Simulation Evaluation of Null Method for Operational Amplifier Testing

Riho Aoki, S. Katayama, Y. Sasaki, K. Machida, T. Nakatani, J. Wang, A. Kuwana, K. Hatayama, H. Kobayashi
K. Sato, T. Ishida, T. Okamoto, T. Ichikawa

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

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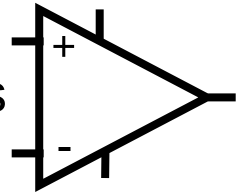
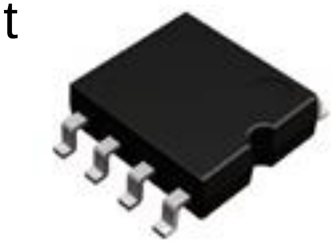
What is Operational Amplifier ?

Operational Amplifier

Differential inputs



Single-ended output



Extremely high gain

Past

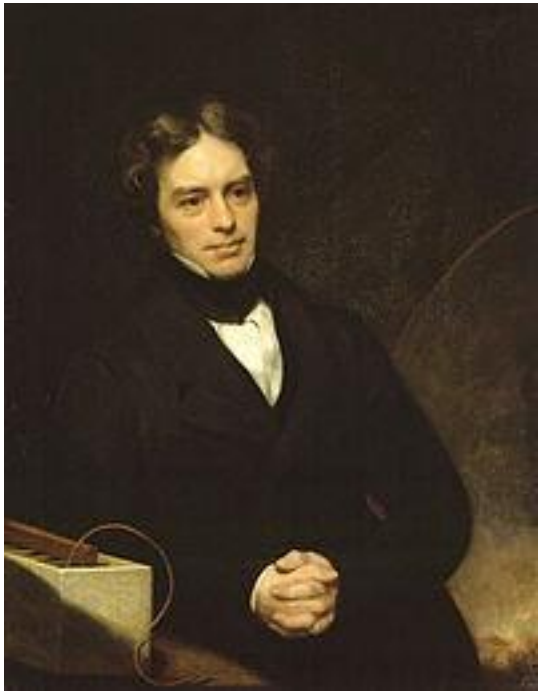
Analog computers

Present

Sensor・Interface analog circuit

Spread of IoT (Internet of Things) technology

Faraday's Experiment

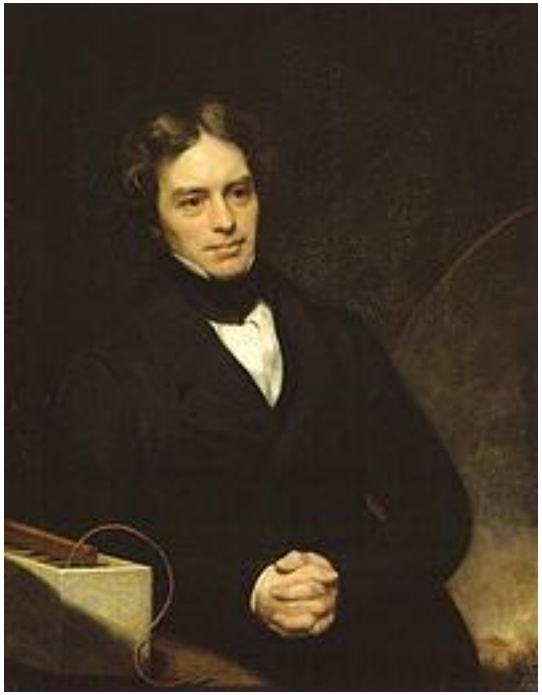


Michael Faraday
(1791 ~ 1867)
British chemist / physicist

Flow velocity measurement
on the principle of electromagnetic flowmeter

River Thames

Faraday's Experiment



Michael Faraday
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British chemist / physicist

Flow velocity measurement
on the principle of electromagnetic flowmeter

River Thames

Reason

No electronic circuit for amplification
of the detected weak electrical signal

Importance of
analog signal conditioning circuits
such as operational amplifier

Research Objective

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

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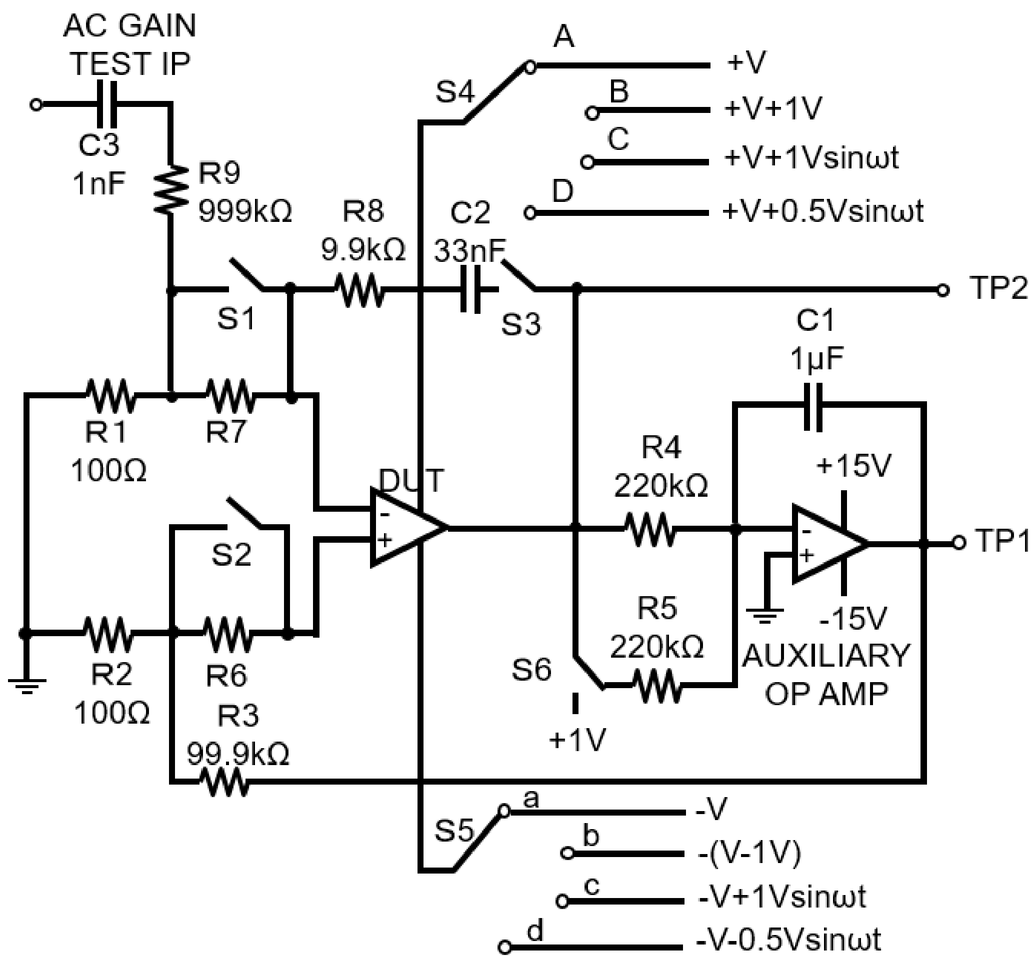
Basic Measurement Circuit



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

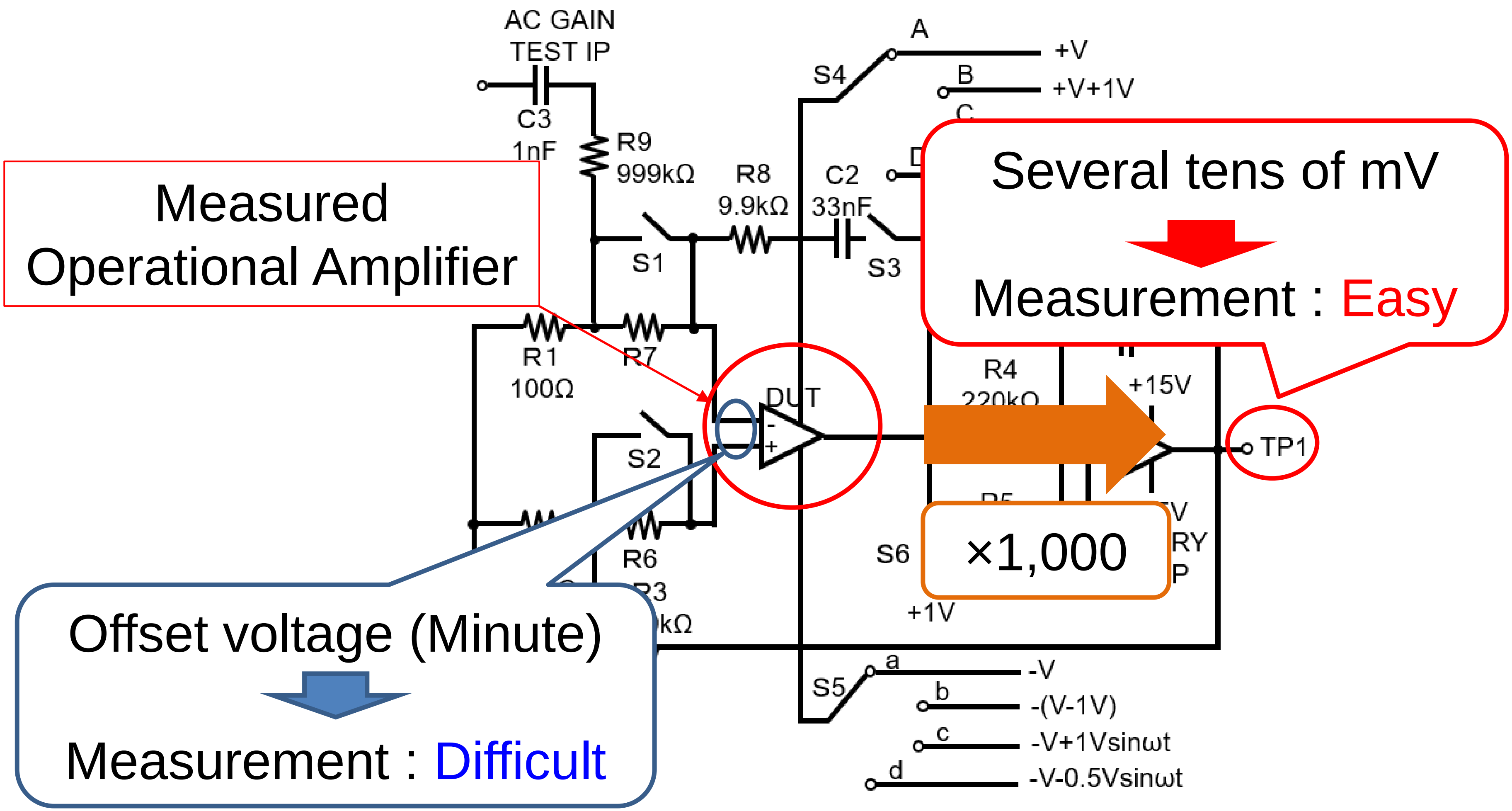
Source：Analog Dialogue Vol 45 Apr.2011 Analog Devices

Operational Amplifier Measurement Items

Switch States and Operational Amplifier Measurement Items

Parameter	S1	S2	S3	S4	S5	S6
Offset	short	short	open	A	a	open
Offset and bias current	short/open	short/open	open	A	a	open
DC gain	short	short	open	A	a	open/short
AC gain	short	short	open	A	a	open
DC CMRR	short	short	open	A/B	a/b	open
DC PSRR	short	short	open	A/B	a/b	open
AC CMRR	short	short	short	C	c	open
AC PSRR	short	short	short	D	d	open

Operational Amplifier Measurement Circuit using NULL Method



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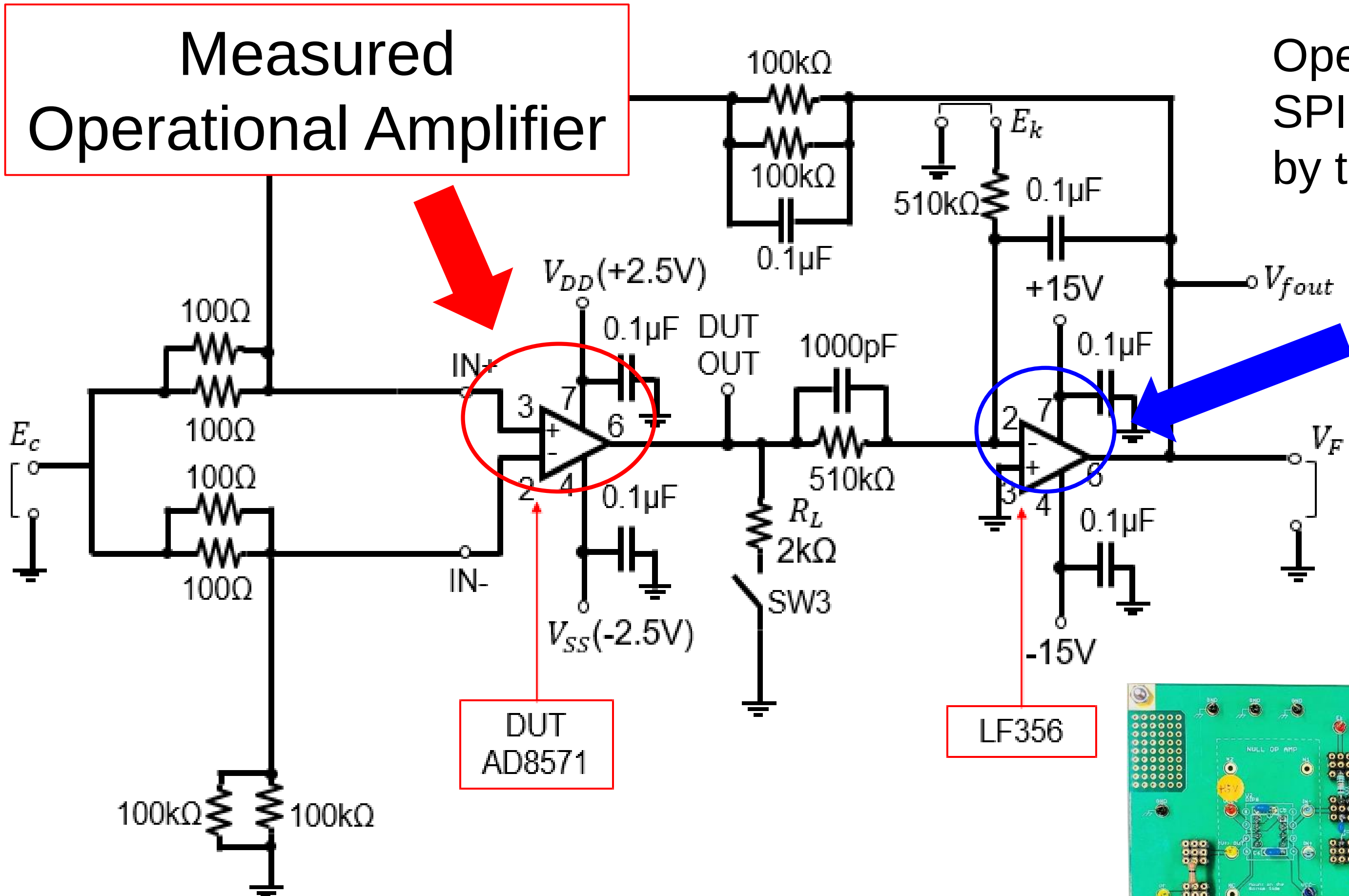
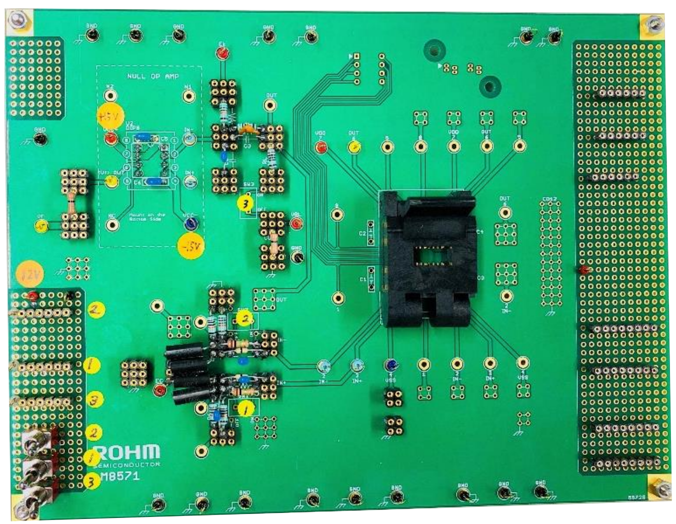
NULL Method Prototype Circuit

Operational Amplifier: SPICE model provided by the manufacturer





Experimental Circuit using the NULL Method

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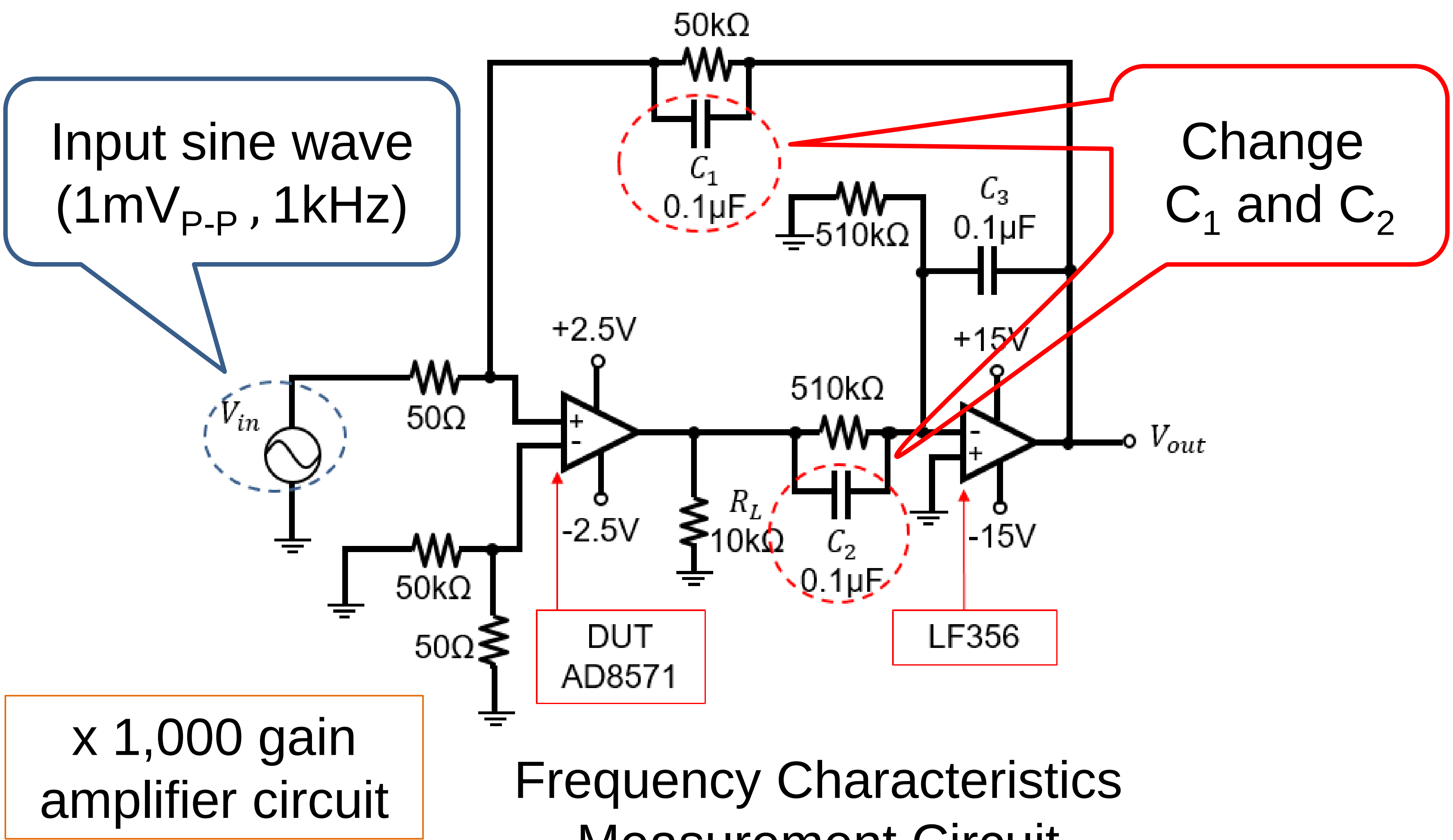
Frequency Characteristics



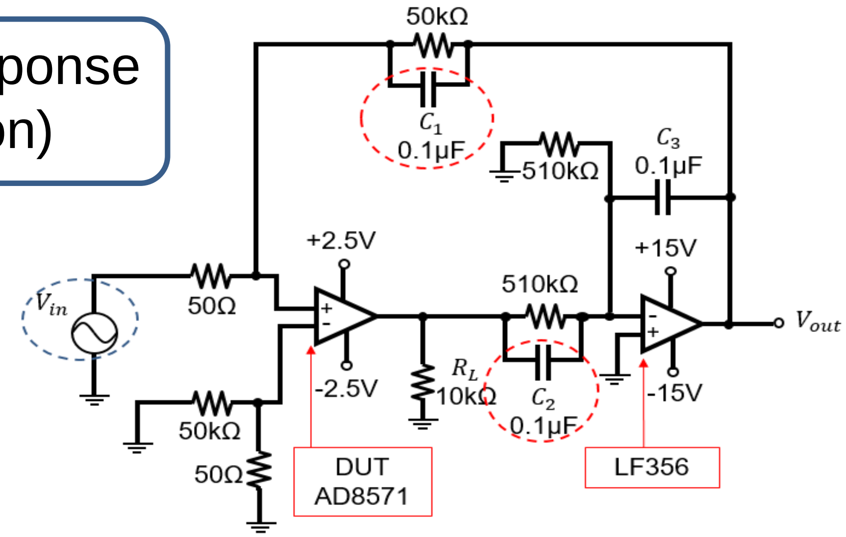
Frequency Characteristics
Measurement Circuit

Result (C_1=0.1μF, C_2=0.1μF)

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

Amplifier

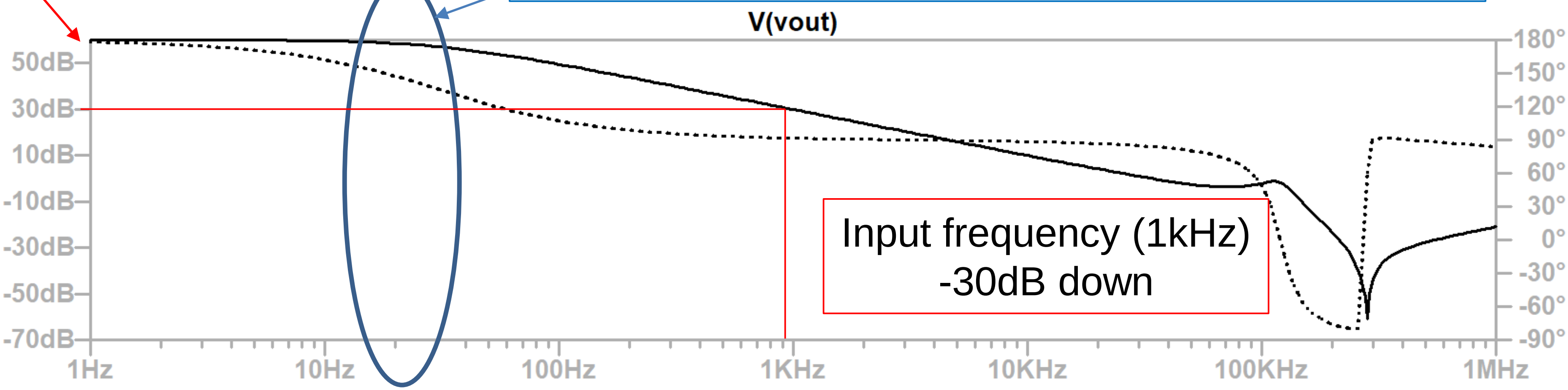
Gain＝20log1000=60dB



No peak ⇒ Stable

60dB

Cutoff frequency f_c≅30Hz ⇒ Slow response

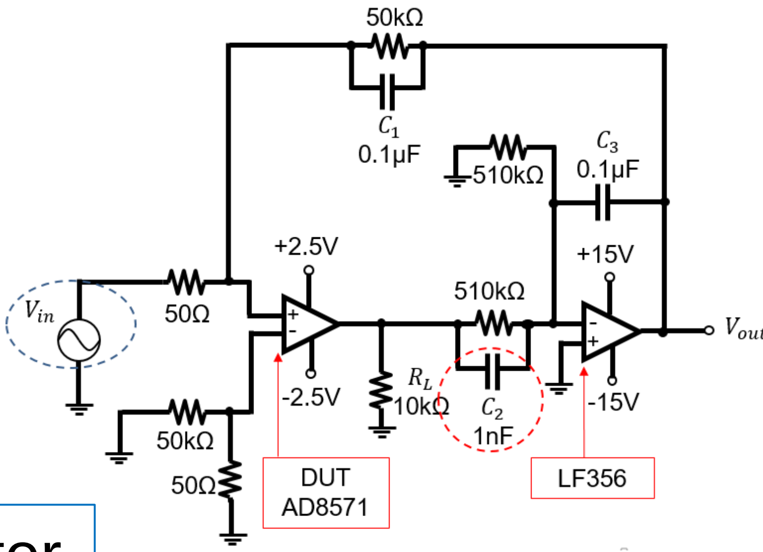


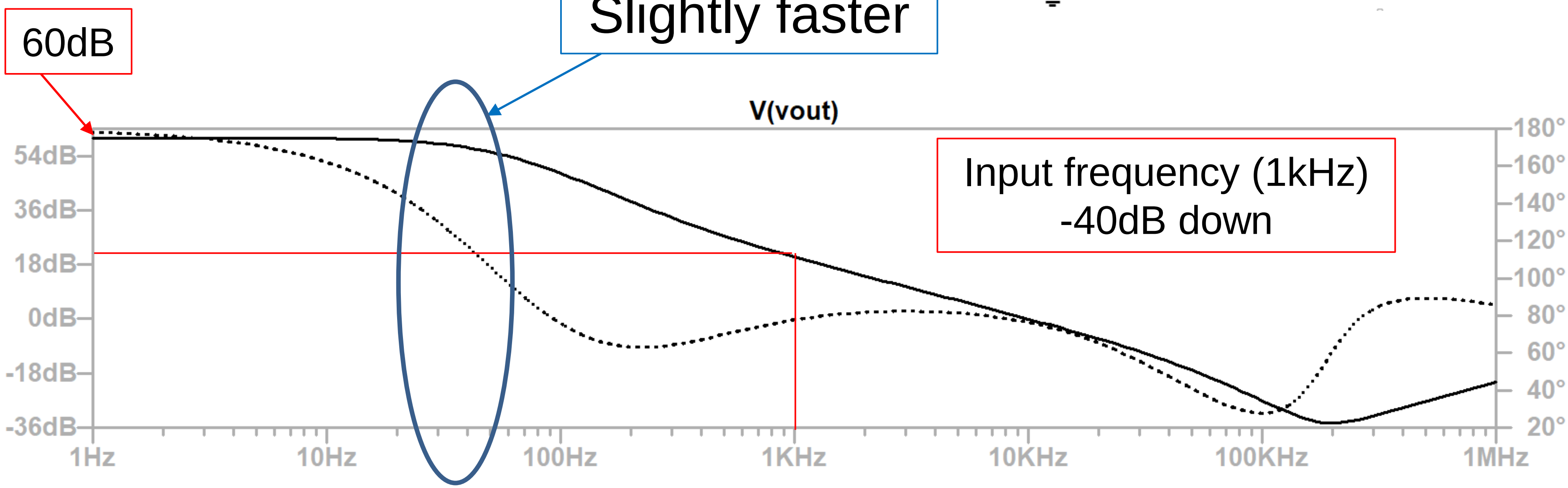
Frequency Characteristics when C_1=0.1μF, C_2=0.1μF

Result (C_1=0.1μF, C_2=1nF)

C_1 → 0.1μF (fixed)
C_2 → Small

Slightly faster response





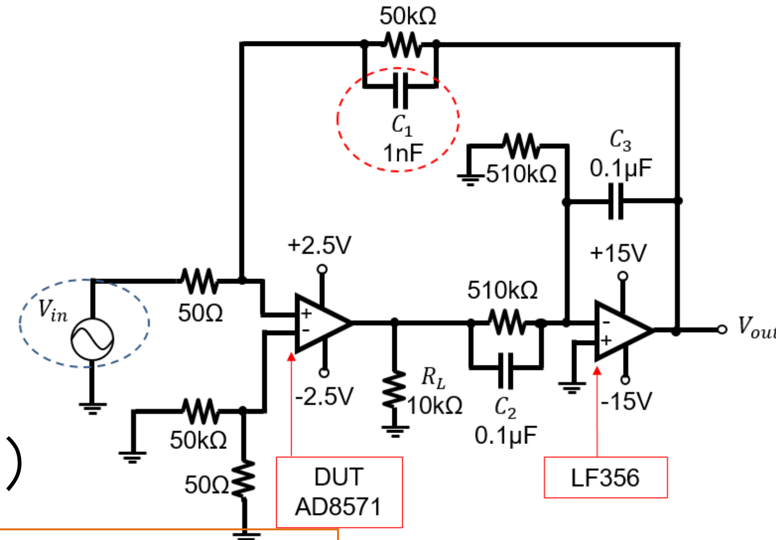
Frequency Characteristics when C_1=0.1μF, C_2=1nF

Result (C_1=1nF, C_2=0.1μF)

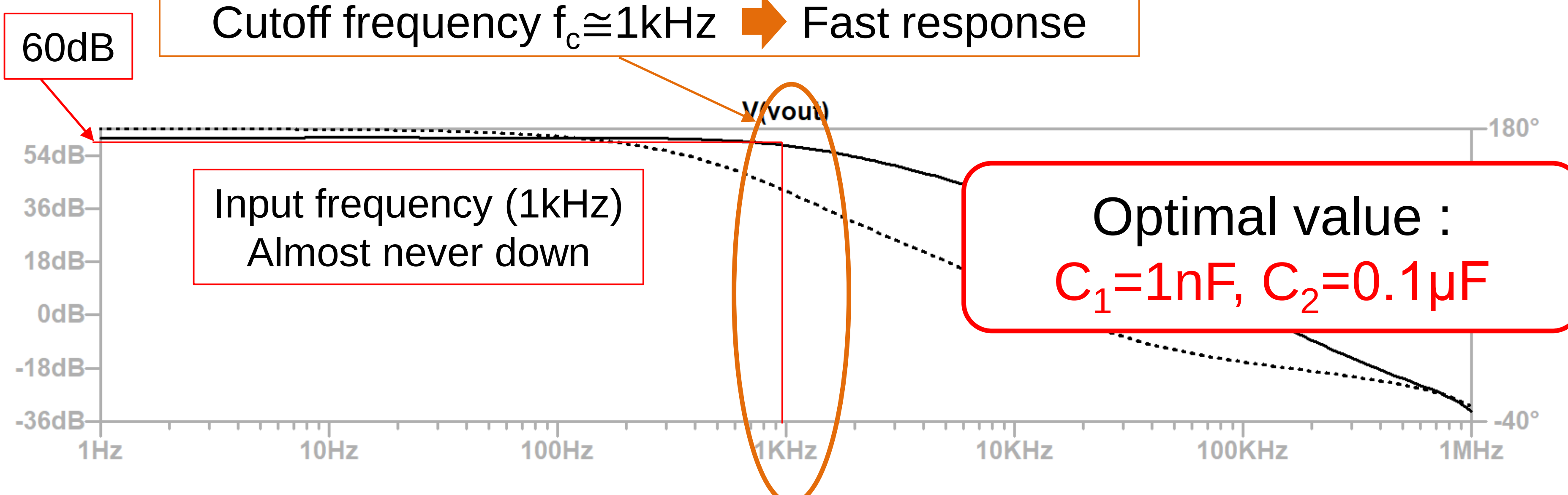
C_1 → Small
C_2 → 0.1μF (fixed)

30 times faster

than when C_1, C_2=0.1μF（f_c≅30Hz）



Cutoff frequency f_c≅1kHz → Fast response



Optimal value :
C_1=1nF, C_2=0.1μF

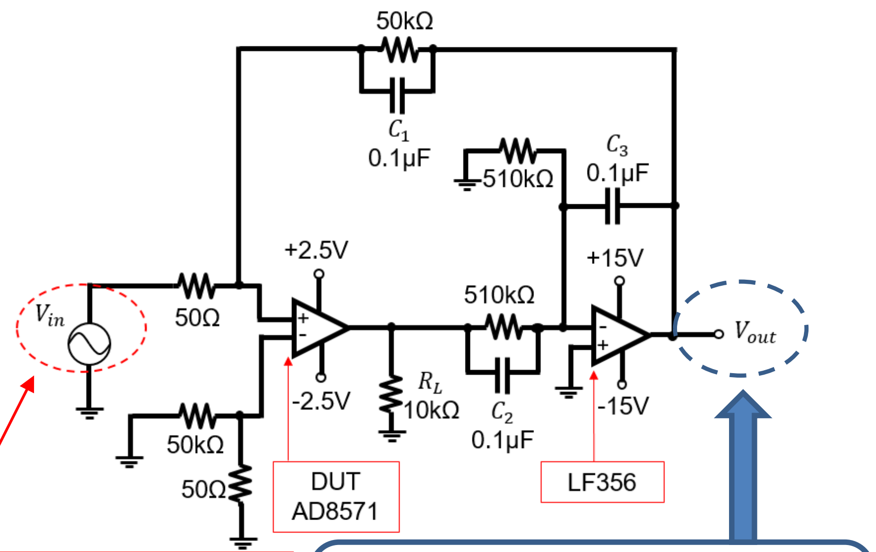
Frequency Characteristics when C_1=1nF, C_2=0.1μF

Transient characteristics (Sine wave input)(1)

C_1=0.1μF, C_2=0.1μF

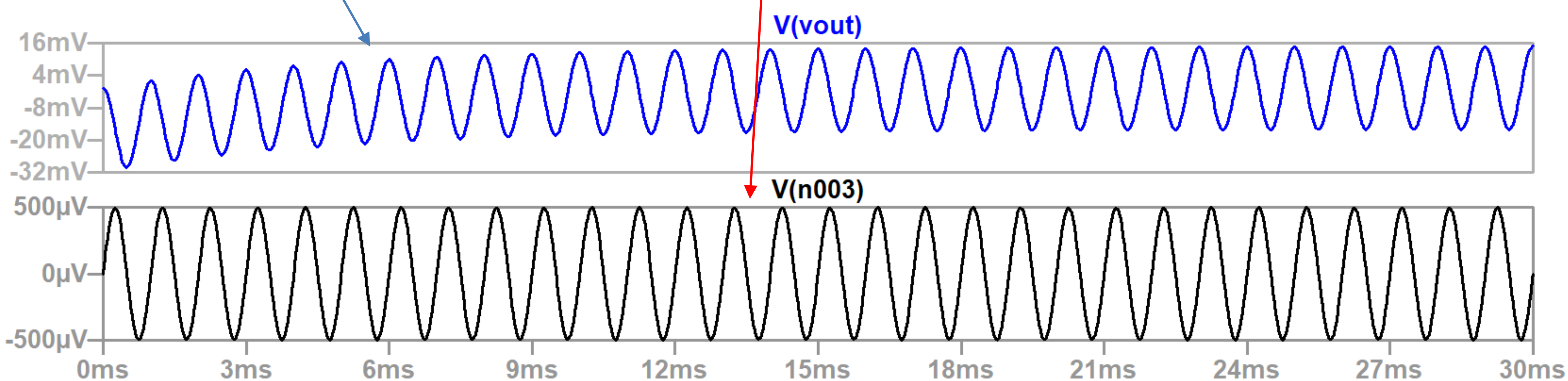
Input frequency (1kHz)
-30dB down (P.17)

$30mV_{P\text{-}P}$ (About 1/30)



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

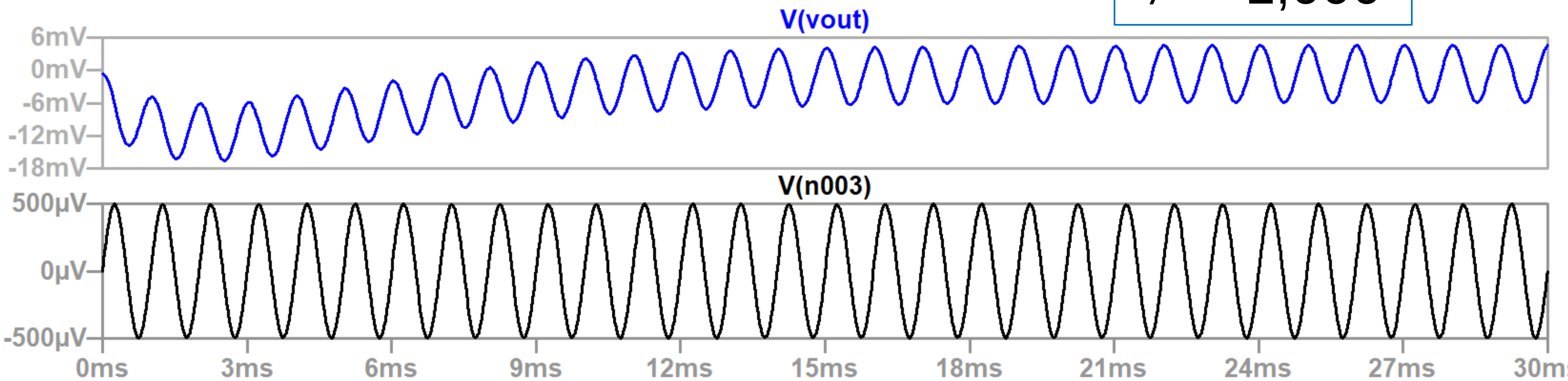
Observe
output waveform V_{out}



Transient characteristics (Sine wave input)(2)

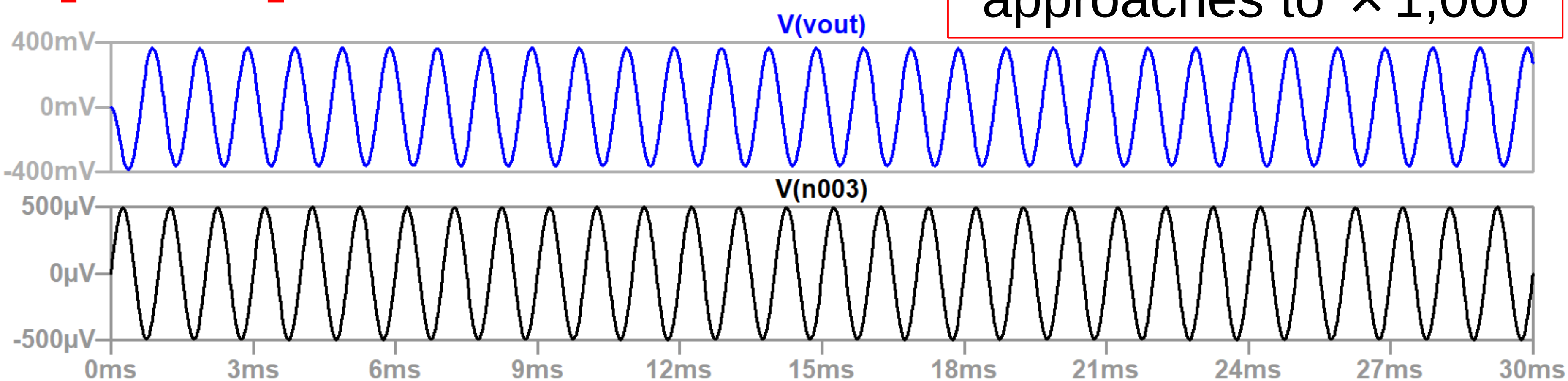
C_1=0.1μF, C_2=1nF

$10mV_{P-P}$
≠ ×1,000



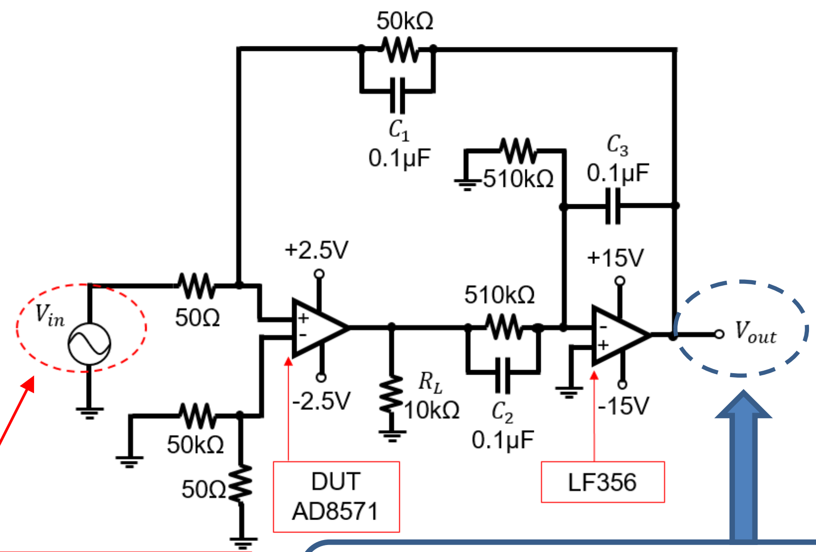
C_1=1nF, C_2=0.1μF (Optimal value)

$700mV_{P-P}$
approaches to ×1,000



Transient characteristics (Square wave input)(1)

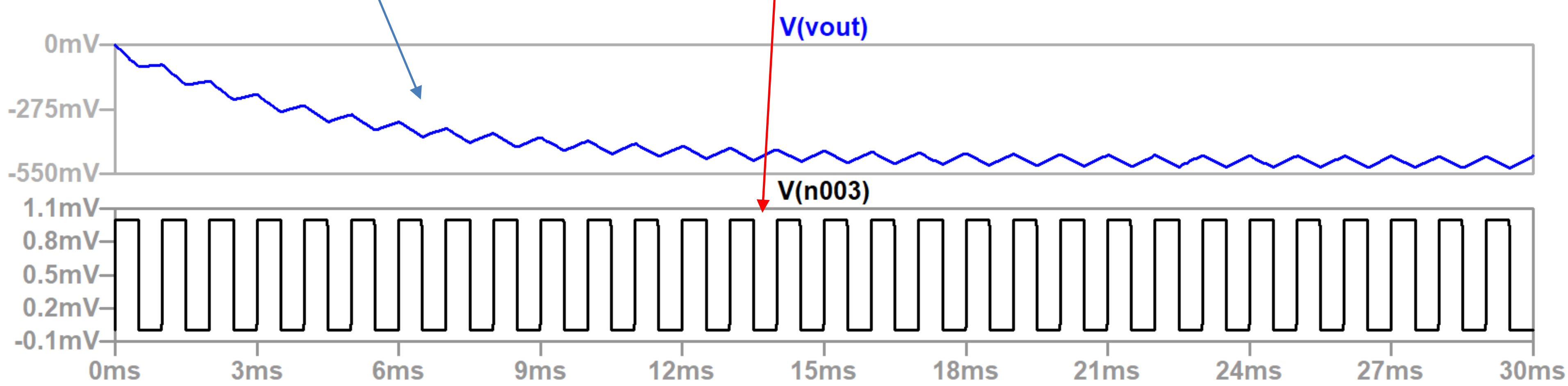
C_1=0.1μF, C_2=0.1μF



50mV$_{P-P}$
≠ ×1,000

Square wave input
(1mV$_{P-P}$, 1kHz)

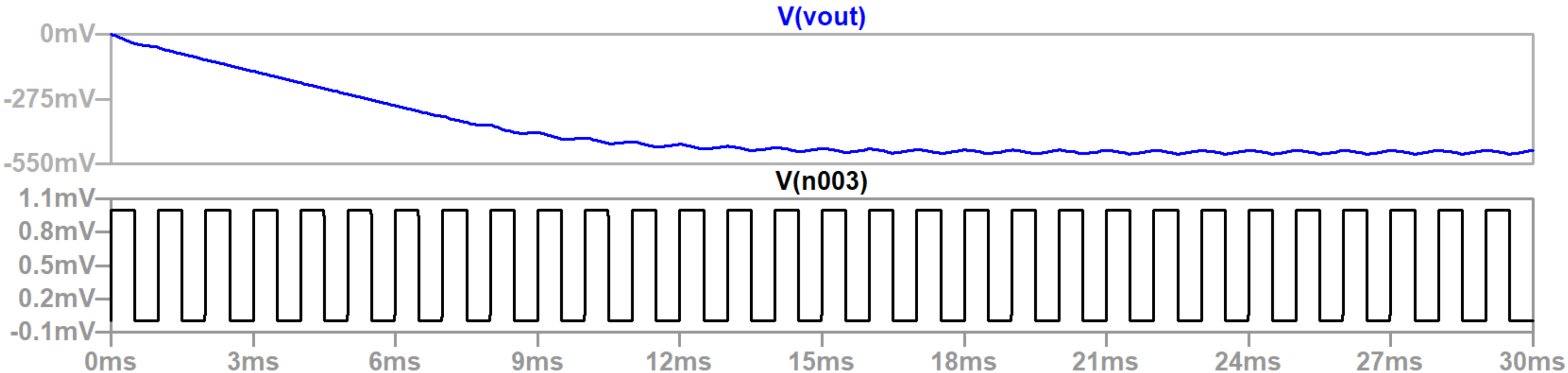
Observe
output waveform V_{out}



Transient characteristics (Square wave input)(2)

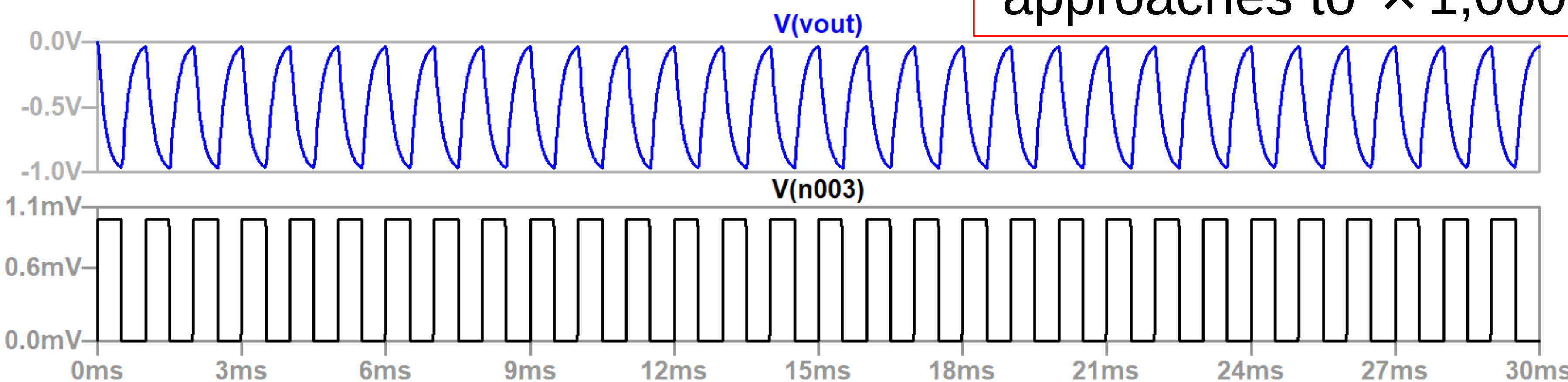
C_1=0.1μF, C_2=1nF

17mV_{P-P}
≠ ×1,000



C_1=1nF, C_2=0.1μF (Optimal value)

950mV_{P-P}
approaches to ×1,000



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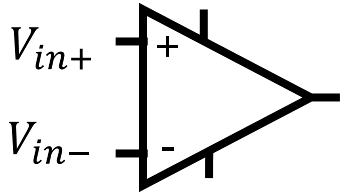
Offset Voltage Measurement Circuit



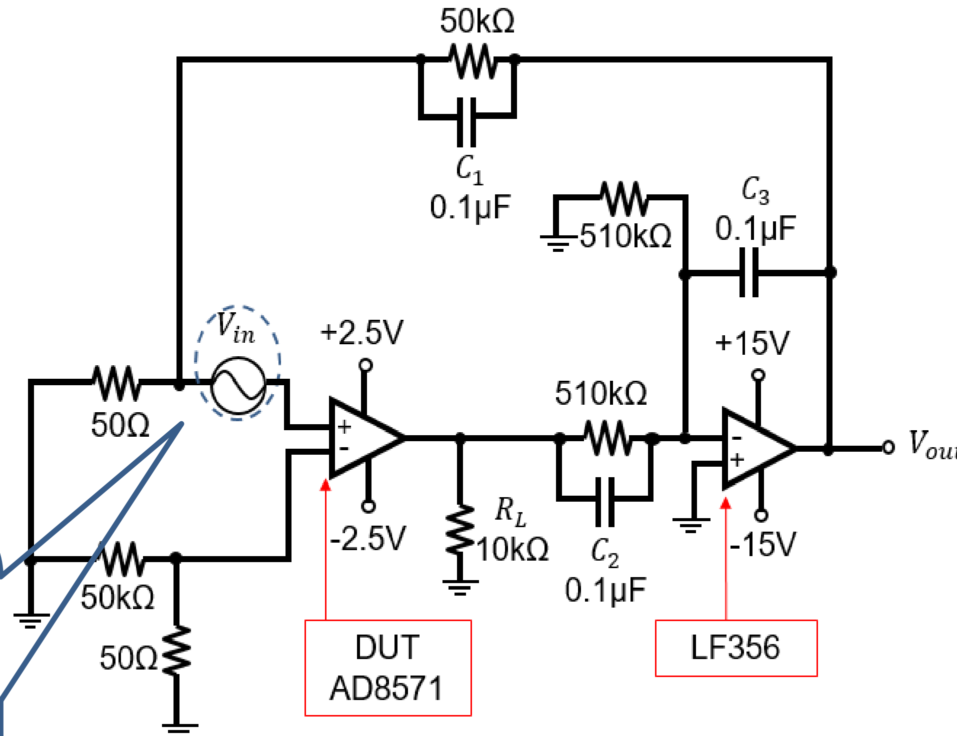
Ideal $V_{in+} = V_{in-}$

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

Measure input-referred offset voltage

Square wave input
($1\mu V_{P\text{-}P}$, 1Hz)

Equivalently
Apply DC Offset Voltage

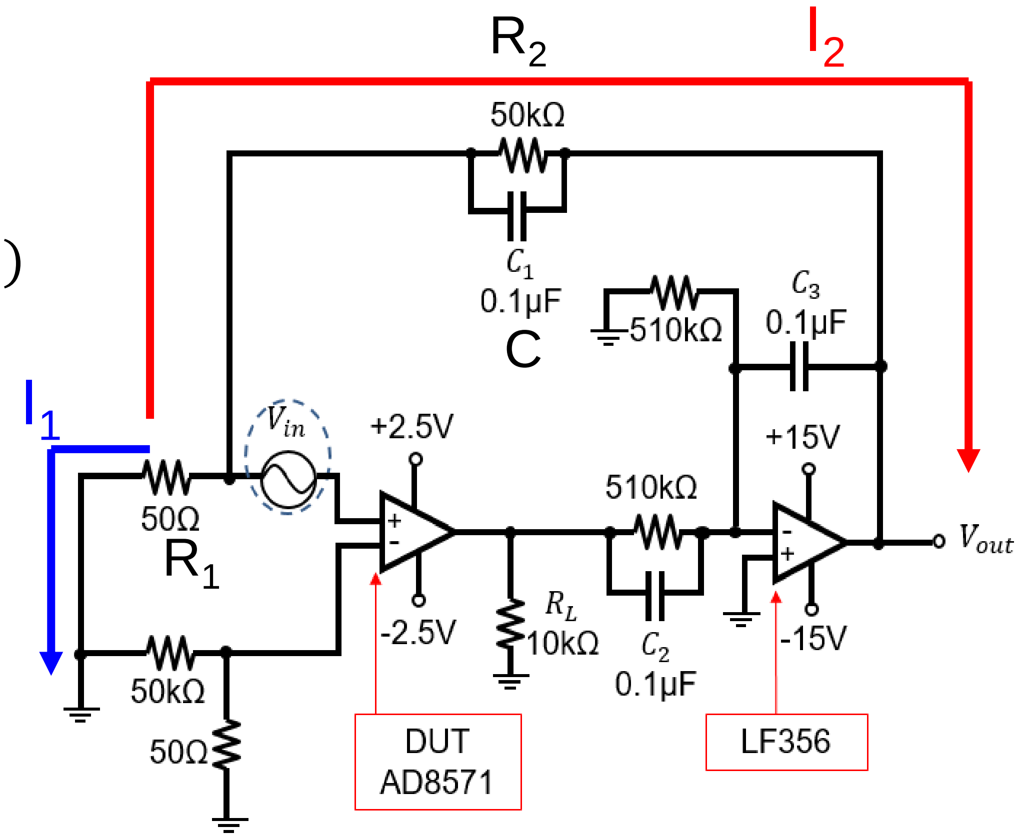


Offset Voltage
Measurement Circuit

Transfer function

$$\begin{cases} I_1 = \dfrac{V_{in}}{R_1} \\ I_2 = \left(\dfrac{1}{R_2} + \dfrac{1}{1/j\omega C}\right)(V_{in} - V_{out}) \\ \quad = \dfrac{1 + j\omega C R_2}{R_2}(V_{in} - V_{out}) \\ I_1 = -I_2 \end{cases}$$

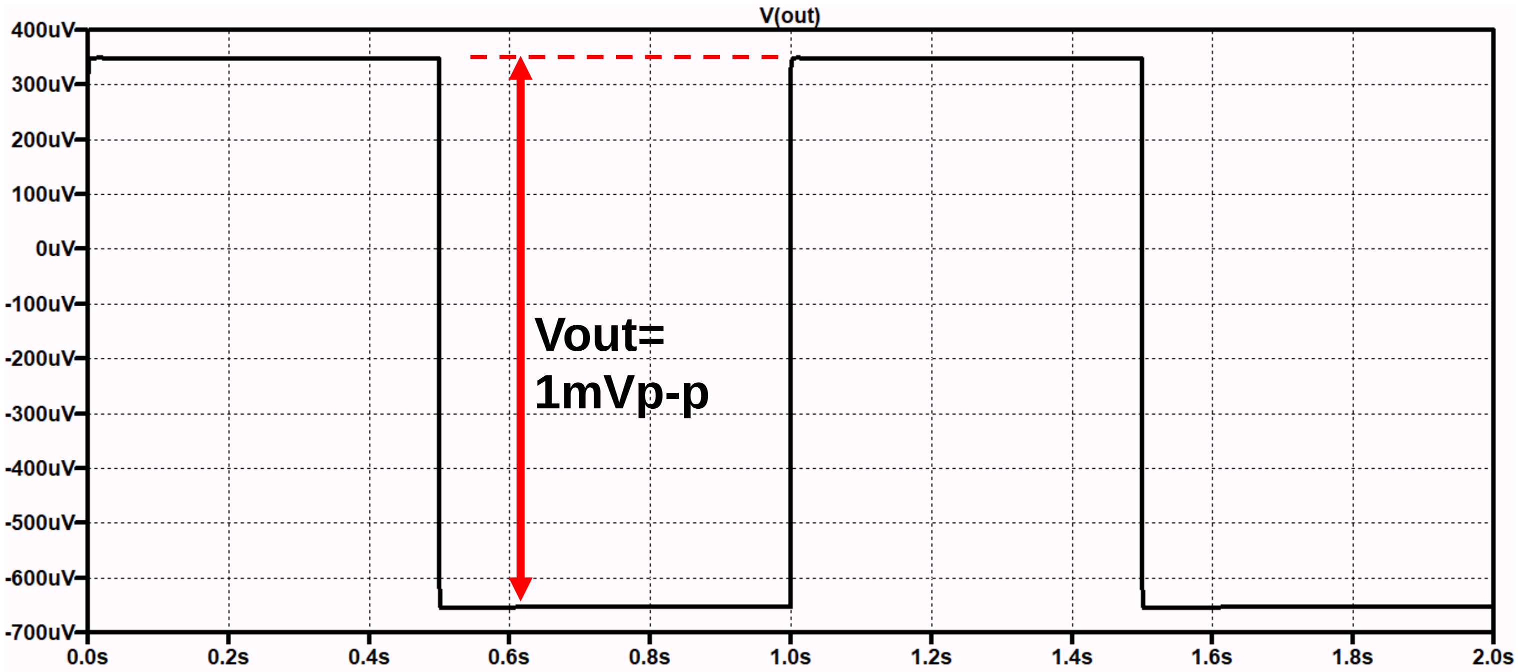
$$\therefore \left|\frac{V_{out}}{V_{in}}\right| = \frac{R_2}{\sqrt{{R_1}^2 + (\omega C R_1 R_2)^2}} + 1$$



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

$$\left|\frac{V_{out}}{V_{in}}\right| = 1{,}000.5068\cdots \cong 1{,}000$$

Offset Voltage Measurement Result



Offset Voltage Measurement Result

$1\mu V_{P\text{-}P}$ → $1mV_{P-P}$

Minute error → x 1,000

→ Easy Measurement

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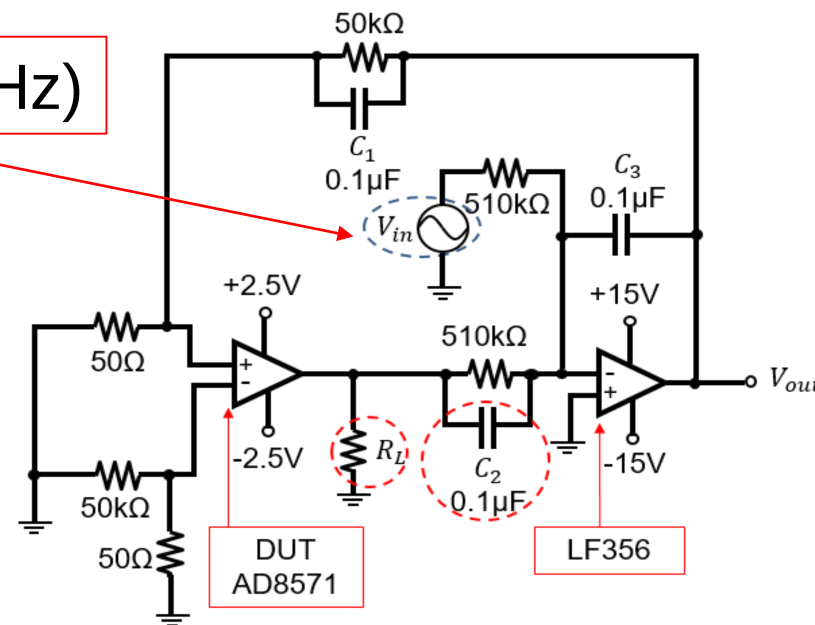
Open Loop Gain (A_{OL}) (1)

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

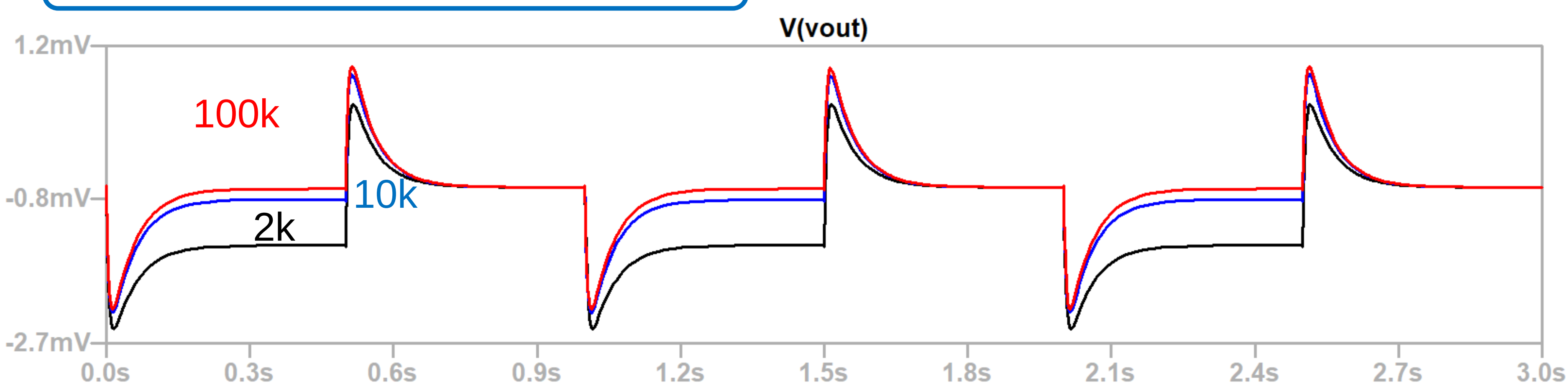


Open Loop Gain Measurement Circuit

Open Loop Gain Simulation Result

R_L	A_{OL}
2k	122dB
10k	136dB
100k	154dB

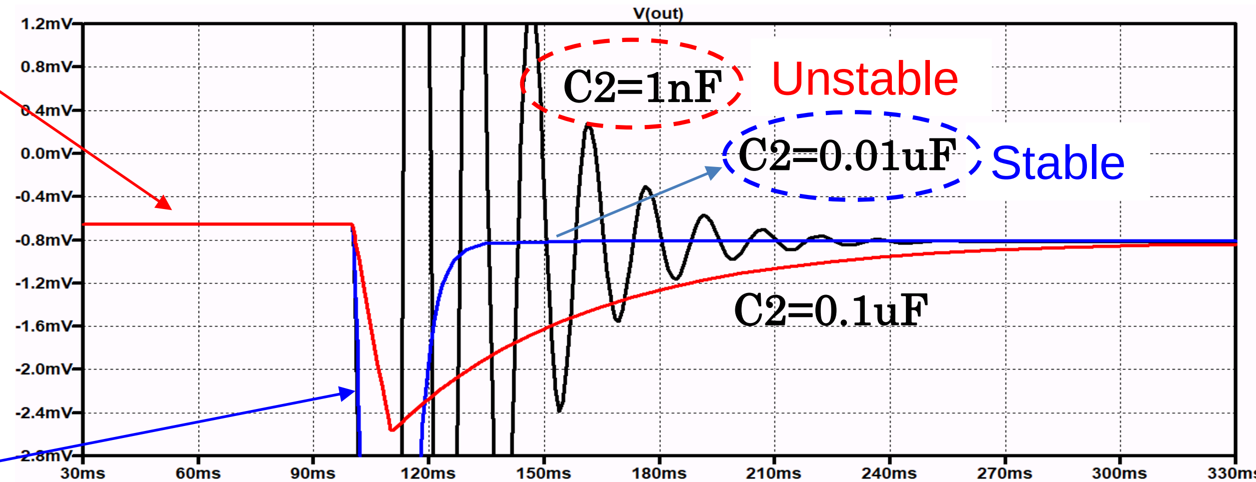
$R_L \rightarrow$ Large ➡ $A_{OL} \rightarrow$ High



Open Loop Gain (A_{OL}) (2)

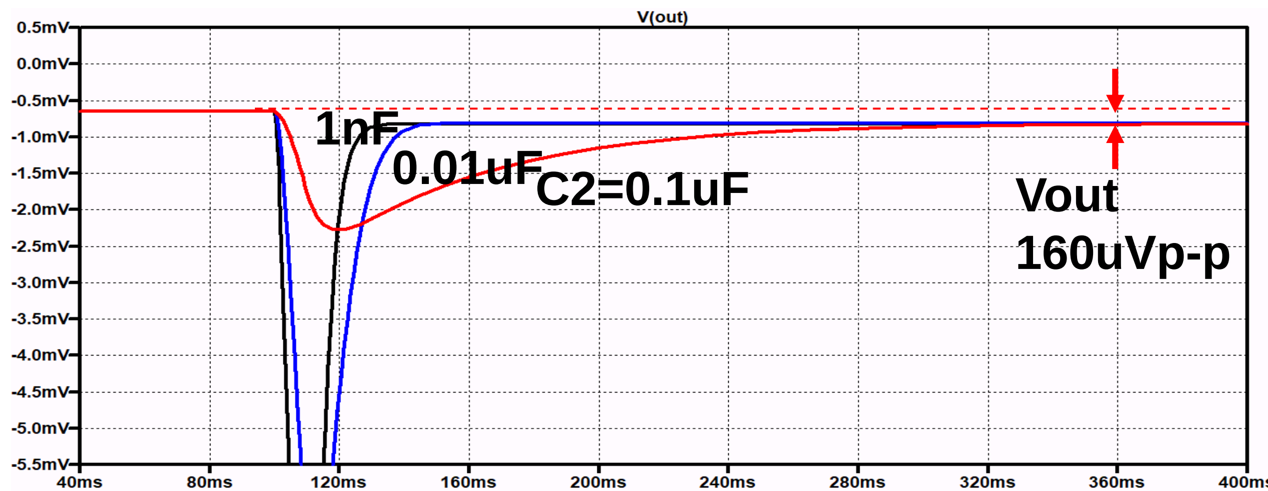
Settling time
→ 200ms

Settling time
→ 30ms



C_1=1nF, C_2 is varied

Settling time
1/10



C_1=0.1μF, C_2 is varied

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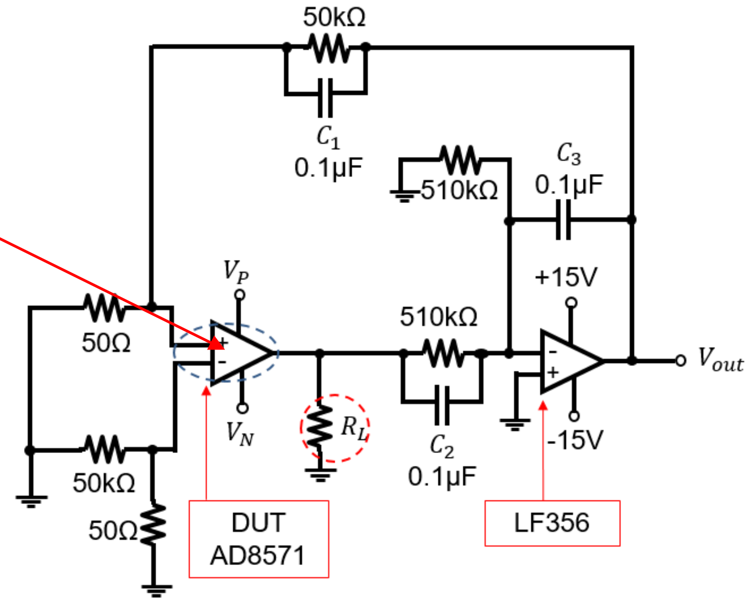
CMRR (1)

Shift power supply voltages
Find CMRR equivalently
V_P ... +2.5V → +3.0V
V_N ... -2.5V → -2.0V

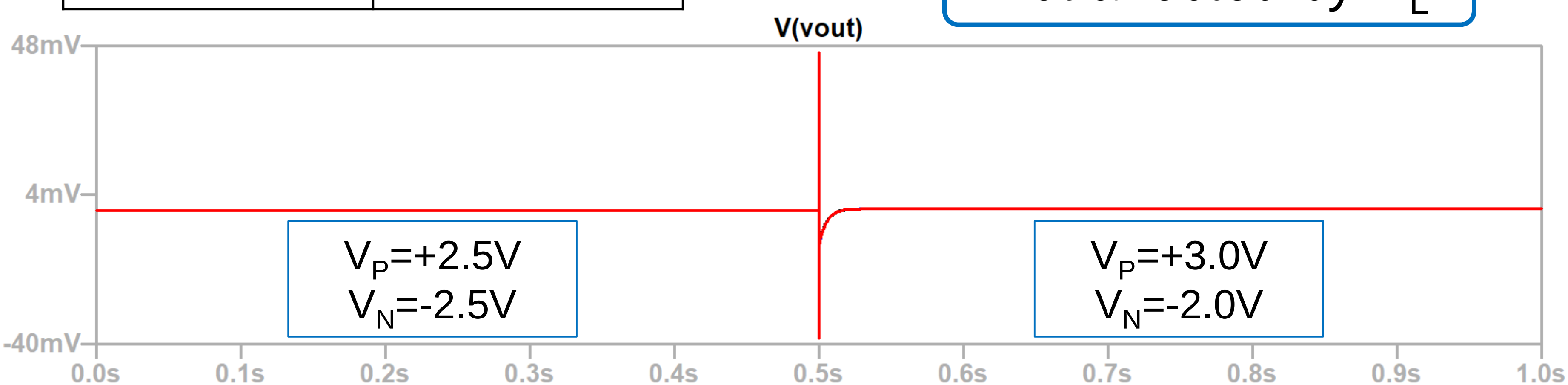


CMRR Measurement Circuit

CMRR Simulation Result

R_L	CMRR
2k	126dB
10k	126dB
100k	126dB

Not affected by R_L

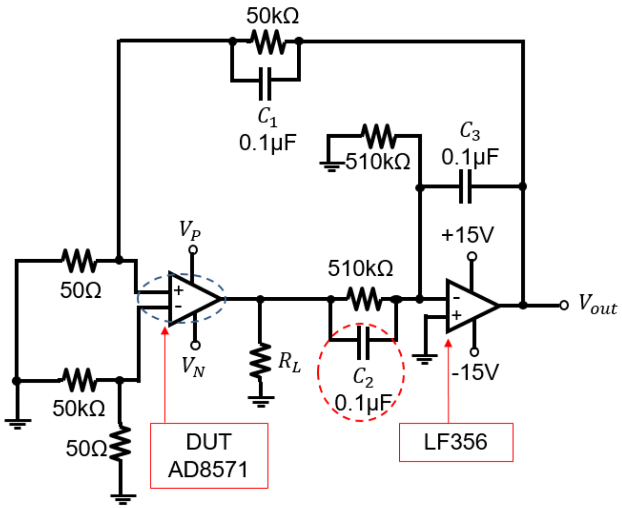


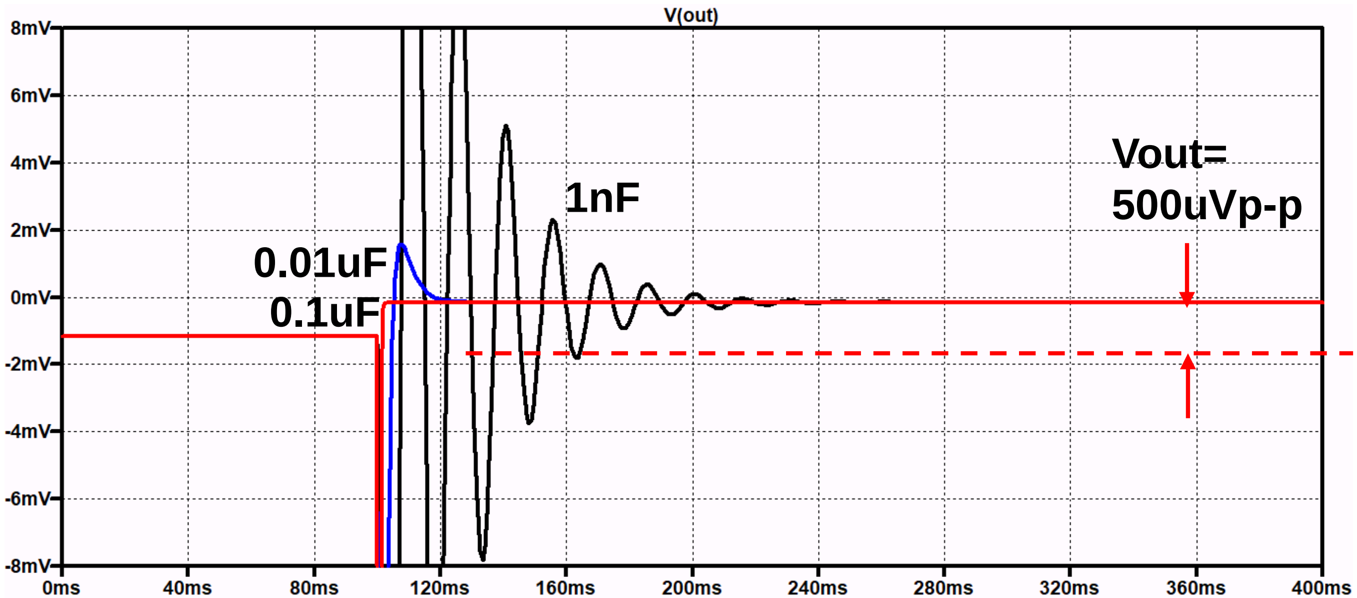
CMRR (2)

$R_L \rightarrow 10k\Omega$, $C_1 \rightarrow 1nF$

$C_2 \rightarrow$ Large

CMRR → Fast response





CMRR Simulation Result when C_1=1nF, C_2 is varied.

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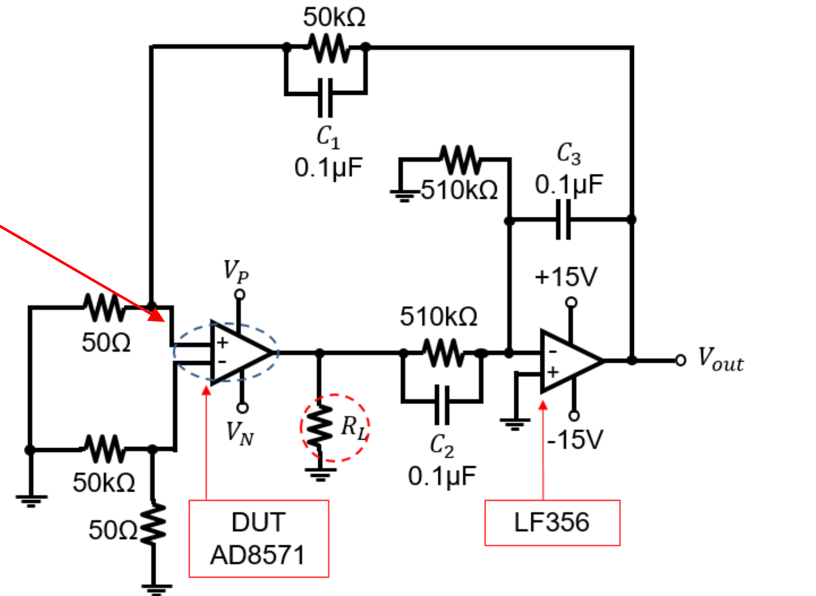
PSRR (1)

Same configuration as CMRR
V_P ... +2.0V → +2.5V
V_N ... -2.0V → -2.5V

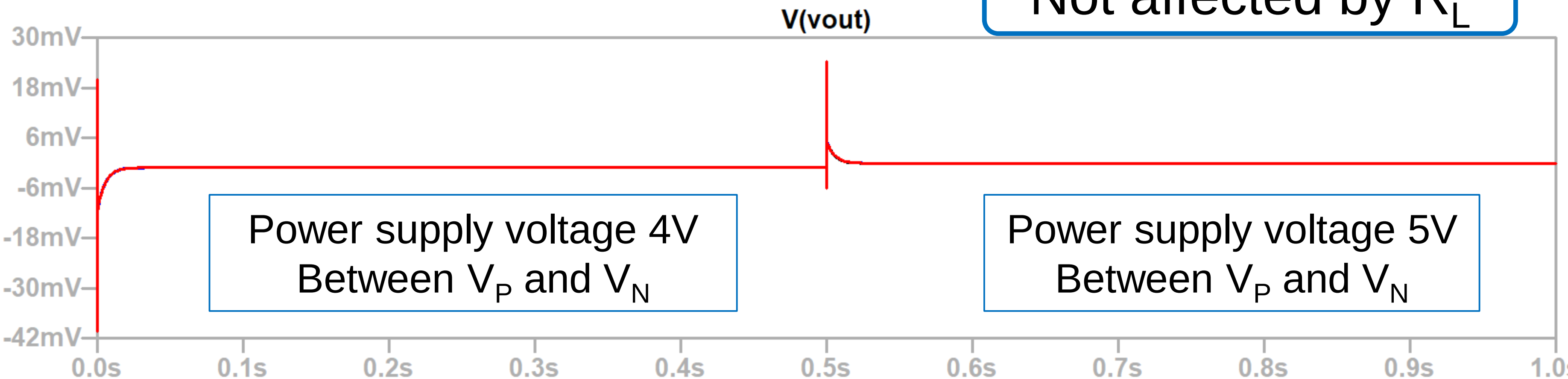
PSRR Simulation Result

R_L	PSRR
2k	120dB
10k	120dB
100k	120dB



Same as CMRR Measurement Circuit

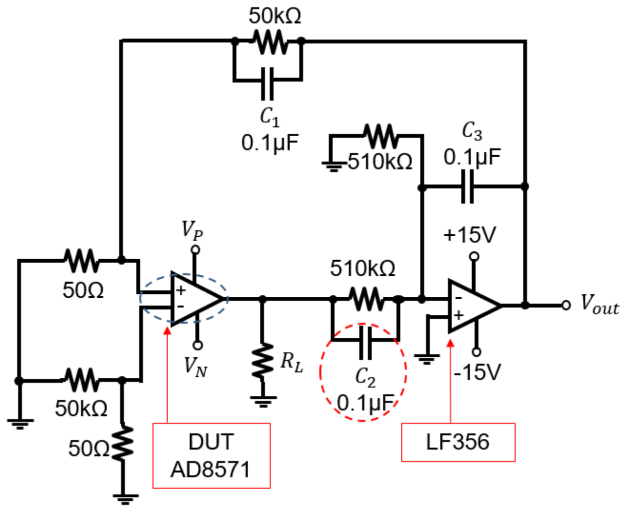
Not affected by R_L

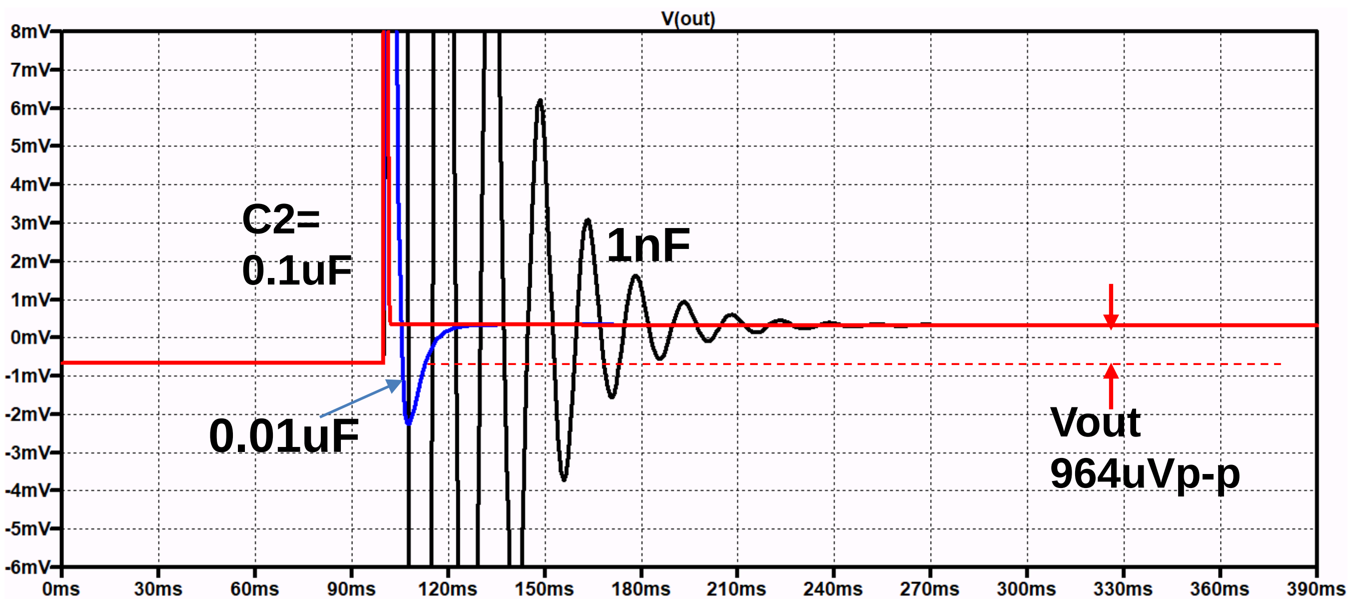


PSRR (2)

$R_L \rightarrow 10k\Omega$, $C_1 \rightarrow 1nF$
$C_2 \rightarrow$ Large

PSRR → Fast response
(Same as CMRR)





PSRR Simulation Result when C_1=1nF, C_2 is varied.

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Conclusion

- Optimization of phase compensation constants

  C_1=1nF, C_2=0.1μF

  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 → ≒ 1/10

Q&A

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。