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Simulation Evaluation of Null Method for Operational Amplifier Testing

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Abstract. This paper investigates the NULL method to apply for the mass production testing of the operational amplifier. The NULL method is widely used to measure the operational amplifier characteristics accurately at the laboratory level, but it takes relatively a long time. Then, we have derived good capacitor values in the NULL method circuit for its fast and stable testing for mass production. We have verified the operation of the NULL method circuit where the amplifier under test itself by SPICE simulation, and examined the proper selection of the compensation capacitor values for fast mass production testing.

1. Introduction

Operational amplifiers have been developed and widely used as important components in sensor interface analog circuits as well as various analog processing circuits. Michael Faraday tried to measure the flow velocity of the River Thames in London, based on the principle of electromagnetic flowmeter. However, at that time, there was no electronic circuit to amplify the detected weak electrical signal, so that it was not possible to put it into practical use. This story gives light on the importance of analog electronic circuits such as operational amplifiers. In recent years, Internet-of-Things (IoT) technology has become widely spread; there, sensors are widely used and operational amplifiers are becoming increasingly important as analog circuits of their interfaces [1-5]. Also low-cost yet highly-reliable IoT systems are demanded, and hence their low-cost and high-quality testing is required.

In this paper, we investigate the feasibility of the NULL method to apply for the mass production testing of the operational amplifier. The NULL method is widely used to measure the operational amplifier characteristics accurately at the laboratory level, but it takes relatively a long time so that it is difficult to use the mass production testing, where short time testing is mandatory for low cost; 1second test time for 1 US dollar is reasonable. Then, we derive good capacitor values in the NULL method circuit for its fast and stable testing, using SPICE simulation; this reduces the measurement time of operational amplifier characteristics significantly.

The operational amplifier has differential inputs with high impedance, a single-ended output with low impedance, and an extremely high gain. Accurate performance measurement is demanded in high precision analog circuits. However, there is a problem that the high open loop gain prevents accurate performance measurement such as the minute voltage error generation at the amplifier input due to the influence of peripheral circuits / environments (noise, thermal electromotive force by Seebeck effect, GND return current). Therefore, we have confirmed the operation of the NULL method circuit [1] using SPICE simulations, where the amplifier under test itself measures by using the servo loop to force the amplifier negative input voltage to zero potential, and discuss the appropriate selection of capacitor values in the NULL circuit method. In addition, we notice that we describe experiments on this NULL method circuit in [6], and also the DC-AC conversion technique that realizes a high accuracy test of a minute offset voltage in a short time using multi-channel measurement in [7].

2. Basic Operational Amplifier Measurement Circuit

The operational amplifier measurement circuit using the NULL method is shown in Fig. 1. The auxiliary operational amplifier is used as an integrator to form a stable loop with extremely high DC open loop gain. By switching the switches S1 to S6 in Fig. 1 as shown in Table 1, various parameters such as offset and bias current can be measured accurately. The offset voltage of the operational amplifier (DUT) to be measured here is equal to the correction voltage applied to the input of the DUT, but it is difficult to measure directly because it is minute (μV-order). However, since the test point voltage (TP1) is output by 1,000 times of the correction voltage applied to the input of the DUT, the accurate measurement becomes easy because the value is several tens of mV or more.

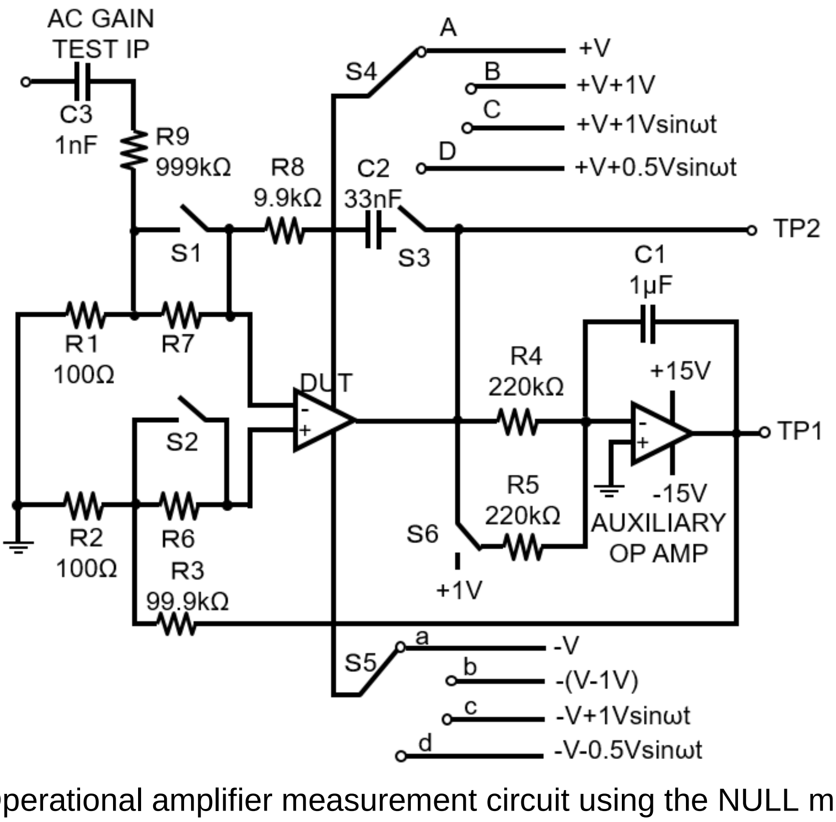


Fig. 1. Operational amplifier measurement circuit using the NULL method.

Table 1. 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

3. NULL Method Prototype Circuit

The NULL method prototype circuit and its photo are shown in Fig. 2 and Fig.3, respectively. The operational amplifier to be measured (DUT) uses the high-precision CMOS operational amplifier (AD8571), and the auxiliary operational amplifier used as an integrator uses the general-purpose FET input operational amplifier (LF356). The parameters in Table 1 are measured using this circuit, and simulation verification is shown when the load resistance and capacitor are varied. The results of measurement experiments are reported in [6].

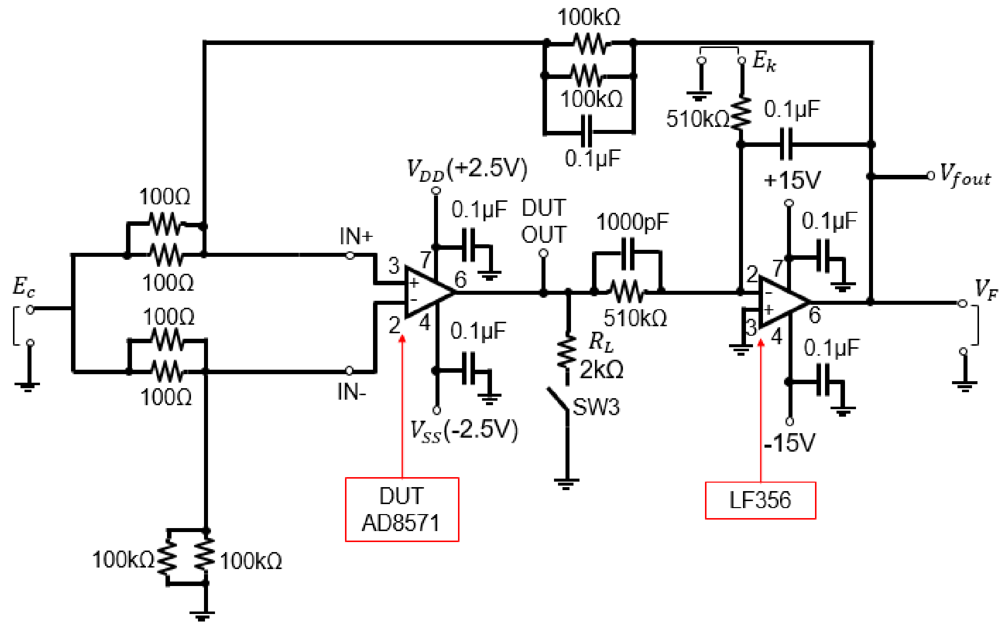


Fig. 2. Experimental circuit using the NULL method

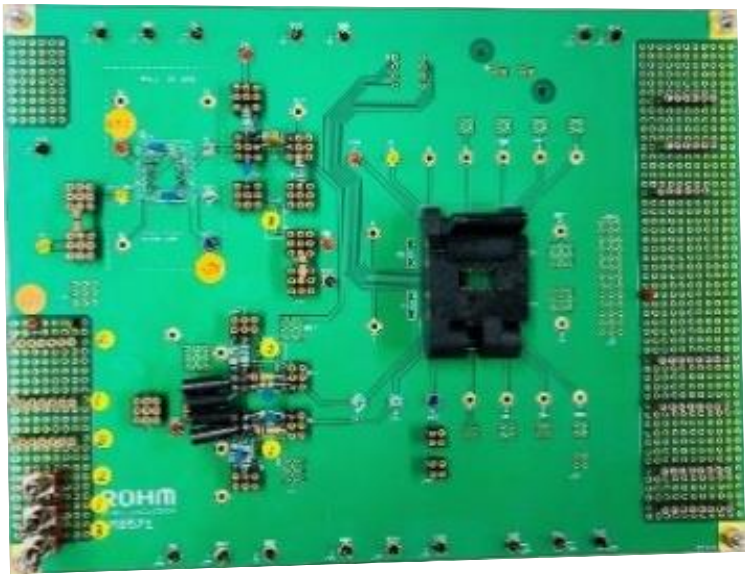


Fig. 3. Photo of the circuit in Fig. 2.

4. SPICE Simulation Verification

Here, we used the model of an operational amplifier AD8571 as device under test (DUT) for SPICE simulation. In addition, we used the SPICE model provided by the manufacturer as it was.

4.1 Frequency Characteristics

When the sinusoidal signal of $1mV_{p\text{-}p}$ is provided as an input to the circuit of Fig. 4 and the values of C_1 and C_2 are changed, we obtain the frequency characteristic simulation results using the NULL method circuits in Fig. 5; this is an amplifier circuit with gain of 1,000 (60dB). If the gain of 60dB does not decrease much in the high frequency region, the response is faster. We see in Fig. 5 that the cutoff frequency f_c is 30Hz at C_1=0.1μF and C_2=0.1μF, but at C_1=1nF and C_2=0.1μF, f_c is 1kHz and approximately 30 times faster response is possible.

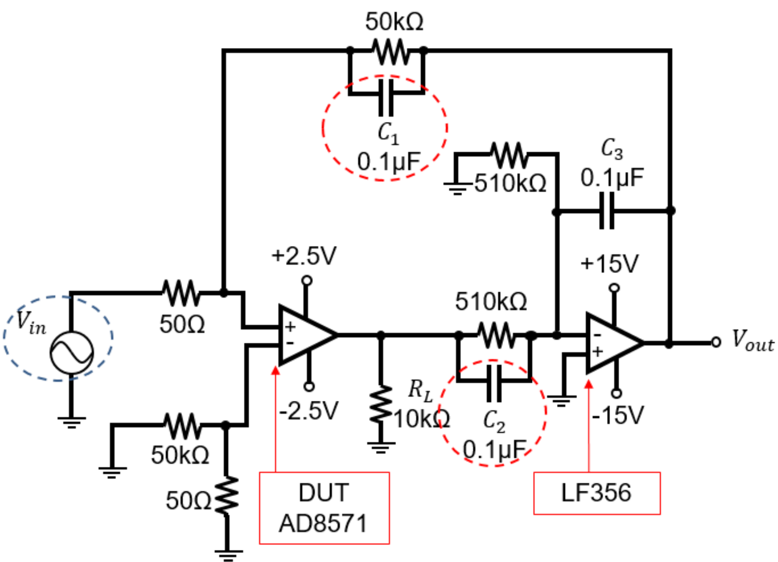


Fig. 4. Frequency characteristics measurement circuit

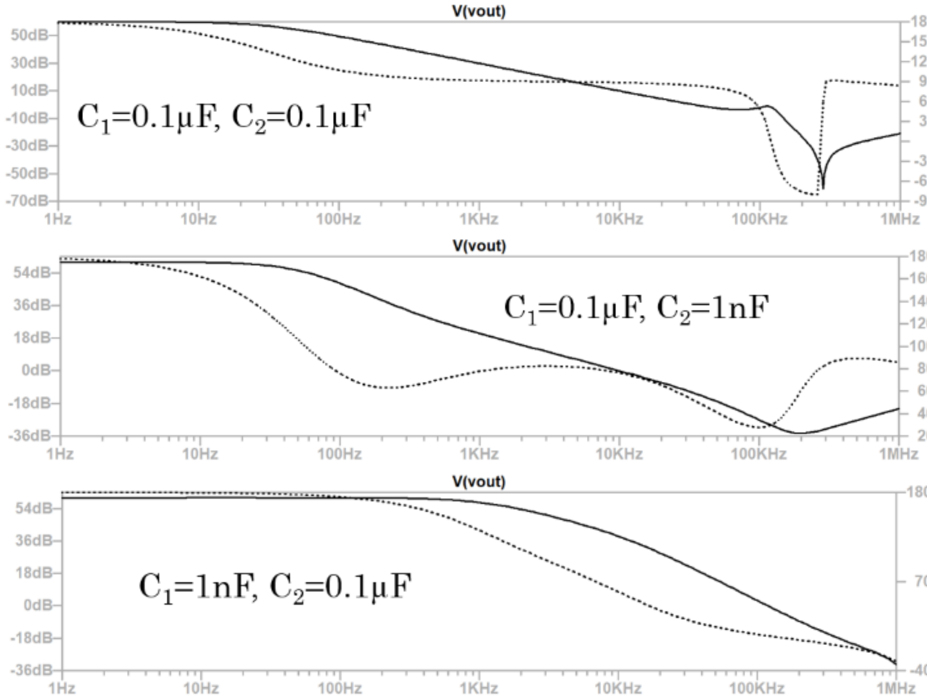


Fig. 5. Frequency characteristics of the circuit in Fig. 4.

4.2 Operational Amplifier Offset Voltage Measurement

Ideally, when the output voltage of the operational amplifier is zero, the positive and negative terminal sides of the input are equal. However, in practice they can mismatch slightly, and their difference is called as an input-referred offset voltage. A circuit for measuring this minute input offset voltage is shown in Fig. 6. Here we assume that the offset of the DUT (AD8571) is 1μV. By providing a 1Hz square wave of $1\mu V_{p\text{-}p}$ as an input to the positive terminal side of the operational amplifier AD8571, the DC offset voltage of 1μV is equivalently applied. Its SPICE simulation result is shown in Fig. 7. Since the output at $1mV_{p\text{-}p}$ level is produced, the minute error between positive and negative terminals is output multiplied by 1,000. As a result, the minute voltage, which is difficult to measure directly, is multiplied by 1,000 and provided as an output, so that it can be confirmed that the measurement is ease.

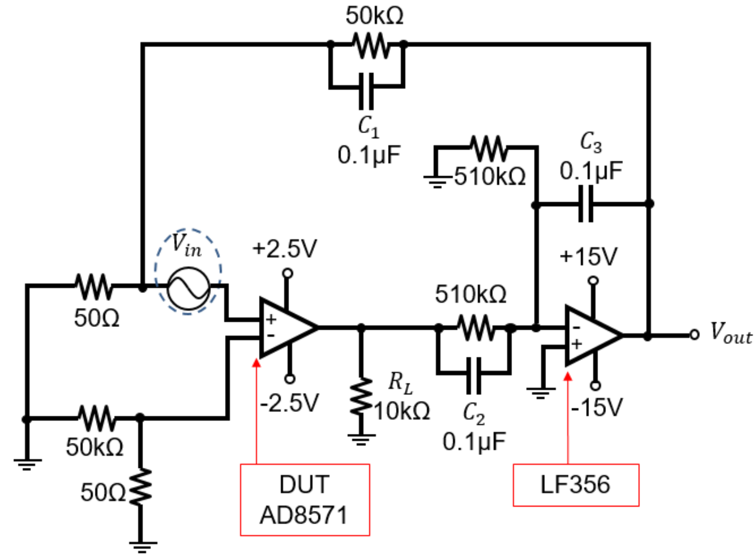


Fig. 6. Offset voltage measurement circuit

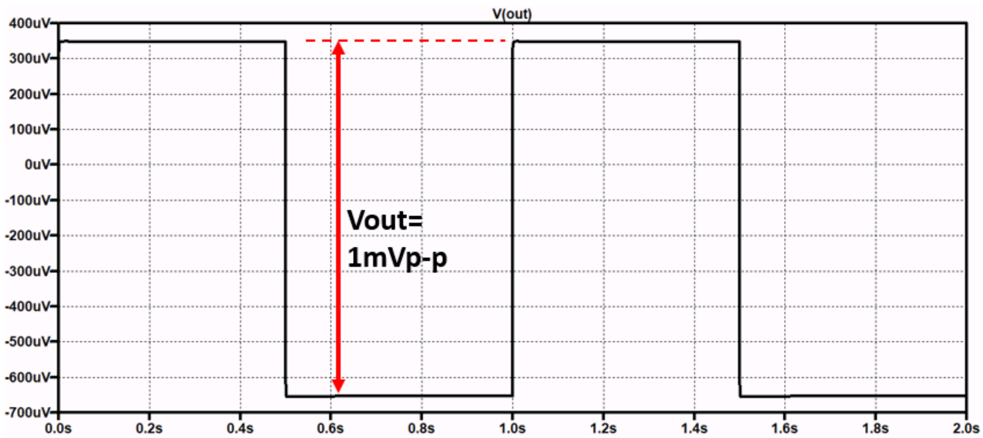


Fig. 7. Offset voltage measurement result

4.3 Open Loop Gain (A_{OL})

Table 2 shows open loop gain characteristics simulation results for the circuit in Fig. 8, where a square wave of $1V_{p-p}$ and 1Hz is provided to the negative terminal side of the operational amplifier used as an integrator for the load resistance R_L of 2kΩ, 10kΩ and 100kΩ.

The open loop gain is defined by the equation (1).

$$A_{OL} = 20log\left(1000 \times \frac{1V}{V_{outp-p}}\right) dB \tag{1}$$

We see from Table 2 that the open loop gain is related to the value of the load resistance R_L, and the larger the load resistance, the higher the open loop.

Fig. 9 shows the transient response simulation results when R_L is 10kΩ, and C_1, C_2 are varied. When C_1=1nF, the circuit becomes unstable in case C_2 =1nF, while it is stable in case C_2 =0.01μF, and the settling time is about 30ms. If C_2= 0.1μF, settling time becomes approximately 200ms; the measurement time can be shortened by a factor of 1/10 with the phase compensation capacitors C_1, C_2 of appropriate values.

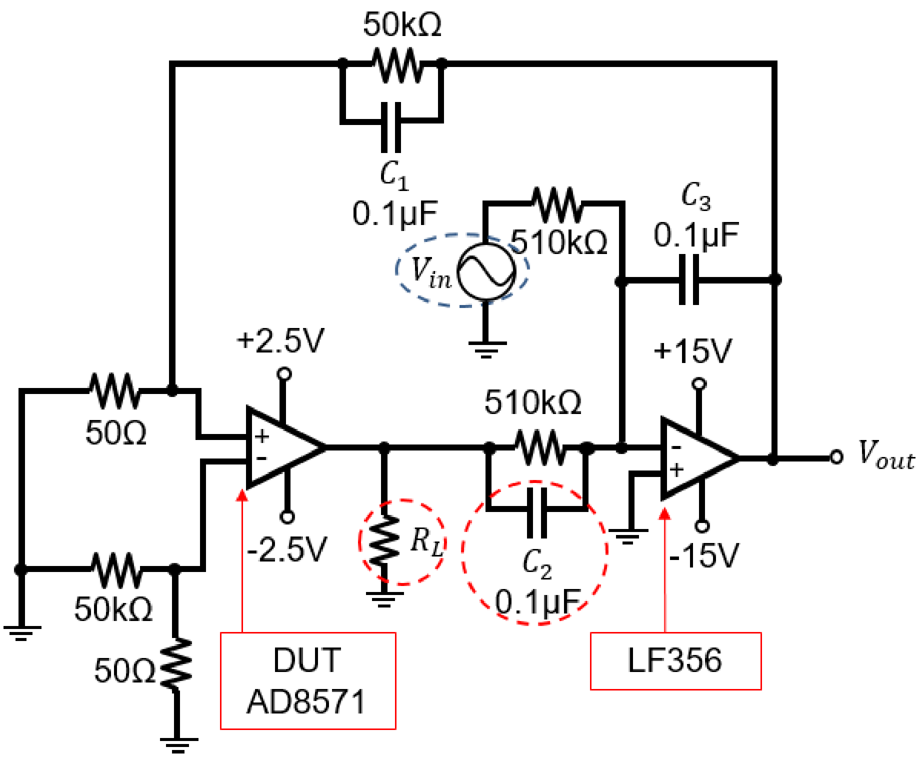
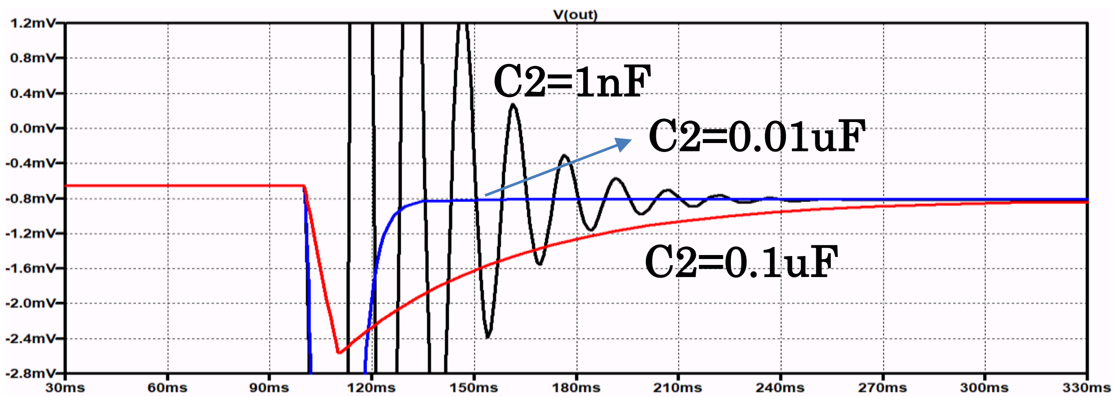


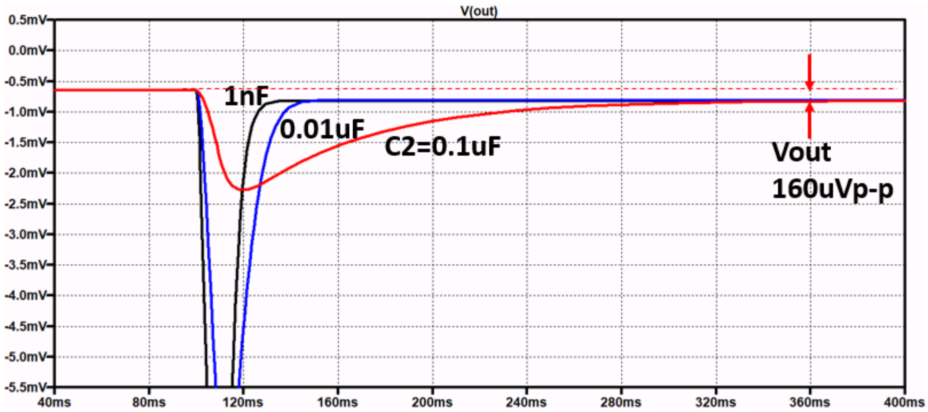
Fig. 8. Open loop gain measurement circuit

Table 2. Open loop gain simulation result

R_L [kΩ]	A_{OL} [dB]
2	122
10	136
100	154



(a) C_1=1nF, C_2 is varied.



(b) C_1=0.1μF, C_2 is varied.
Fig. 9. Open loop gain simulation result when C_1, C_2 are varied.

4.4 Common-Mode Rejection Ratio (CMRR)

The Common-Mode Rejection Ratio (CMRR) can be measured by changing the common mode voltage of the input of the operational amplifier in principle. However, the NULL method measures it equivalently by changing the power supply voltage of the DUT in Fig. 10. In order to measure the output change for common mode input change by 1V, V_P is shifted from +2.5V to +3.0V and V_N is shifted from -2.5V to -2.0V. Here Similar to in the open loop, the load resistance R_L is varied, and then the simulation result of CMRR is shown in Table 3. The power supply voltage between V_P and V_N is constant (5V). We see from the simulation result that the influence of load resistance R_L does not appear, which is different from the open loop characteristics; this is because the DUT output is fixed at 0V when the negative feedback works and the integrator input E_k is 0V in the NULL circuit, so that there is no change in the output current due to the R_L value.

Fig.11 shows the simulation result of the output voltage when changing C_2 to 0.1μF, 0.01μF, 1nF in the case of R_L=10kΩ and C_1=1nF. We see that CMRR shows faster response as C_2 becomes larger.

Notice that we need to use two resistors of 50 Ω with very good matching as well as two resistors of 50k Ω in Fig.10, so that accurate CMRR of the DUT can be measured; otherwise, only the underestimated value of the DUT CMRR is obtained.

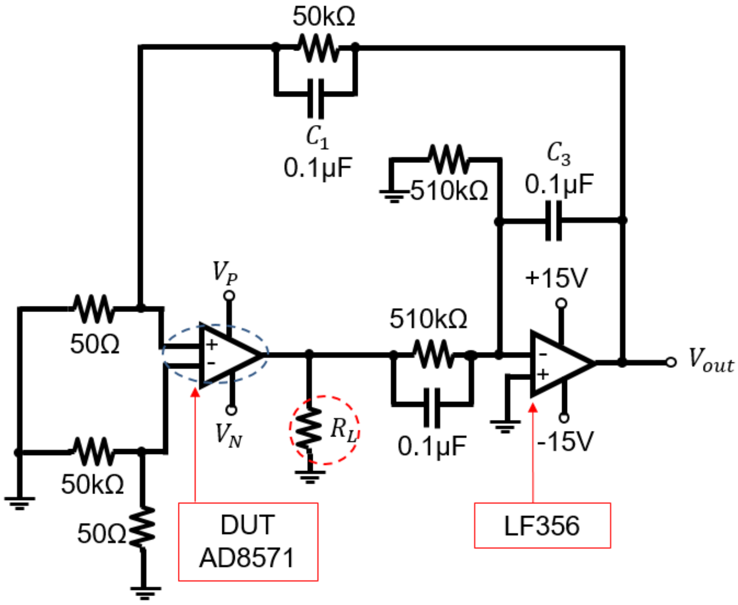


Fig. 10. CMRR measurement circuit

Table 3. CMRR simulation result

R_L [kΩ]	CMRR [dB]
2	126
10	126
100	126

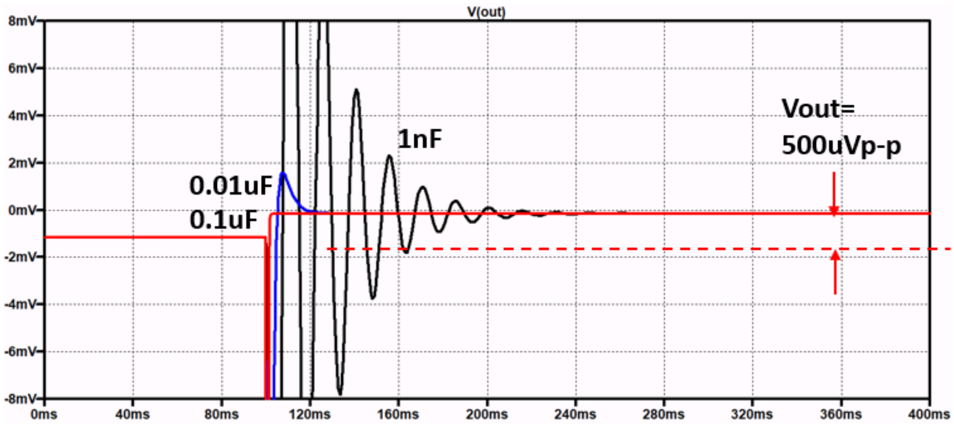


Fig. 11. CMRR simulation result when C_2 is varied.

4.5 Power Supply Rejection Ratio (PSRR)

The Power Supply Rejection Ratio (PSRR) can be obtained with the same configuration as CMRR. The way of giving V_P and V_N is different, and it can be obtained by observing the V_{out} output voltage fluctuation when the power supply voltage between V_P and V_N changes by 1V. Here, V_P is shifted from +2.0V to +2.5V, V_N is shifted from -2.0V to -2.5V, and the power supply voltage is changed from 4V to 5V. Similar to the open loop and CMRR, PSRR when changing the load resistance R_L is shown in Table 4. We see from the simulation results that PSRR does not show the influence of the load resistance R_L like CMRR. Similar to the CMRR case, the negative feedback effect in the NULL circuit is observed. Fig. 12 shows the output voltage when changing C_2 to 0.1μF, 0.01μF, 1nF, with R_L=10kΩ, C_1=1nF. From this, PSRR has a similar response to the CMRR case.

Table 4. PSRR simulation result

R_L [kΩ]	CMRR [dB]
2	120
10	120
100	120

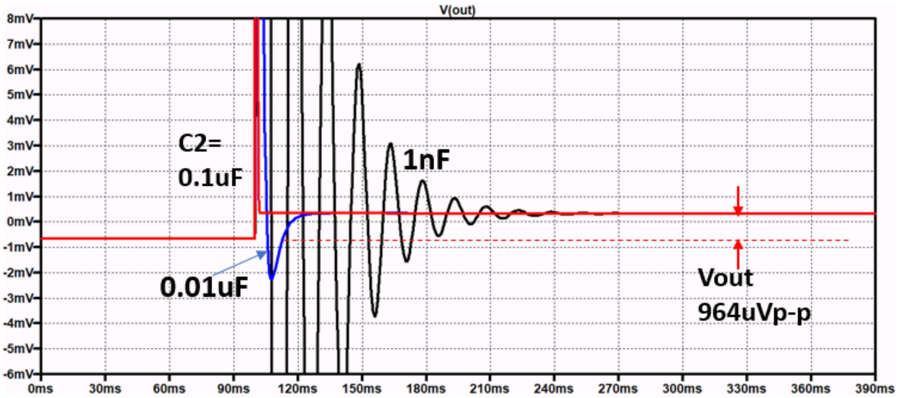


Fig. 12. PSRR simulation result when C_2 is varied.

5. Conclusion

In this paper, we have investigated the NULL circuit that can measure various parameters of an operational amplifier accurately and easily; we have described how to measure the parameters of the operational amplifier with it, and verified it by SPICE simulation. It is shown that optimization of the phase compensation (C_1, C_2) is important for the NULL circuit to operate with short settling time and good stability. By using a general operational amplifier circuit, the signal input and the output parts are fixed, and the negative feedback is set so that the phase compensation constant optimizes the input and output (for both stability and high speed). We have confirmed that in the NULL circuit, the signal application point differs depending on the measurement item, and when the signal input section changes, the response characteristics of each input and output differ if the phase compensation constant is fixed. In our simulation, in order to stabilize the circuit at any measurement item (change in input part) with a fixed phase compensation constant, it is necessary to apply negative feedback so that the entire system becomes stable in low frequency region. A waiting time of 100ms or more is required every time the measurement condition is changed, but switching the phase compensation constant depending on the measurement item could reduce the settling time by about 1/10.

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