

A Test Methodology to Measure the Open-Loop Voltage Gain of an Operational Amplifier

Maninder Kaur Gill, Alpana Agarwal

Abstract—It is practically not feasible to measure the open-loop voltage gain of the operational amplifier in the open loop configuration. It is because the open-loop voltage gain of the operational amplifier is very large. In order to avoid the saturation of the output voltage, a very small input should be given to operational amplifier which is not possible to be measured practically by a digital multimeter. A test circuit for measurement of open loop voltage gain of an operational amplifier has been proposed and verified using simulation tools as well as by experimental methods on breadboard. The main advantage of this test circuit is that it is simple, fast, accurate, cost effective, and easy to handle even on a breadboard. The test circuit requires only the device under test (DUT) along with resistors. This circuit has been tested for measurement of open loop voltage gain for different operational amplifiers. The underlying goal is to design testable circuits for various analog devices that are simple to realize in VLSI systems, giving accurate results and without changing the characteristics of the original system. The DUTs used are LM741CN and UA741CP. For LM741CN, the simulated gain and experimentally measured gain (average) are calculated as 89.71 dB and 87.71 dB, respectively. For UA741CP, the simulated gain and experimentally measured gain (average) are calculated as 101.15 dB and 105.15 dB, respectively. These values are found to be close to the datasheet values.

Keywords—Device under test, open-loop voltage gain, operational amplifier, test circuit.

I. INTRODUCTION

THE characterization of analog circuits is quite difficult and time consuming when compared with the digital circuits. The reasons are the variation of parameters over their complete voltage and frequency range, variation of process parameters (doping of different layers, extent of etching and thickness of the oxide). All these reasons make the testing of analog circuits a tough and demanding task. Thus, keeping in mind the convolutedness of analog testability, it requires a standardized methodology for the design of test circuits for the characterization of the different parts of the large analog system. The operational amplifier is a vital part of large number of analog and mixed signal systems. Ample disquisition can be explored on the measurement and simulation of the frequency-dependent operational amplifiers characteristics such as the slew rate [1]-[4], open loop gain A_{OL} [5]-[9], the common mode rejection ratio CMRR [10]-[12], and power supply rejection ratio PSRR [13], [14]. The

linear and non-linear behavior of the operational amplifier has a huge impact on the characteristics and the operation of analog circuits like ADC, DAC, switched capacitor filters, and so on. Hence, a precise approximation of these circuit parameters is imperative to evaluate the performance of the entire analog system. The linear parameters are the open loop voltage gain, gain bandwidth product, phase margin, first pole of the operational amplifier, whereas slew rate is the non-linear parameter. The measurement procedures discussed in [15]-[17] utilize additional operational amplifiers other than DUT, thereby making the circuit more tortuous together with large observed deviation between modelled and measured open-loop voltage gain. This paper proposes a simple and accurate test circuit for measuring open-loop voltage gain of operational amplifier in Section II. The simulation results and experimental measurements for different DUTs are given in Sections III and V, respectively. The paper is concluded in Section V.

II. TEST CIRCUIT

The proposed test circuit for the measurement of open-loop voltage gain, A_{OL} , of an operational amplifier is shown in Fig. 1. A negative feedback and four resistors form the basic idea of this circuit. The negative input has the voltage divider which increases the sensitivity of voltage V_a by 100 times, thereby making it a possible task to measure the open loop voltage gain, A_{OL} , of order of 10^5 .

The measurement procedure for open loop voltage gain is based on the output behavior of operational amplifier. Ideally, the operational amplifier could swing to both the power supply rails. However, practically open loop voltage gain is confined at some distance from power supply rails. The relation between differential input voltage V_a and voltage at junction X, V_x is defined in (1)

$$V_a = V_x / (1 + R_3/R_4) \quad (1)$$

Assume that the output voltage can swing from V_{out1} (maximum positive swing) and V_{out2} (maximum negative swing). When the output is driven to V_{out1} , the voltage on the input of the DUT will be V_{in1} . V_{in1} is the input voltage required to drive the output to V_{out1} . On the contrary, when the output is driven to V_{out2} , the voltage on the input of the DUT will be V_{in2} . V_{in2} is the input voltage required to drive the output to V_{out2} . The procedure for the measurement of the A_{OL} implementing test circuit of Fig. 1 has been explained from (i)-(vi).

i. Connect the appropriate load to the DUT.

Maninder Kaur Gill is with Electronics and Communication Engineering Department, Thapar University, Patiala, Punjab 147004, India (phone: +918437849677; e-mail: maninder.kaur@thapar.edu).

Alpana Agarwal is with Electronics and Communication Engineering Department, Thapar University, Patiala, Punjab 147004, India (e-mail: alpana@thapar.edu).

- ii. Force the input voltage to V_{in1} in order to drive the output to V_{out1} .
- iii. Measure V_{x1} and calculate V_{a1} using (1).
- iv. Again, force the input voltage to V_{in2} in order to drive the output to V_{out2} .
- v. Measure V_{x2} and calculate V_{a2} using (1).
- vi. The open loop gain A_{OL} is finally computed as per (2).

$$A_{OL} = |(V_{out1} - V_{out2}) / (V_{a1} - V_{a2})| \quad (2)$$

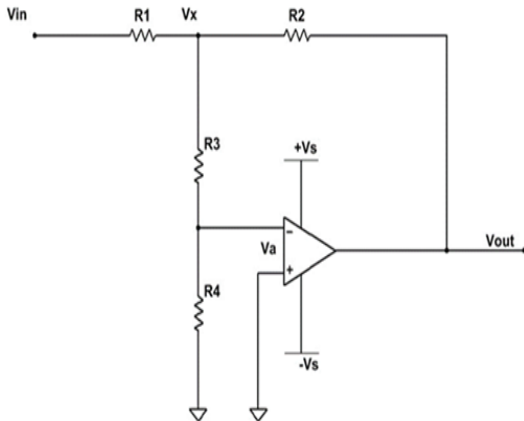
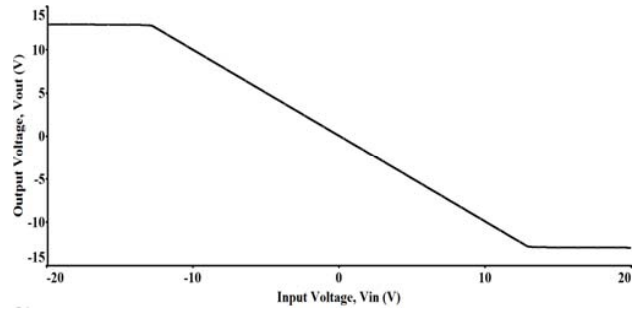
Fig. 1 The presented test circuit for measurement of A_{OL} 

Fig. 2 The DC sweep analysis of the test circuit

III. SIMULATION RESULTS

The test circuit of Fig. 1 is implemented in the software environment using NI Multisim 12.0.1. The one amplifier loop test circuit has been designed such that it satisfies its design requirements as per (1). The DUTs used are LM741CN and UA741CP one at a time with resistor values as $R1 = R2 = 100 \text{ k}\Omega$, $R3 = 10 \text{ k}\Omega$ and $R4 = 100 \text{ }\Omega$. The rail to rail supply voltage is $\pm 15 \text{ V}$.

In order to obtain the values of maximum positive and negative voltage swing, DC sweep analysis of DUT as shown in Fig. 2 is done. The input voltage is swept from -15 V to $+15 \text{ V}$. As a consequence, V_{in1} and V_{in2} are obtained, respectively, for both LM741CN and UA741CP.

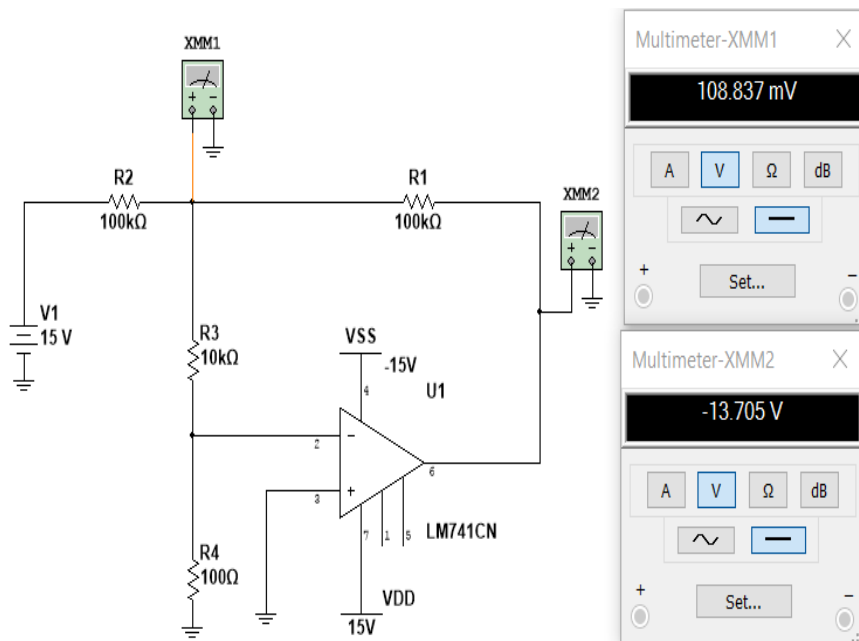


Fig. 3 The simulation results for LM741CN

Apply the input voltage V_{in1} so as to obtain the maximum positive swing. The test circuit has been simulated as depicted in Fig. 3. The values of V_{x1} and V_{out1} are measured using the virtual multimeters. Now, change the input voltage to V_{in2} to obtain the maximum negative swing. Again, simulate the test circuit to obtain the values of V_{x2} and V_{out2} .

The values of V_{a1} and V_{a2} have been calculated using (1). Thus, open loop voltage gain of DUT can be calculated using (2).

IV. EXPERIMENTAL RESULTS

The test circuit of Fig. 1 has been implemented in laboratory using breadboard. Fig. 4 shows the implementation of one amplifier loop test circuit on breadboard. The rail to rail supply voltage is ± 15 V.

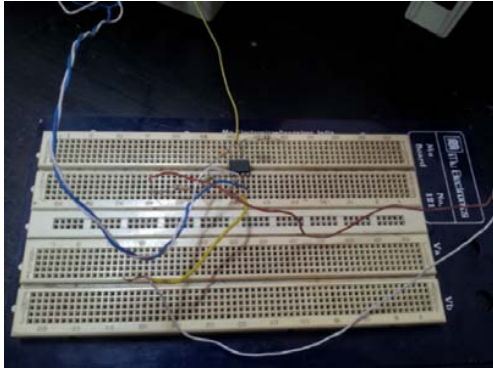


Fig. 4 Implementation of one amplifier loop test circuit on the breadboard

The devices under test (DUT) are LM741CN and UA741CP. The input signal is provided by a power supply ST4073. The supply voltage is provided by a multiple power supply PSD3304. The voltages are measured by using digital multimeter (TRUE RMS).

The open loop voltage gain measurements are done for five samples of both types of DUTs. The experimental setup for One Amplifier Loop Test Method is shown in Fig. 5. The comparative analysis between the simulated results and experimental measurements for both DUTs has been summarized in Table I.



Fig. 5 Experimental setup for one amplifier loop test method

V. CONCLUSION

In this paper, a novel test methodology for operational amplifier characterization has been presented by comprising of the design, software simulations, and experimental measurements using breadboard in laboratory. The operational amplifier parameter being measured is open loop voltage gain. The goal has been to design such a test circuit for operational amplifier characterization which is less complex, requires minimum hardware (circuitry), and has high precision. From Table I, it is obvious that the simulated values as well as experimental measurements closely matched with the datasheet values. The average percentage errors of 2.235% and 3.837% have been observed for devices LM741CN and UA741CP, respectively.

TABLE I
COMPARATIVE ANALYSIS BETWEEN SIMULATED RESULTS AND EXPERIMENTAL MEASUREMENTS FOR OPEN LOOP VOLTAGE GAIN AOL FOR LM741CN AND UA741CP

Device No	LM741CN				UA741CP			
	Datasheet Values (dB)	Simulation Results (dB)	Experimental Measurements (dB)	Percentage Error (%)	Datasheet Values (dB)	Simulation Results (dB)	Experimental Measurements (dB)	Percentage Error (%)
1			87.79	2.15			105.05	3.85
2			87.61	2.33			105.06	3.87
3	86.02-106.02	89.71	87.65	2.30	86.02-106.02	101.15	105.01	3.81
4			87.70	2.25			105.36	4.16
5			87.79	2.14			104.66	3.47

REFERENCES

- [1] W. M. C. Sansen, M. Steyaert, and P. J. V. Vandeloo, "Measurement of operational amplifier characteristics in the frequency domain," *IEEE Trans. Instrum. Meas.*, vol. IM-34, pp. 59–64, Feb. 1985.
- [2] K. Higuchi and H. Shintani, "New measurement methods of dominant pole-type operational amplifier parameters," *IEEE Trans. Ind. Electron.*, vol. IE-34, pp. 357–365, June 1987.
- [3] S. S. Awad, "A simple method to estimate the ratio of the second pole to the gain-bandwidth product of matched operational amplifiers," *IEEE Trans. Instrum. Meas.*, vol. 39, pp. 429–432, Apr. 1990.
- [4] S. Natarajan, "A simple method to estimate gain-bandwidth product and the second pole of the operational amplifiers," *IEEE Trans. Instrum. Meas.*, vol. 40, pp. 43–45, Feb. 1991.
- [5] S. Porta and A. Carlosena, "On the experimental methods to characterize the opamp response: A critical view," *IEEE Trans. Instrum. Meas.*, vol. 43, pp. 245–249, Apr. 1996.
- [6] G. Di Cataldo, G. Paltnisano, G. Palumbo and S. Pennisi, "High-speed voltage buffers for the experimental characterization of CMOS transconductance operational amplifiers", *IEEE Trans. Instrum. and Meas.* vol.48, no. 1, pp. 31-33, 1999.
- [7] R. Pintelon and J. Schoukens, "Measurement and modeling of linear systems in the presence of non-linear distortions," *Mechanical System and Signal Processing*, vol. 16, no.5, pp. 785-801, 2002.
- [8] R. Pintelon, J. Schoukens, W. Van Moer and Y. Rolain, "Identification of linear systems in the presence of nonlinear distortions," *IEEE Trans. Instrum. and Meas.*, vol. 50, no. 4, pp. 855-863, 2001.
- [9] G. Giustolisi and G. Palumbo, "An approach to test open-loop parameters of feedback amplifiers," *IEEE Trans. Circuits Syst. I*, vol. 49, pp. 70–75, Jan. 2002.
- [10] R. Pallás-Areny and J. G. Webster, "Common mode rejection ratio in differential amplifiers," *IEEE Trans. Instrum. Meas.*, vol. 40, pp. 669–676, June 1991.

- [11] M. E. Brinson and D. J. Faulkner, "New approaches to measurement of operational amplifier common-mode rejection ratio in the frequency domain," *Proc. Inst. Elect. Eng. Circuits Devices Syst.*, vol. 142, no. 4, pp. 247–253, 1995.
- [12] G. Giustolisi, G. Palmisano, and G. Palumbo, "CMRR frequency response of CMOS operational transconductance amplifiers," *IEEE Trans. Instrum. Meas.*, vol. 49, pp. 137–143, Feb. 2000.
- [13] M. S. J. Steyaert and W. M. C. Sansen, "Power supply rejection ratio in operational transconductance amplifiers," *IEEE Trans. Circuits Syst.*, vol. 37, pp. 1077–1084, Oct. 1990.
- [14] M. E. Brinson and D. J. Faulkner, "Measurement and modeling of operational amplifier power supply rejection," *Int. J. Electron.*, vol. 78, no.4, pp. 667–678, 1995.
- [15] Pintelon R., Vandersteen G., Ludwig De Locht, Rolain Y, Schoukens J., "Experimental characterization of operational amplifiers: a system identification Approach-part I&II: theory and simulations", *Instrumentation and Measurement, IEEE Transactions on*, on page(s): 854 - 876 Volume: 53, Issue: 3, June 2004.
- [16] James M Bryant, "Simple Op Amp Measurements", *Analog Dialogue*, Vol. 45- April 2011.
- [17] Pintelon, R. Vandersteen, G. Rolain, Y. "Experimental characterization of operational amplifiers: A system identification approach", *Instrumentation and Measurement Technology Conference, 2003. IMTC '03. Proceedings of the 20th IEEE*, On page(s): 362 - 367 Volume: 1, 20-22 May 2003.