Simulation Evaluation of Null Method for Operational Amplifier Testing


Division of Electronics and Informatics
Gunma University
ROHM Semiconductor
Outline

• Research Background
• Basic Operational Amplifier Measurement Circuit
• NULL Method Prototype Circuit
• SPICE Simulation Verification
  ➢ Frequency Characteristics
  ➢ Operational Amplifier Offset Voltage Measurement
  ➢ Open Loop Gain ($A_{OL}$)
  ➢ Common-Mode Rejection Ratio (CMRR)
  ➢ Power Supply Rejection Ratio (PSRR)
• Conclusion
Outline

• Research Background
• Basic Operational Amplifier Measurement Circuit
• NULL Method Prototype Circuit
• SPICE Simulation Verification
  ➢ Frequency Characteristics
  ➢ Operational Amplifier Offset Voltage Measurement
  ➢ Open Loop Gain ($A_{OL}$)
  ➢ Common-Mode Rejection Ratio (CMRR)
  ➢ Power Supply Rejection Ratio (PSRR)
• Conclusion
What is Operational Amplifier?

Operational Amplifier

- Differential inputs
- Single-ended output
- Extremely high gain

Past
Analog computers

Present
Sensor-Interface analog circuit

Spread of IoT (Internet of Things) technology
Faraday’s Experiment

Flow velocity measurement on the principle of electromagnetic flowmeter

River Thames

Michael Faraday
(1791 ~ 1867)
British chemist / physicist
Faraday’s Experiment

Michael Faraday
(1791 ~ 1867)
British chemist / physicist

Flow velocity measurement on the principle of electromagnetic flowmeter

Impossible

Reason
No electronic circuit for amplification of the detected weak electrical signal

Importance of analog signal conditioning circuits such as operational amplifier
Operational Amplifier: Accurate measurement

Problem
- Open loop gain: High
- Small voltage error generation
- Minus input voltage of amplifier → Zero potential with servo loop

Verification of NULL method circuit
NULL Method

Low-cost, high-quality testing of operation amplifier

Goal

NULL Method → Apply for mass production testing

NULL Method

Measurement time: Long

Mass production testing: Difficult

1 second testing for 1 US dollar chip

Good capacitor value selection → Fast, stable operation
Outline

• Research Background
• Basic Operational Amplifier Measurement Circuit
• NULL Method Prototype Circuit
• SPICE Simulation Verification
  ➢ Frequency Characteristics
  ➢ Operational Amplifier Offset Voltage Measurement
  ➢ Open Loop Gain ($A_{OL}$)
  ➢ Common-Mode Rejection Ratio (CMRR)
  ➢ Power Supply Rejection Ratio (PSRR)
• Conclusion
Basic Measurement Circuit

Operational Amplifier Measurement Circuit using the NULL Method

Switches (S1,.., S6)
- Offset
- Bias Current
- DC gain
- AC gain
- DC CMRR
- DC PSRR
- AC CMRR
- AC PSRR etc.

can be measured accurately

Source: Analog Dialogue Vol 45 Apr.2011 Analog Devices
## Operational Amplifier Measurement Items

### Switch States and Operational Amplifier Measurement Items

<table>
<thead>
<tr>
<th>Parameter</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offset</td>
<td>short</td>
<td>short</td>
<td>open</td>
<td>A</td>
<td>a</td>
<td>open</td>
</tr>
<tr>
<td>Offset and bias current</td>
<td>short/open</td>
<td>short/open</td>
<td>open</td>
<td>A</td>
<td>a</td>
<td>open</td>
</tr>
<tr>
<td>DC gain</td>
<td>short</td>
<td>short</td>
<td>open</td>
<td>A</td>
<td>a</td>
<td>open/short</td>
</tr>
<tr>
<td>AC gain</td>
<td>short</td>
<td>short</td>
<td>open</td>
<td>A</td>
<td>a</td>
<td>open</td>
</tr>
<tr>
<td>DC CMRR</td>
<td>short</td>
<td>short</td>
<td>open</td>
<td>A/B</td>
<td>a/b</td>
<td>open</td>
</tr>
<tr>
<td>DC PSRR</td>
<td>short</td>
<td>short</td>
<td>open</td>
<td>A/B</td>
<td>a/b</td>
<td>open</td>
</tr>
<tr>
<td>AC CMRR</td>
<td>short</td>
<td>short</td>
<td>short</td>
<td>C</td>
<td>c</td>
<td>open</td>
</tr>
<tr>
<td>AC PSRR</td>
<td>short</td>
<td>short</td>
<td>short</td>
<td>D</td>
<td>d</td>
<td>open</td>
</tr>
</tbody>
</table>
Operational Amplifier Measurement Circuit using NULL Method

Measured Operational Amplifier

Offset voltage (Minute)
Measurement: Difficult

Several tens of mV
Measurement: Easy

×1,000

Source: Analog Dialogue Vol 45 Apr.2011 Analog Devices
Outline

• Research Background
• Basic Operational Amplifier Measurement Circuit
• NULL Method Prototype Circuit
• SPICE Simulation Verification
  ➢ Frequency Characteristics
  ➢ Operational Amplifier Offset Voltage Measurement
  ➢ Open Loop Gain ($A_{OL}$)
  ➢ Common-Mode Rejection Ratio (CMRR)
  ➢ Power Supply Rejection Ratio (PSRR)
• Conclusion
NULL Method Prototype Circuit

**Measured Operational Amplifier**

**Operational Amplifier:** SPICE model provided by the manufacturer

**Auxiliary Operational Amplifier**

**Experimental Circuit using the NULL Method**
Outline

• Research Background
• Basic Operational Amplifier Measurement Circuit
• NULL Method Prototype Circuit
• SPICE Simulation Verification
  ➢ Frequency Characteristics
  ➢ Operational Amplifier Offset Voltage Measurement
  ➢ Open Loop Gain ($A_{OL}$)
  ➢ Common-Mode Rejection Ratio (CMRR)
  ➢ Power Supply Rejection Ratio (PSRR)
• Conclusion
Frequency Characteristics

Input sine wave (1mV\(_{P-P}\), 1kHz)

\(V_{in}\)

\(x\ 1,000\) gain amplifier circuit

Change \(C_1\) and \(C_2\)

DUT AD8571

LF356

Frequency Characteristics Measurement Circuit
Result \((C_1=0.1\mu F, C_2=0.1\mu F)\)

Frequency characteristics, transient response of the NULL circuit (SPICE simulation)

Amplifier

Gain = \(20\log_{10}1000 = 60\text{dB}\)

No peak ⇒ Stable

\(60\text{dB}\)

Cutoff frequency \(f_c \approx 30\text{Hz}\) ⇒ Slow response

Input frequency (1kHz) -30dB down

Frequency Characteristics when \(C_1=0.1\mu F, C_2=0.1\mu F\)
Result \((C_1=0.1\mu F, C_2=1\text{nF})\)

- \(C_1 \to 0.1\mu F\) (fixed)
- \(C_2 \to\) Small

Slightly faster response

Frequency Characteristics when \(C_1=0.1\mu F, C_2=1\text{nF}\)

Input frequency (1kHz) -40dB down
Result (C₁=1nF, C₂=0.1μF)

C₁ → Small
C₂ → 0.1μF (fixed)

30 times faster than when C₁, C₂=0.1μF (f_c≈30Hz)

Cutoff frequency f_c≈1kHz → Fast response

Optimal value: C₁=1nF, C₂=0.1μF

Input frequency (1kHz) Almost never down

60dB

Frequency Characteristics when C₁=1nF, C₂=0.1μF
Transient characteristics (Sine wave input)(1)

\[ C_1 = 0.1 \mu F, \quad C_2 = 0.1 \mu F \]

Input frequency (1kHz) -30dB down (P.17)
30mV_{P-P} (About 1/30)

Sine wave input (1mV_{P-P}, 1kHz)

Observe output waveform \( V_{out} \)
Transient characteristics (Sine wave input)(2)

$C_1 = 0.1 \mu F, \ C_2 = 1 nF$

$10 mV_{P-P} \neq \times 1,000$

$C_1 = 1 nF, \ C_2 = 0.1 \mu F$ (Optimal value)

$700 mV_{P-P}$ approaches to $\times 1,000$
Transient characteristics (Square wave input) (1)

$C_1 = 0.1 \mu F$, $C_2 = 0.1 \mu F$

50mV_{P-P} \neq 1000$

Square wave input (1mV_{P-P}, 1kHz)

Observe output waveform $V_{out}$
Transient characteristics (Square wave input)(2)

$C_1 = 0.1\mu F, C_2 = 1nF$

$17mV_{P-P} \neq \times 1,000$

$C_1 = 1nF, C_2 = 0.1\mu F$ (Optimal value)

$950mV_{P-P}$ approaches to $\times 1,000$
Outline

- Research Background
- Basic Operational Amplifier Measurement Circuit
- NULL Method Prototype Circuit
- SPICE Simulation Verification
  - Frequency Characteristics
  - Operational Amplifier Offset Voltage Measurement
  - Open Loop Gain ($A_{OL}$)
  - Common-Mode Rejection Ratio (CMRR)
  - Power Supply Rejection Ratio (PSRR)
- Conclusion
Offset Voltage Measurement Circuit

Ideal $V_{in+} = V_{in-}$

In practice $V_{in+} \neq V_{in-}$

Measure input-referred offset voltage

Square wave input (1μV_{P-P}, 1Hz)

Equivalently Apply DC Offset Voltage

Equivalently Apply DC Offset Voltage
Transfer function

\[
\begin{align*}
I_1 &= \frac{V_{in}}{R_1} \\
I_2 &= \left(\frac{1}{R_2} + \frac{1}{1/j \omega C}\right) (V_{in} - V_{out}) \\
&= \frac{1 + j \omega CR_2}{R_2} (V_{in} - V_{out}) \\
I_1 &= -I_2
\end{align*}
\]

\[
\left| \frac{V_{out}}{V_{in}} \right| = \frac{R_2}{\sqrt{R_1^2 + (\omega CR_1 R_2)^2}} + 1
\]

At \( R_1 = 50 \Omega, \ R_2 = 50k \Omega, \ C = 0.1 \mu F, \ f = 1Hz \)

\[
\left| \frac{V_{out}}{V_{in}} \right| = 1,000.5068 \ldots \approx 1,000
\]
Offset Voltage Measurement Result

$V_{out} = 1\text{mV}_{p-p}$

Minute error $\rightarrow$ $\times 1,000$

Easy Measurement
Outline

• Research Background
• Basic Operational Amplifier Measurement Circuit
• NULL Method Prototype Circuit
• SPICE Simulation Verification
  ➢ Frequency Characteristics
  ➢ Operational Amplifier Offset Voltage Measurement
  ➢ Open Loop Gain ($A_{OL}$)
  ➢ Common-Mode Rejection Ratio (CMRR)
  ➢ Power Supply Rejection Ratio (PSRR)
• Conclusion
Open Loop Gain ($A_{OL}$) (1)

**Square wave input ($1V_{P-P}, 1Hz$)**

**Open Loop Gain Simulation Result**

<table>
<thead>
<tr>
<th>$R_L$</th>
<th>$A_{OL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2k</td>
<td>122dB</td>
</tr>
<tr>
<td>10k</td>
<td>136dB</td>
</tr>
<tr>
<td>100k</td>
<td>154dB</td>
</tr>
</tbody>
</table>

$R_L \rightarrow$ Large $\Rightarrow A_{OL} \rightarrow$ High

**Open Loop Gain Measurement Circuit**

![Circuit diagram with measurements](image)
Open Loop Gain \((A_{OL})\) (2)

- **Settling time** → 200ms
- **Settling time** → 30ms
- **Settling time** → 1/10

### Graph Details

- **C_1 = 1\, \text{nF}, \; C_2\text{ is varied}**
  - **Unstable**
  - **Stable**
  - **C_2 = 1\, \text{nF}**
  - **C_2 = 0.1\, \text{uF}**
  - **C_2 = 0.01\, \text{uF}**

- **C_1 = 0.1\, \text{\mu F}, \; C_2\text{ is varied}**
  - **V_{out} = 160\, \text{uVp-p}**

- **Settling time** → 1/10
Outline

- Research Background
- Basic Operational Amplifier Measurement Circuit
- NULL Method Prototype Circuit
- SPICE Simulation Verification
  - Frequency Characteristics
  - Operational Amplifier Offset Voltage Measurement
  - Open Loop Gain ($A_{OL}$)
  - Common-Mode Rejection Ratio (CMRR)
  - Power Supply Rejection Ratio (PSRR)
- Conclusion
Shift power supply voltages
Find CMRR equivalently
\[ V_P \rightarrow +2.5V \rightarrow +3.0V \]
\[ V_N \rightarrow -2.5V \rightarrow -2.0V \]

**CMRR Simulation Result**

<table>
<thead>
<tr>
<th>( R_L )</th>
<th>CMRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2k</td>
<td>126dB</td>
</tr>
<tr>
<td>10k</td>
<td>126dB</td>
</tr>
<tr>
<td>100k</td>
<td>126dB</td>
</tr>
</tbody>
</table>

**CMRR Measurement Circuit**

Not affected by \( R_L \)

**Graph**

\[ V_{P}=+2.5V \]
\[ V_{N}=-2.5V \]

\[ V_{P}=+3.0V \]
\[ V_{N}=-2.0V \]
$R_L \rightarrow 10k\Omega, C_1 \rightarrow 1nF$

$C_2 \rightarrow \text{Large}$

**CMRR → Fast response**
Outline

• Research Background
• Basic Operational Amplifier Measurement Circuit
• NULL Method Prototype Circuit
• SPICE Simulation Verification
  ➢ Frequency Characteristics
  ➢ Operational Amplifier Offset Voltage Measurement
  ➢ Open Loop Gain ($A_{OL}$)
  ➢ Common-Mode Rejection Ratio (CMRR)
  ➢ Power Supply Rejection Ratio (PSRR)
• Conclusion
Same configuration as CMRR

\[ V_P \rightarrow +2.0V \quad \rightarrow +2.5V \]
\[ V_N \rightarrow -2.0V \quad \rightarrow -2.5V \]

PSRR Simulation Result

<table>
<thead>
<tr>
<th>( R_L )</th>
<th>PSRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2k</td>
<td>120dB</td>
</tr>
<tr>
<td>10k</td>
<td>120dB</td>
</tr>
<tr>
<td>100k</td>
<td>120dB</td>
</tr>
</tbody>
</table>

Same as CMRR Measurement Circuit

Not affected by \( R_L \)

Power supply voltage 4V Between \( V_P \) and \( V_N \)

Power supply voltage 5V Between \( V_P \) and \( V_N \)
**PSRR (2)**

- $R_L \rightarrow 10k\Omega$, $C_1 \rightarrow 1nF$
- $C_2 \rightarrow \text{Large}$
- PSRR $\rightarrow$ Fast response (Same as CMRR)

---

**Graph:**

- $C_2=0.1\mu F$
- $0.01\mu F$
- 1nF

**Simulation Result:**

- $V_{out}$: 964uVp-p

---

**Diagram:**

- Circuit diagram with $R_L$, $C_1$, $C_2$, and other components.
- DUT AD8571, LF356.
Outline

• Research Background
• Basic Operational Amplifier Measurement Circuit
• NULL Method Prototype Circuit
• SPICE Simulation Verification
  ➢ Frequency Characteristics
  ➢ Operational Amplifier Offset Voltage Measurement
  ➢ Open Loop Gain ($A_{OL}$)
  ➢ Common-Mode Rejection Ratio (CMRR)
  ➢ Power Supply Rejection Ratio (PSRR)
• Conclusion
Conclusion

- Optimization of phase compensation constants
  \[ C_1 = 1 \text{ nF}, \; C_2 = 0.1 \mu\text{F} \]

  NULL Circuit → Fast and Stable

- NULL Circuit: Change of signal application point depending on the measurement item

  Signal input change (\(C_1, C_2\) : Fixed)

  Different response characteristics of each input / output

- Switching \(C_1\) and \(C_2\) depending on the measurement item

  Settling time reduction → \(\approx 1/10\)
Q. 補助オペアンプに印加する電源電圧(+15V, -15V)にばらつきがある場合はどうなるか？DUTに印加する電源電圧(+2.5V, -2.5V)を補助オペアンプと同じ(+15V, -15V)にしたらどうなるか？

A. まだ検証していないので、今後の課題とさせていただきます。

Q. PSRRの$V_P$, $V_N$の値は？

A. $V_P$ ... +2.0V → +2.5V
$V_N$ ... -2.0V → -2.5V

Q. CMRR, PSRRが$R_L$の影響によらない原因は？

A. NULL回路での負帰還影響によるものと推測します。