Analyzing Gain using Transistor Circuits

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1 Abstract

This report investigates the performance characteristics of a differential amplifier and a Darlington pair circuit, both utilizing transistors as their core components. For the differential amplifier, The experimental differential gain was measured to be 31.5 ± 11.5, while the common-mode gain was experimentally determined to be -0.475 ± 0.157, give a CMRR of 66.316 ± 32.65. When power supply was replaced by a constant source, the CMRR came out to 750 ± 179, confirming the benefits of a constant current supply. In the Darlington pair configuration, consisting of two transistors, the total current gain was examined by varying resistance at the first transistor's base. Results demonstrate the effectiveness of transistors in amplification and signal processing applications, highlighting their significance in modern electronics.

2 Introduction

Transistors are the building blocks of modern electronics, advancing semiconductor technology. The development of transistors represents a revolution in electronics history, changing the way circuits are able to perform, being used to used to control the flow of current in a circuit, functioning as amplifiers, switches, or signal modulators. This function is crucial for the amplification of weak signals, as well as for digital electronics, such as phones. Developed in Bell Laboratories in 1947, the device allowed for small-solid devices to be added to circuits instead of using bulky vacuum tubes, lost lots of electrical power to heat, shortening the tube's life (Watkins). The transistor has three parts: the emitter, the base, and the collector. In principle, a small current flowing into the base controls the current flowing between the emitter and collector. This lab will investigate the gain properties of transistors, when used in different configurations.

3 Theory

transistors have fundamental relationships between the emitter, base, and collector. Some of these relations are:

$$V_E = V_B - 0.6V \tag{1}$$

$$I_E = I_B + I_C \tag{2}$$

$$I_C = \beta I_B \tag{3}$$

Using these relations, transistors can be configured in ways such that the current or voltage at some input can be increased or decreased, giving a gain. In the circuit used for this lab, the voltage input is put through two resistors and can give a gain based off the voltage amplitude and direction. When the input voltage is equal but opposite, the gain be calculated as follows:

$$G_{diff} = R_C/[2(r_e + R_E)] \tag{4}$$

While when the inputs are equal and in the same direction, this is called the common mode, and the gain can be calculated as follows:

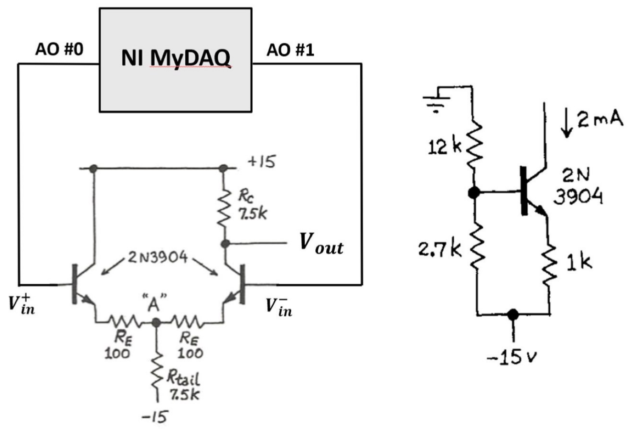
$$G_{CM} = -R_C/[r_e + R_E + 2R_{tail}] \tag{5}$$

Using these circuit relations, the circuit can be analyzed to comprehend the purpose of operational amplifiers and optimization of transistor-based circuits.

4 Results

First, a differential amplifier was constructed, which consists of a pair of transistors, with a current source applied to the emitter, and a power source from their base. This power source was manipulated to look at the differential gain as well as the common mode gain. The differential gain is when the signals are equal but opposite, while the common mode is when the current sources are in magnitude and phase equal. By calculating the common-mode rejection ratio, an analysis of the performance of this circuit can be calculated. The current at the emitter was first dictated by simple voltage source and resistor, but then was replaced by a constant current source, to see the significance of the current at the emitter in relation to the collector. This importance will show through the gain and the common-mode rejection ratio.

The following diagram is a schematic of the differential amplifier transistor circuit:



Differential Amp (per Fig. L6.1)

Current Source (per Fig. L.6.4)

The resistors used measured out as follows:

$$R_C = 7.5k\Omega \pm 5\% = 7.51 \pm 0.3755k\Omega \tag{6}$$

$$R_{tail} = 7.5k\Omega \pm 5\% = 7.55 \pm 0.3775k\Omega \tag{7}$$

$$R_E = 100\Omega \pm 5\% = 98.6 \pm 4.93\Omega \tag{8}$$

$$R_E = 100\Omega \pm 5\% = 98.7 \pm 4.94\Omega \tag{9}$$

The resistors used for the 2 mA current source measured as follows:

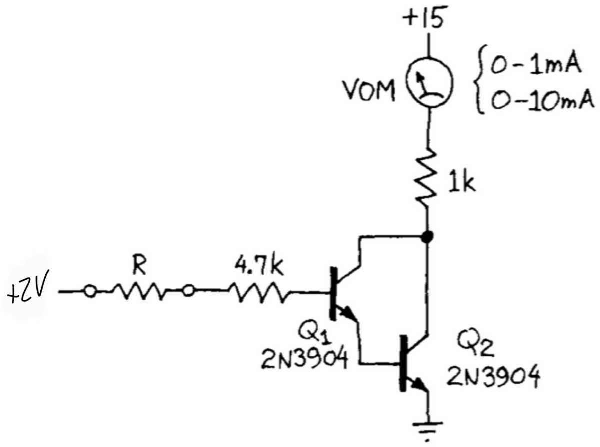
$$R_{12k} = 12k\Omega \pm 5\% = 11.84 \pm 0.592k\Omega \tag{10}$$

$$R_{2.7k} = 2.7k\Omega \pm 5\% = 2.674 \pm 0.134k\Omega \tag{11}$$

$$R_{1k} = 1k\Omega \pm 5\% = 0.99 \pm 0.05k\Omega \tag{12}$$

The lab also investigates the Darlington pair configuration, which is an arrangement of two transistors with one having the emitter be the base of the former. This type of circuit was developed by Sidney Darlington and is known for its exceptionally high current gain. By testing different resistance at the first transistor's base, the total current gain of the circuit was analyzed.

The following diagram is a schematic of the Darlington pair transistor circuit:



The 2V source was made using a voltage divider giving a value of 2 ± 0.5 V. The resistors used include a decade variable resistance box for R and the measurements as follows:

$$R_{4.7k} = 4.7k \pm 5\% = 4.637 \pm 0.235k\Omega \tag{13}$$

$$R_{1k} = 1k \pm 5\% = 0.979 \pm 0.04895k\Omega \tag{14}$$

The following section shows the results for both the differential amplifier and the Darlington Pair circuit.

4.1 Differential Amplifier

First, the differential gain was calculated, experimentally and theoretically. Theoretically, the gain can be calculated using the equation (4). Using the resistor values measured, $G_{diff} = 33.798 \pm 1.645$. By setting the output voltage, measured to be $1.26 \pm 0.46V$, as a ratio over the input, powered at $40 \pm 0.5mV$, for the differential mode. The experimental gain V_{out}/V_{in} comes out to 31.5 ± 11.5. Which closely relates to the theoretical, confirming proper measurement.

To calculate the common mode gain, the input voltages are set to be equal and in the same direction. The negative gain comes from the voltage in being out of phase with the output voltage. Using the resistor values measured and the derived equation (5), $G_{CM} = -0.494 \pm 0.014$. The experimental common mode gain was measured the same way, but with the input voltage being at $4 \pm 0.5V$ and the output voltage measured at $1.9 \pm 0.58V$ giving an experimental value of -0.475 ± 0.157.

The experimental value for the common-mode rejection ratio, using the equation $|G_{diff}/G_{CM}|$, comes out to 66.316 ± 32.65. This is a measure of an amplifier's ability to reject common-mode signals. A higher ratio indicates better rejection and thus minimizing the impact of noise or interference, which can arise from the power supply.

With constant mA source

The 2mA circuit source was theoretically calculated measuring the voltage drop through a load 1k resistor, which measured out to $0.98 \pm 0.049k\Omega$ with a voltage drop of $-1.964 \pm 0.005V$, giving a current of $-2.004 \pm 0.1mA$. When measured directly, the current measured to be $-1.98 \pm 0.05mA$. Using this constant current source, the G_{diff} and G_{CM} was once again measured and calculated, giving $G_{diff} = 37.5 \pm 7.51$ and $G_{CM} = -0.05 \pm 0.0065$. Using these new found values, the common-mode rejection ratio of this amplifier comes out to 750 ± 179. This confirms the definition of the ratio, showing a much higher common-mode rejection when the power supply is constant, This means the common-mode is better rejected for the differential amplifier, when the current out of the emitters are constant.

4.2 Darlington Pair

The saturation voltage at the collector was first obtained by adding a $5k\Omega$ resistance, giving $V_C = 0.65 \pm 0.05$ V. This is a drawback for the Darlington pair because it is much lower when regular. The I_C would come out to $120 \pm 0.5\mu A$. Next, different resistances, between $500k\Omega - 1M\Omega$, were applied to see the current amplification properties of the Darlington pair configuration. The following chart shows the values obtained.

$R(K\Omega)$	$V_B(V)$	$I_B(\mu A)$	$I_C(mA)$	$V_C(V)$	h_{FE}	β
500 ± 5	1.367 ± 0.005	2.734 ± 0.0029	13.78 ± 0.005	0.89 ± 0.005	5040 ± 60	71 ± 0.42
750 ± 7.5	1.367 ± 0.005	1.82 ± 0.002	13.76 ± 0.005	0.92 ± 0.005	7560 ± 85	86.95 ± 0.488
1000 ± 10	1.364 ± 0.005	1.364 ± 0.0015	13.59 ± 0.005	1.1 ± 0.005	9960 ± 120	99.80 ± 0.6
2500 ± 25	1.297 ± 0.005	0.5188 ± 0.0006	5.02 ± 0.005	9.47 ± 0.005	9680 ± 140	98.4 ± 0.7
5000 ± 50	1.28 ± 0.005	0.256 ± 0.0003	1.41 ± 0.005	13.08 ± 0.005	5510 ± 200	74.23 ± 1.347
7500 ± 75	1.51 ± 0.005	0.201 ± 0.0002	0.36 ± 0.005	14.12 ± 0.005	1790 ± 250	42.3 ± 2.95
8000 ± 80	1.134 ± 0.005	0.142 ± 0.00016	0.26 ± 0.005	14.22 ± 0.005	1830 ± 35	42.78 ± 0.41
10000 ± 100	1.051 ± 0.005	0.105 ± 0.0001	0.08 ± 0.005	14.4 ± 0.005	762 ± 4.8	27.6 ± 0.087

Table 1: Darlington Pair Circuit Measurements

Using the theory for the Darlington gain pair, $h_{FE} = \beta_1\beta_2 + \beta_1 + \beta_2 \approx \beta_1\beta_2$, and assuming that both transistors have equal equation $\beta = \beta_1 = \beta_2$. β can be calculated by simply having $\beta = \sqrt{h_{FE}}$. which has been calculated and added into the table. The large gain values show the effectiveness of the Darlington pair configuration.

5 Conclusion

The results obtained from this experiment provides valuable insight into the performance of transistors in different configurations, being a differential amplifier, with both a simple power supply as well as a constant current source, and a Darlington Pair circuit, to amplify the voltage and current, respectively. The first circuit with the simple 15V power supply gave a common mode rejection ratio of 66.316 ± 32.65, while when a constant current source was applied instead, gave a CMRR of 750 ± 179. This is a notable improvement in the rejection ration. The current source kept the differential gain at the same value, while decreasing the common mode gain significantly. While the first circuit looked at voltage gain, the Darlington Pair looked at current gain. This circuit showed exceptionally current gain across various resistor values. This report demonstrates the transistor's ability to amplify signals, for both voltage and current.

6 Reference

Mercer, D. (2017, June 6). *Analog Devices Wiki.* Chapter 12: Differential amplifiers [Analog Devices Wiki]. https://wiki.analog.com/university/courses/electronics/text/chapter-12

Poole, I. *Transistor Darlington pair.* Electronics Notes. https://www.electronics-notes.com/articles/analogue_circuits/transistor/darlington-pair.php

SM = T. C. Hayes, P. Horowitz, *Student Manual for The Art of Electronics* (Cambridge Univ. Press)

Watkins, T. (n.d.). The History of the Transistor. San Jose State University. www.sjsu.edu/faculty/watkins/transist.htm#:~:text=The%20transistor%20was%20successfully%20demonstrated,John%20Bardeen%20and%20Walter%20Brattain.