Amplifiers
   • Stability test for shunt-shunt feedback amplifiers

3. Ringing Test for Op Amps with Feedback Loops
   • Stability test for unity-gain and inverting amplifiers

4. Ringing Test for High-Order Low-Pass Filters
   • Stability test for 2nd-order Åkerberg-Mossberg filters

5. Conclusions
3. Ringing Test for Op Amps with Feedback Loops

Analysis of Op Amp without Miller’s Capacitor

Without frequency compensation

**Simplified model**

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**Small signal model**

**Transfer function** $H(\omega)$ and **self-loop function** $L(\omega)$

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

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

Where,

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

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

\[
a_0 = R_D C_{GD}; \quad a_1 = -R_D g_m
\]
3. Ringing Test for Op Amps with Feedback Loops

Unity-Gain Amplifier without Miller’s Capacitor

Unity-Gain Amplifier

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

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

Phase margin $= 13$ degrees

15 dB
3. Ringing Test for Op Amps with Feedback Loops

Two-stage Op Amp with Frequency Compensation

With Miller’s capacitor and resistor

Simplified model

Small signal model

Transfer function $H(\omega)$

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

Self-loop function $L(\omega)$

$$L(\omega) = a_0 (j\omega)^4 + a_1 (j\omega)^3 + a_2 (j\omega)^2 + a_3 j\omega$$
3. Ringing Test for Op Amps with Feedback Loops

Unity-Gain Amplifier with Miller’s Capacitor

Unity-gain amplifier with Miller’s capacitor

Simplified model of unity gain amplifier

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:
\[ R1 = 2\, \text{k}\Omega, \quad C1 = 1\, \text{pF} \]

Critical damping:
\[ R1 = 3.5\, \text{k}\Omega, \quad C1 = 0.2\, \text{pF} \]

Over-damping:
\[ R1 = 3.5\, \text{k}\Omega, \quad C1 = 0.8\, \text{pF} \]
3. Ringing Test for Op Amps with Feedback Loops
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

- Phase margin
  - 30 degrees

- 5dB

- 79°
- 90°
- 150°
Inverting Amplifier with Frequency Compensation

3. Ringing Test for Op Amps with Feedback Loops

Inverting Amplifier with Miller’s Capacitor

Under-damping:
R3 = 2 kΩ, C1 = 1 pF

Critical damping:
R3 = 3.5 kΩ, C1 = 0.2 pF

Over-damping:
R3 = 3.5 kΩ, C1 = 0.8 pF

Transfer function and self-loop function

\( H(\omega) = \frac{-R_2}{1 + L(\omega)} \approx -\frac{R_2}{R_1} \);

\( L(\omega) = \frac{1}{A(\omega)} \left( 1 + \frac{R_2}{R_1} \right) \);
3. Ringing Test for Op Amps with Feedback Loops

Behaviors of Inverting Amplifier

Simplified model of **inverting amplifier**

**Bode plot** of transfer function

**Nichols plot** of self-loop function

Simulated transient response

- **Phase margin 41 degrees**
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   • Stability test for 2
     nd-order Åkerberg-Mossberg filters

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

Analysis of 2nd-Order Åkerberg-Mossberg LPF

Single ended Åkerberg-Mossberg 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 = 100 Ω, R2 = 50 kΩ,
R3 = R4 = 50 kΩ, C1 = 5 nF, C2 = 10 nF, C3 = 3.18 nF, at \( f_0 = 100 \text{ kHz}. \)

- Over-damping (R5 = 0.5 kΩ),
- Critical damping (R5 = 1 kΩ), and
- Under-damping (R5 = 2 kΩ).

Fully differential Åkerberg-Mossberg LPF
4. Ringing Test for High-Order Low-Pass Filters

Simulation Results of 2\textsuperscript{nd}-Order Ladder LPF

**Bode plot of transfer function**

- Under-damping
- Critical damping
- Over-damping

**Transient response**

- Under-damping
- Critical damping
- Over-damping

**Nichols plot of self-loop function**

- Under-damping
- Critical damping
- Over-damping

**Over-damping:**

$\rightarrow$ Phase margin is 81 degrees.

**Critical damping:**

$\rightarrow$ Phase margin is 71 degrees.

**Under-damping:**

$\rightarrow$ Phase margin is 45 degrees.
4. Ringing Test for High-Order Low-Pass Filters

Implemented Circuit of Åkerberg-Mossberg LPF

Schematic of Åkerberg-Mossberg LPF

Measurement set up

Device Under Test

Signal generator

Buffer

Device Under Test

Buffer

Oscilloscope

Analog Discovery II
Digilent (1 kHz ~ 10 kHz)
4. Ringing Test for High-Order Low-Pass Filters
Measurement Results of Åkerberg-Mossberg LPF

**Bode plot of transfer function**

- Under-damping
- Critically-damping
- Under-damping

- Frequency (Hz)
- Magnitude (dB)
- 1 kHz, 10 kHz, 100 kHz, 1 MHz
- 0 dB, 12 dB, 20 dB

**Nichols plot of self-loop function**

- Under-damping
- Critical damping
- Over-damping

- Phase (deg)
- Magnitude (dB)
- 85, 90, 95, 100, 105, 110, 115, 120, 125, 130, 135, 140

- Phase margin
  - 103°, 110°, 116°
  - 64 degrees

**Transient response**

- Under-damping
- Critical damping
- Over-damping

- Time (s)
- Amplitude (V)
- 0 ms, 0.5 ms, 1 ms, 1.5 ms, 2 ms, 2.5 ms, 3 ms, 3.5 ms

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**Over-damping:**

→ Phase margin is 77 degrees.

**Critical damping:**

→ Phase margin is 70 degrees.

**Under-damping:**

→ Phase margin is 64 degrees.
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5. Conclusions
## 5. Comparison

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<tr>
<th>Features</th>
<th>Comparison measurement</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>Loop gain</td>
<td>Loop gain</td>
</tr>
<tr>
<td><strong>Transfer function</strong></td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>accuracy</strong></td>
<td></td>
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</tr>
<tr>
<td><strong>Breaking feedback loop</strong></td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Operating region</strong></td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>accuracy</strong></td>
<td></td>
<td></td>
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<tr>
<td><strong>Phase margin</strong></td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>accuracy</strong></td>
<td></td>
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</tr>
<tr>
<td><strong>Passive networks</strong></td>
<td>Yes</td>
<td>No</td>
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</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

(Network Analyzer)

(Technology limitations)
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


Thank you very much!