Common-Mode Rejection Ratio of Multiple Integrated Circuits

EGR334 Analog-Digital Interface

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I. Introduction

An operational amplifier is an integrated circuit that amplifies weak electrical signals. Generally, op-amps have a pair of input pins (non-inverting and inverting pins) and output pin. Its primary role is to amplify and output the voltage difference between two input pins. In the real world, op-amps are not used alone but are designed to be connected to other circuits to perform a variety of operations. For example, it greatly amplifies the input signal and can remove noise from the input signal. When selecting an operational amplifier, check the items and explain the properties of the operational amplifier, check the operating voltage (operating power supply voltage range, common-mode input voltage range), check the input signal frequency (gain-bandwidth product), and check the signal amplification accuracy (input offset voltage) [1]. This project uses the operational amplifier in the differential amplifier circuit to amplify and output two signals.

Common-mode rejection ratio (CMRR) in differential amplifiers, and multiple electronic components, quantify the components' ability to reject common-mode signals that appear subsequently whether these signals were in-phase on both non-inverting and inverting pins of the operational amplifier. It is noted when evaluating such a system there lies a difference between Common Mode Noise and Differential Mode Noise. However, when plotting such data, the relationship is fairly similar. Differential Mode noise is measured between two sections of an interconnect with equal and opposite polarity, while common-mode noise applies to interconnects with the same phase and polarity [2].

Differential mode noise, in a basic sense, is found by subtracting a first signal applied to an input of the op-amp to the second signal being applied to the second input of the op-amp. In contrast, a command-mode signal is found by adding these two signals together. Information on the common-mode input range and the CMRR can be found in the electrical characteristics section of a data sheet associated with the evaluated op-amp. The project requires the procurement of four differential operational amplifiers, the configuration of an electrical network per operational amplifiers datasheet, and testing of the gain output by operational amplifiers. This project aims to compare four different operational amplifiers in their ability to reject the signal common to both positive and negative inputs to the device for reference to future students and researchers looking to obtain clear and accurate information about CMRR. The data collected from the evaluations of the CA3140, LM324, BA10324A, and LM358-N will be reflected within the Testing section of the write-up of the project which would allow for accurate future implementation of operational amplifiers for Embedded Systems of a larger mechanical or electronic system.

II. Problem Statement

It is crucial for this project to help inform researchers, students, and hobbyists about the importance of the signal conditioning process; selecting optimal components to do so becomes the foundation of a successful design in Embedded Systems of a larger mechanical or electronic system. Given the opportunity to display collected data from four separate operational amplifiers will be able to answer the following questions: Why is the CMRR characteristic of an operational amplifier important to a designer of an electrical system? Why do CMRRs differ from manufacturer to manufacturer? Why is signal conditioning important? Does the CMRR shown in the datasheet reflect the exact amount found in a non-ideal circuit?

When evaluating the CMRR of an operational amplifier, designers and engineers must keep in mind the “why” when an op-amp is integrated into an electrical system. An op-amp's ability to minimize the noise of the audio, video, and other communications is an integral characteristic of a successful implementation of the component into a larger system. Thus indicating that an op-amp’s CMRR is a key feature that must be considered when choosing an optimal operational amplifier for a specific system. The practical applications were crucial in linking the sensors to the analog-to-digital converter (ADC) input of a microcontroller as it performs signal conditioning in power-constrained embedded applications, especially when sensors produce a very small voltage and the signal needs to be boosted before being digitized. The CMRR of the op-amp depends on the features like gain and bandwidth, temperature coefficients, and manufacturing variations. They are also determined by external factors such as frequency spikes and power-supply voltage changes [3].

III. Engineering Goals

This project aims to build a simple circuit network to test the following op-amps' ability to reject common-mode signals: LM324, LM358, CA3140, and BA10324A to verify their ability to reject common-mode signals. As these operational amplifiers are optimal for the networks that the team is building and testing, some alternatives produce a result superior to the models that the team has selected for the project. For more complex designs in Embedded Systems of a larger electronic system, an operational amplifier with higher accuracy and better signal conditioning ability is optimal depending on the system that it is being integrated into. When Evaluating an operational amplifier out of the scope of this project, the LM324 high precision operational amplifier cascade design allows high precision input specifications and uncompromised high-speed performance. The datasheets show the ideal CMRR of the op-amps and those numbers are what the team will use as a reference to prove the reliability of the datasheets. Please refer to Appendix A for the Electrical characteristics of the op-amps.

IV. Specifications

Reviewing the datasheet for all four of the operational amplifiers the team was assessing and selected specific specifications for each to portray how each operational amplifier performs. Four different specifications of CMRR were the operating temperature range of each component, the CMRR, the input Voltage of the Operational Amplifier as well as the Common-mode input voltage. All data collected from the datasheet for each respective component have been performed at 25℃.

Table 1. BA10324-A

Operating Temperature Range	-40℃ to 85℃
CMRR	75db at 25℃
Input Voltage	5V
Common-Mode Input Voltage Range	-0.3V to 5V

Table 2 - CA3140

Operating Temperature Range	-55℃ to 120℃
CMRR	32db at 25℃
Input Voltage	8V
Common-Mode Input Voltage Range	-15.5V to 12.5V

Table 3 - LM324

Operating Temperature Range	-55℃ to 125℃
CMRR	85db at 25℃
Input Voltage	-0.3V to 32V
Common-Mode Input Voltage Range	32V

Table 4 - LM358-N

Operating Temperature Range	0℃ to 70℃
CMRR	85db at 25℃
Input Voltage	-1.5V to 4.5V
Common-Mode Input Voltage Range	0V to 1.5V

V. Definitions

1. Common Mode Rejection Ratio (CMRR): The op-amp common-mode rejection ratio is the ratio of the common-mode gain to differential-mode gain [4].
2. Differential Mode Noise: The differential mode noise is an electrical signal which appears in one or two of the lines in a closed loop. The noise appears on two conductors of a closed-loop, it appears in series with the desired signal while the current flows in opposite directions [5].
3. Embedded System: An embedded system is a microprocessor- or microcontroller-based system of hardware and software designed to perform dedicated functions within a larger mechanical or electrical system [6].
4. Operational Amplifier: An operational amplifier, commonly known as Op-amp is an integrated circuit that can amplify weak electric signals' voltage. An operational amplifier has two input pins and one output pin. Its primary role is to amplify and output the voltage difference between the two input pins [1].
5. Signal Conditioning: In electronics, signal conditioning is the manipulation of an analog signal in such a way that it meets the requirements of the next stage for further processing. In an analog-to-digital converter (ADC) application, signal conditioning includes voltage or current limiting and anti-aliasing filtering [7].

Nomenclature

Table 5 - Nomenclature

Quantity	Symbol	Unit of Measurement	Unit Abbreviation
Current	I	Ampere (Amp)	A

Voltage/Potential Difference	E or V	Volt	V
Resistance	R	Ohm	Ω
Common-Mode Rejection Ratio	CMRR	Decibel	dB

VI. Design Solutions and Evaluations

From the specifications, the team will use the normal circuit of differential mode and common mode to verify the datasheet's reliability of the CMRR values. The team needed to verify the values through a multimeter between the outputs of each model. Below is the circuitry that the team breadboarded, the left is the differential mode and the right is the common mode.

Figure 1 was the schematic used from EGR 334 Lab 1. $V_{Out}1$ is from the first circuit which is in a differential configuration. $V_{Out}2$, Common Mode output voltage is found from the second circuit which is in the Common Mode Configuration. In the ideal condition, the output from the Common Mode Configuration would be 0 V, but in real conditions, there is some voltage passed from the output of the op-amp.

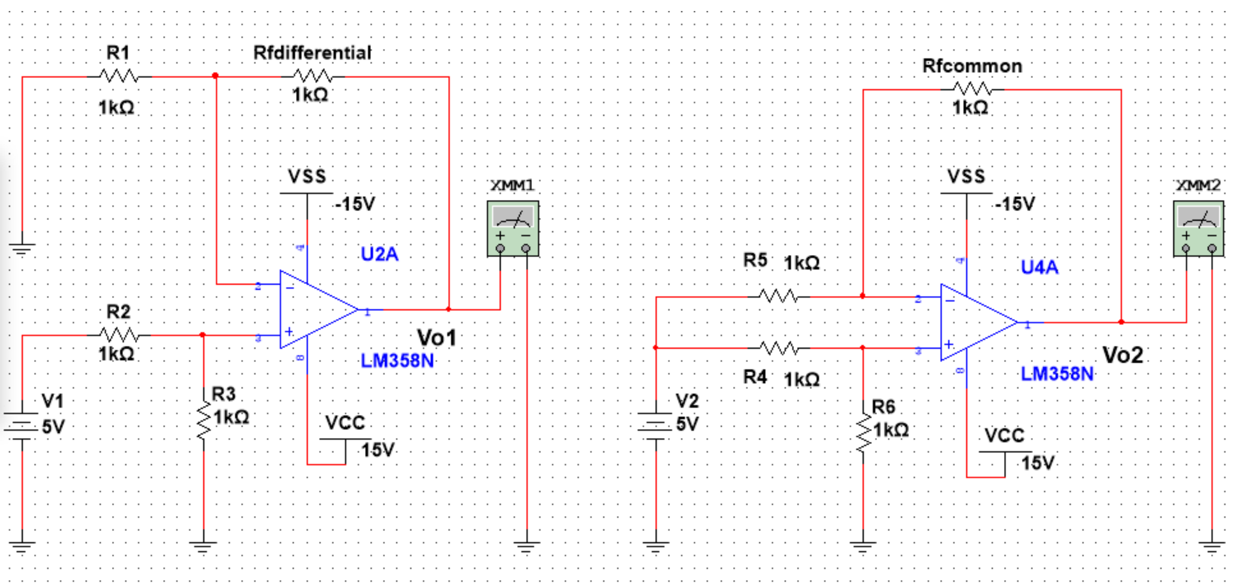

Figure 1. Circuitry of Differential and Common Mode

The following formula was used to find CMRR for each op-amp:

$$CMRR = 20 * log(\frac{V_{Out}1}{V_{Out}2}) \tag{1}$$

$V_{Out}1$ is the output voltage from the first circuit and $V_{Out}2$ is the voltage output from the second circuit. The final CMRR is found in dBs.

Sine, rectangular, or triangular waves can also be passed through the circuit to find the CMRR of the op-amp. The peak to peak voltages measured from the oscilloscope gives $V_{Out}1$ and $V_{Out}2$. And substituting them in equation (1), which gives the CMRR in dB.

The circuit discussed above needs four 1kΩ resistors with two external power supplies that provide positive and negative voltage to the op-amps. This calculated CMRR is not reliable in a laboratory setting because the whole circuit was constructed on the breadboard. Breadboarding the circuit adds external noise giving some variation from the actual design. And being on a breadboard, this circuit is difficult to set up and with the wrong material, the board is prone to damage. The CMRR calculated will be different as it depends on the surrounding temperature. The team needed to cross-check the final answer with a multisim model and data to check if they were getting optimal results.

The second design proposal the team used is based on a Youtube lecture from an electrical professor, David Pearce. The designs were similar to what the team proposed earlier which attributes to the reliability of the team design and also the gain/value of needed resistors to make an efficient circuit. The only drawback of the circuit is that this only applies to an ideal situation, the team needs to find some values of the resistors that tolerate them in real-life situations. David's calculations are also helpful to the team to see how the values interconnect each other. The following figure below shows circuits to the solution for CMRR.

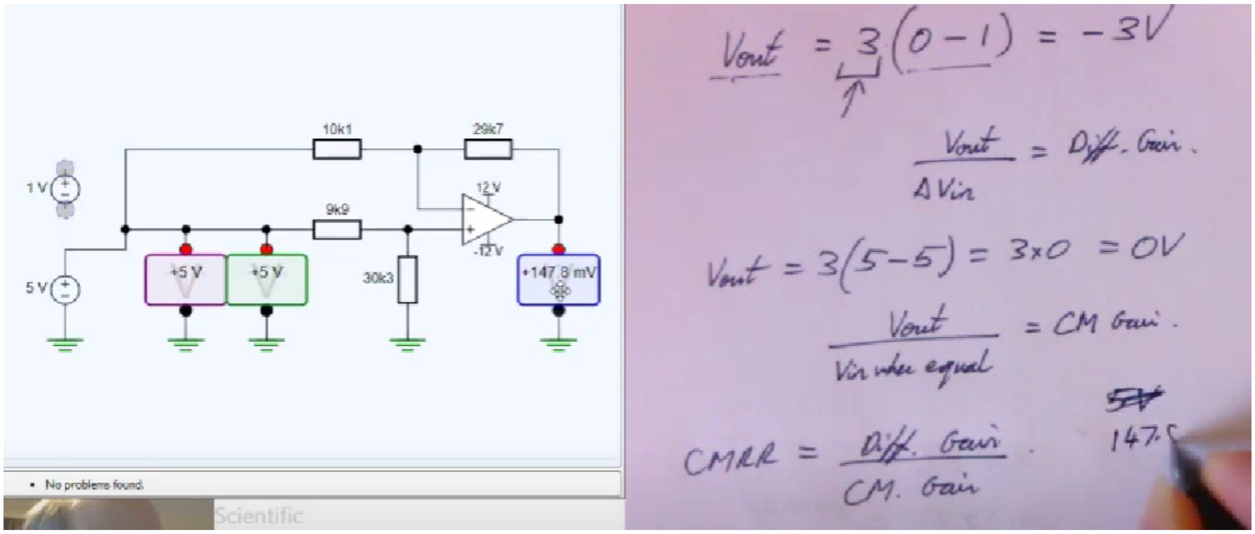

Figure 2. Youtube Lecture on CMRR Designs

The second model discussed above was different from what was discussed during the lectures. And the calculations were more complicated when compared to the first model. In this model, the team needs to calculate Vout from each circuit. From this, the differential and Common-mode gain should be calculated and then substituted in the following formula,

$$CMRR = \frac{Differential\ Gain}{Common\ Mode\ Gain} \tag{2}$$

To perform this model, the team needs to measure the resistance of the resistor due to the actual resistance being different from the resistance mentioned on the resistors.

VII. Selection of Final Design

The Team used the circuit in Figure 1 to calculate the CMRR of each operational amplifier. All the op-amps were tested with a 5V input voltage and powered the op-amp with +5V and -5V. The team also passed sin waves in the circuit to verify the results that were calculated with 5V input voltage.

The circuit was relatively simple to construct and was based on the labs that were performed in EGR 334 class. All the resistors used in the circuit had 1kΩ resistance which were available to the team from Peralta 109 room. Despite the fact that the circuit was breadboarded, the results would be close to what was mentioned in the datasheets.

VIII. Testing

The testing of op-amps will be done individually through breadboarding and measurements through the outputs of the op-amps. The team will need to know the pins and diagram of the op amps to follow the given normal circuit of the differential and common mode. The team went through a few steps for conducting the test. The first step of the testing was to find the resistors that fit with the proposed gain of the circuit. Next, the team will breadboard the circuit shown in the design solution. To make sure the circuit works properly, the team does a continuity test on each connection. The third step was to apply the calculated voltage through a power supply. An analog discovery board and 9V battery were used to generate the lower voltage supply and the high voltage supply was taken from the desk power supply. For the negative supply, the team connects the positive end of probe 1 to a negative probe 2 from another power supply and then places the negative end of probe 1 to the input pin of the negative supply. The team will also check the voltage throughout the circuit to ensure the circuit was supplied properly. With the assumption that the circuit was working properly, the team can finally measure the voltage output. Finally, the team can use this measured voltage to calculate the CMRR by using the formula (1). The table below shows the findings from each op-amp.

Table 6 - Common-mode Rejection Ratio forum from each op-amp.

Op-Amp	CMRR found by Team
LM358N	61.33 dB
BA10324A	107.12 dB
CA3140	60.51 dB

LM324	106.87 dB

Team used BK Precision DC Regulated 1671A power supply which provides a 30V max potential difference. The team used Agilent 34401A to measure the output voltage from the op-amps and the resistance of each resistor. Please refer to Appendix B for detailed calculations and findings.

IX. Project Evaluation

With the findings from each test, the team can check whether the CMRR values found were valid or not. It was mentioned before that the testing was done in a non-ideal situation, which will make the findings of the testing slightly different from what the actual datasheet proposes. Looking at the datasheet of the first op-amp (LM358N), it was mentioned that the minimum of the common-mode rejection ratio was 65 decibels. Based on the physical testing of LM358N op-amp, the team's circuit managed to produce a CMRR of 61.33 decibels. It was below the minimum of what was mentioned in the datasheet, but it was reasonable because of its non-ideal conditions. The physical testing of BA10324A op-amp was making 107.12 decibels which exceeded the typical CMRR mentioned in the datasheet (75 decibels). The third op-amps, CA3140, were found to have a CMRR of 60.51 decibels. The value seems to be as reasonable as the first op-amps since its minimum value from the datasheet was 70 decibels and it's not that huge of a difference. LM324 was the last op-amp the team tested and its CMRR value was 106.87 decibels which seems to have the same amount of value as the BA10324A op-amp. The typical CMRR value of LM324 was 80 decibels which was quite the difference. As mentioned above, the reasoning behind these flawed values was the non-ideal conditions and situations during the physical testing. If the team can find a way to do these procedures in a perfect/ideal way, it was highly likely that the team would find values the same as the datasheet.

X. Conclusion

The purpose of this project was to verify the CMRR of each operational amplifier to optimize the characteristic of CMRR in respective systems for a variety of performance conditions. As such, the goal was met as the project tested four individual operational amplifiers with data collected found in the testing portion of this write-up. This project can be used for future reference by students, researchers, etc. to conceptualize the importance of an Operational amplifier Common-mode rejection ratio simply. The goal of this project was to create a simple circuit network to evaluate the ability of the following op-amps to reject common-mode signals: LM324, LM358-N, CA3140, and BA10324A.

The CMRR of each operational amplifier was calculated using the circuit shown in Figure 1. All of the op-amps were tested with a 5V input voltage and with +5V and -5V power. When testing Operational Amplifiers to find their respective CMMR, the data collected indicates that along with a working physical model to collect values, a theoretical model should be built on one of the various simulation programs offered. The team can examine whether the CMRR values found were legitimate or not using the results from each test. As previously stated, the cause for these inaccurate values was due to the non-ideal conditions and situations encountered during the physical testing. It was quite possible that the team would get values that were identical to the datasheet if they could find a means to conduct these operations in a perfect/ideal way.

The group recommends building a virtual iteration of the testing circuit for accurate data collection of each operational amplifier to control unforeseen variables (i.e. interference signals, unideal temperature ranges, etc.) to find values favorable to the Manufacturers provided Datasheet. A final recommendation that the group would make is to utilize Print Circuit Boards in lieu of breadboarding the physical model to collect values. A printed circuit Board would mitigate connection issues associated with the integrated circuit and would indicate to a student, researcher, etc. an accurate testing protocol. It is noted that even with a printed circuit board, unforeseen variables as outlined above can affect the collection of accurate data. The physical model should be conducted in a location where interference signals were at a minimum and ambient temperature could be controlled.

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Appendices

This appendix contains tables and figures that may be helpful in understanding the context of the research problem. Electrical characteristics of the op amps, proof of findings, and performed calculations are shown as the contents of this Appendix section.

Appendix A

Electrical Characteristics of Op-Amps

	PARAMETER	TEST CONDITIONS[1]		T_A[2]	LM124, LM224 MIN	LM124, LM224 TYP[3]	LM124, LM224 MAX	LM324, LM324K MIN	LM324, LM324K TYP[3]	LM324, LM324K MAX	UNIT
V_{IO}	Input offset voltage	V_{CC} = 5 V to MAX, $V_{IC} = V_{ICR}$min, V_O = 1.4 V		25°C		3	5		3	7	mV
				Full range			7			9	
I_{IO}	Input offset current	V_O = 1.4 V		25°C		2	30		2	50	nA
				Full range			100			150	
I_{IB}	Input bias current	V_O = 1.4 V		25°C		–20	–150		–20	–250	nA
				Full range			–300			–500	
V_{ICR}	Common-mode input voltage range	V_{CC} = 5 V to MAX		25°C	0 to V_{CC} – 1.5			0 to V_{CC} – 1.5			V
				Full range	0 to V_{CC} – 2			0 to V_{CC} – 2			
V_{OH}	High-level output voltage	R_L = 2 kΩ		25°C	V_{CC} – 1.5			V_{CC} – 1.5			V
		R_L = 10 kΩ		25°C							
		V_{CC} = MAX	R_L = 2 kΩ	Full range	26			26			
			R_L ≥ 10 kΩ	Full range	27	28		27	28		
V_{OL}	Low-level output voltage	R_L ≤ 10 kΩ		Full range		5	20		5	20	mV
A_{VD}	Large-signal differential voltage amplification	V_{CC} = 15 V, V_O = 1 V to 11 V, R_L ≥ 2 kΩ		25°C	50	100		25	100		V/mV
				Full range	25			15			
CMRR	Common-mode rejection ratio	$V_{IC} = V_{ICR}$min		25°C	70	80		65	80		dB

Figure 3. Electrical Characteristics of LM324

PARAMETER	TEST CONDITIONS	LM358 MIN	LM358 TYP	LM358 MAX	LM2904 MIN	LM2904 TYP	LM2904 MAX	UNIT
Input Offset Voltage	See[3], T_A = 25°C		2	7		2	7	mV
Input Bias Current	$I_{IN(+)}$ or $I_{IN(-)}$, T_A = 25°C, V_{CM} = 0 V, See[4]		45	250		45	250	nA
Input Offset Current	$I_{IN(+)} - I_{IN(-)}$, V_{CM} = 0 V, T_A = 25°C		5	50		5	50	nA
Input Common-Mode Voltage Range	V^+ = 30 V, See[5] (LM2904, V^+ = 26 V), T_A = 25°C	0		V^+−1.5	0		V^+−1.5	V
Supply Current	Over Full Temperature Range							
	R_L = ∞ on All Op Amps							
	V^+ = 30 V (LM2904 V^+ = 26 V)		1	2		1	2	mA
	V^+ = 5 V		0.5	1.2		0.5	1.2	mA
Large Signal Voltage	V^+ = 15V, T_A = 25°C,							
Gain	R_L ≥ 2 kΩ, (For V_O = 1 V to 11 V)	25	100		25	100		V/mV
Common-Mode Rejection Ratio	T_A = 25°C, V_{CM} = 0 V to V^+−1.5 V	65	85		50	70		dB

Figure 4. Electrical Characteristics of LM358-N

Electrical Specifications For Equipment Design, at $V_{SUPPLY} = \pm15V$, $T_A = 25^oC$, Unless Otherwise Specified **(Continued)**

PARAMETER	SYMBOL	CA3140 MIN	CA3140 TYP	CA3140 MAX	CA3140A MIN	CA3140A TYP	CA3140A MAX	UNITS
Large Signal Voltage Gain (Note 3) (See Figures 6, 29)	A_{OL}	20	100	-	20	100	-	kV/V
		86	100	-	86	100	-	dB
Common Mode Rejection Ratio (See Figure 34)	CMRR	-	32	320	-	32	320	μV/V
		70	90	-	70	90	-	dB
Common Mode Input Voltage Range (See Figure 8)	V_{ICR}	-15	-15.5 to +12.5	11	-15	-15.5 to +12.5	12	V
Power-Supply Rejection Ratio, $\Delta V_{IO}/\Delta V_S$ (See Figure 36)	PSRR	-	100	150	-	100	150	μV/V
		76	80	-	76	80	-	dB
Max Output Voltage (Note 4) (See Figures 2, 8)	$V_{OM}+$	+12	13	-	+12	13	-	V
	$V_{OM}-$	-14	-14.4	-	-14	-14.4	-	V
Supply Current (See Figure 32)	I+	-	4	6	-	4	6	mA
Device Dissipation	P_D	-	120	180	-	120	180	mW
Input Offset Voltage Temperature Drift	$\Delta V_{IO}/\Delta T$	-	8	-	-	6	-	μV/^{o}C

NOTES:

3. At $V_O = 26V_{P-P}$, +12V, -14V and $R_L = 2k\Omega$.
4. At $R_L = 2k\Omega$.

Figure 5. Electrical Characteristics of CA3140

●Electrical characteristics (unless otherwise noted, Ta = 25°C, Vcc = 5V)

Parameter		Symbol	Min.	Typ.	Max.	Unit	Conditions
Input offset voltage		V_{IO}	—	2	7	mV	$R_S = 50\Omega$
Input offset current		I_{IO}	—	5	50	nA	
Input bias current		Ib	—	20	250	nA	＊1
Common-mode input voltage		V_{ICM}	0	—	$V_{CC} - 1.5$	V	
Common-mode rejection ratio		CMRR	65	75	—	dB	
High-amplitude voltage gain		A_{VOl}	87	100	—	dB	$R_L \geqq 2k\Omega$, $V_{CC} = 15V$
Power supply voltage rejection ratio		PSRR	65	100	—	dB	$R_S = 50\Omega$
Quiescent current		I_Q	—	0.6	2.0	mA	$R_L = \infty$, on All Op - Amps
Maximum output voltage		V_{OH}	$V_{CC} - 1.5$	—	—	V	$R_L = 2k\Omega$
		V_{OL}	—	—	0.25	V	$R_L = \infty$
Maximum output current	Source	I_{OH}	20	35	—	mA	$V_O = 0$
	Sink	I_{OL}	10	20	—	mA	$V_O = V_{CC}$
Channel separation		CS	—	120	—	dB	f = 1kHz input conversion

＊1 Because the first stage is configured with a PNP transistor, input bias current is from the IC.

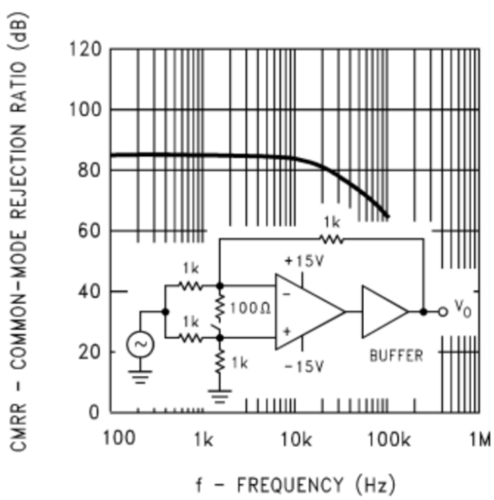
Figure 6. Electrical Characteristics of BA10324A

Appendix B

Testing CMRR of the Op-amps and calculations

LM358N Op-Amps Findings

From datasheet:



Common-Mode Rejection Ratio	T_A = 25°C, V_{CM} = 0 V to V^+−1.5 V	65	85

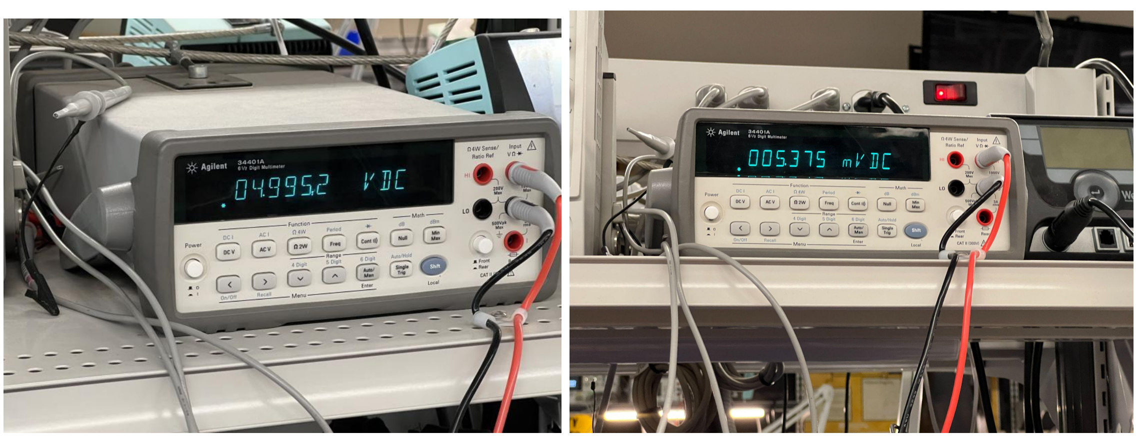


Figure 7 a & 7 b. $V_{Out}1$ and $V_{Out}2$ of LM358N Breadboarded design.

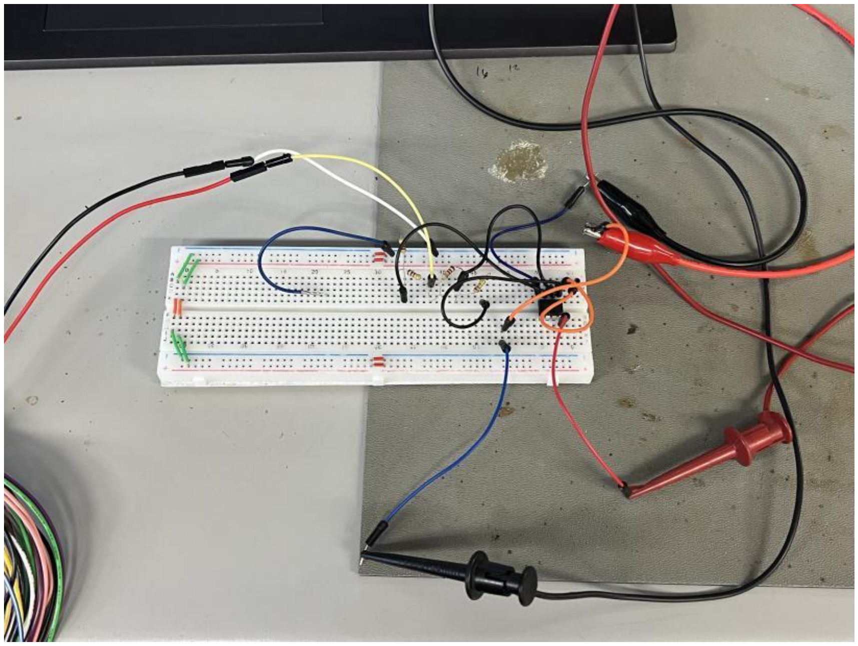


Figure 8. Breadboarded design of LM358N

Calculations:

$$CMRR = 20log(\frac{V_{Out}1}{V_{Out}2})$$

$$CMRR = 20log(\frac{5.004}{0.004299}) = 61.33 \text{ dB}$$

BA10324A Op-Amps Findings

Parameter	Symbol	Min.	Typ.	Max.	Unit	Conditions
Input offset voltage	V_{IO}	—	2	7	mV	R_S = 50Ω
Input offset current	I_{IO}	—	5	50	nA	
Input bias current	Ib	—	20	250	nA	∗1
Common-mode input voltage	V_{ICM}	0	—	V_{CC} – 1.5	V	
Common-mode rejection ratio	CMRR	65	75	—	dB	
High-amplitude voltage gain	A_{VOI}	87	100	—	dB	R_L ≧ 2kΩ, V_{CC} = 15V
Power supply voltage rejection ratio	PSRR	65	100	—	dB	R_S = 50Ω
Quiescent current	I_Q	—	0.6	2.0	mA	R_L = ∞, on All Op - Amps
Maximum output voltage	V_{OH}	V_{CC} – 1.5	—	—	V	R_L = 2kΩ
Maximum output voltage	V_{OL}	—	—	0.25	V	R_L = ∞
Maximum output current — Source	I_{OH}	20	35	—	mA	V_O = 0
Maximum output current — Sink	I_{OL}	10	20	—	mA	V_O = V_{CC}
Channel separation	CS	—	120	—	dB	f = 1kHz input conversion

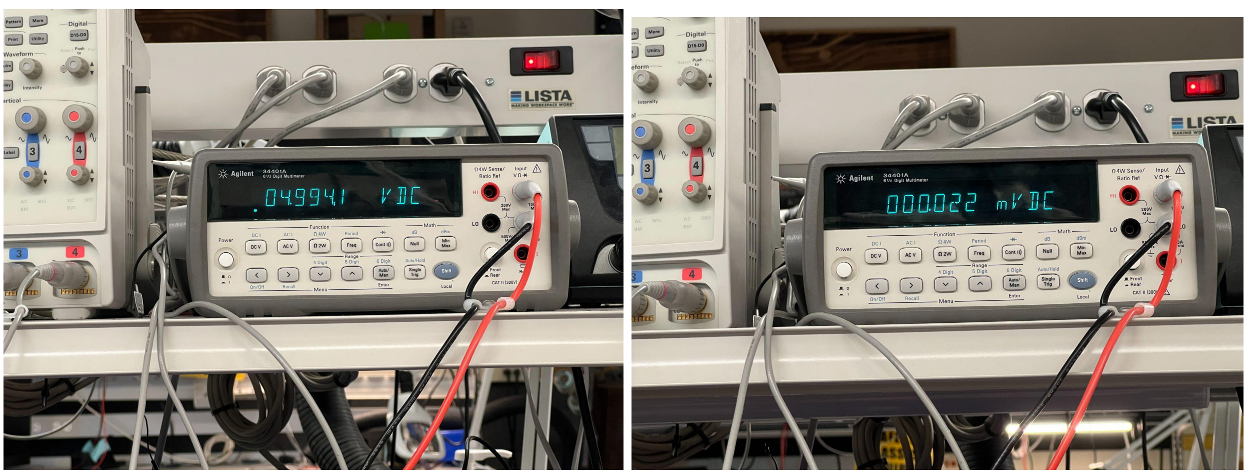


Figure 9 a & 9 b. $V_{Out}1$ and $V_{Out}2$ of BA10324A Breadboarded design.

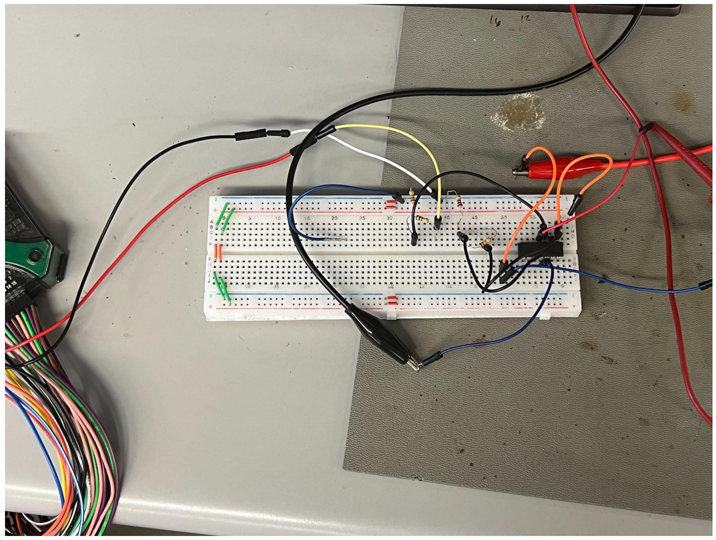


Figure 10. Breadboarded design of BA10324A

Calculations:

$$CMRR = 20log(\frac{V_{Out}1}{V_{Out}2})$$

$$CMRR = 20log(\frac{4.994}{0.000022}) = 107.12 \text{ dB}$$

CA3140 Op-Amps Findings

Electrical Specifications For Equipment Design, at $V_{SUPPLY} = \pm 15V$, $T_A = 25^oC$, Unless Otherwise Specified **(Continued)**

PARAMETER	SYMBOL	CA3140 MIN	CA3140 TYP	CA3140 MAX	CA3140A MIN	CA3140A TYP	CA3140A MAX	UNITS
Large Signal Voltage Gain (Note 3) (See Figures 6, 29)	A_{OL}	20	100	-	20	100	-	kV/V
		86	100	-	86	100	-	dB
Common Mode Rejection Ratio (See Figure 34)	CMRR	-	32	320	-	32	320	µV/V
		70	90	-	70	90	-	dB
Common Mode Input Voltage Range (See Figure 8)	V_{ICR}	-15	-15.5 to +12.5	11	-15	-15.5 to +12.5	12	V
Power-Supply Rejection Ratio, $\Delta V_{IO}/\Delta V_S$ (See Figure 36)	PSRR	-	100	150	-	100	150	µV/V
		76	80		76	80		dB
Max Output Voltage (Note 4) (See Figures 2, 8)	$V_{OM}+$	+12	13	-	+12	13	-	V
	$V_{OM}-$	-14	-14.4	-	-14	-14.4	-	V
Supply Current (See Figure 32)	I+	-	4	6	-	4	6	mA
Device Dissipation	P_D	-	120	180	-	120	180	mW
Input Offset Voltage Temperature Drift	$\Delta V_{IO}/\Delta T$	-	8	-	-	6	-	µV/^{o}C

NOTES:

3. At $V_O = 26V_{P-P}$, +12V, -14V and $R_L = 2k\Omega$.
4. At $R_L = 2k\Omega$.

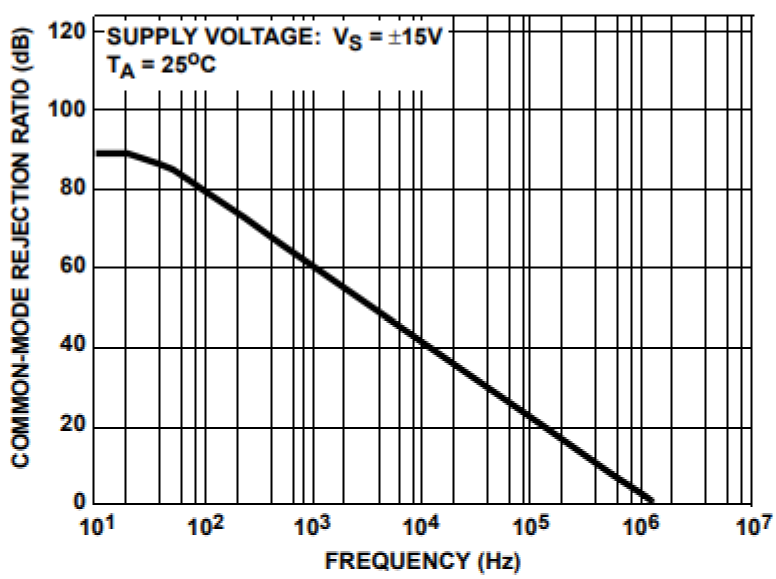


FIGURE 34. COMMON MODE REJECTION RATIO vs FREQUENCY

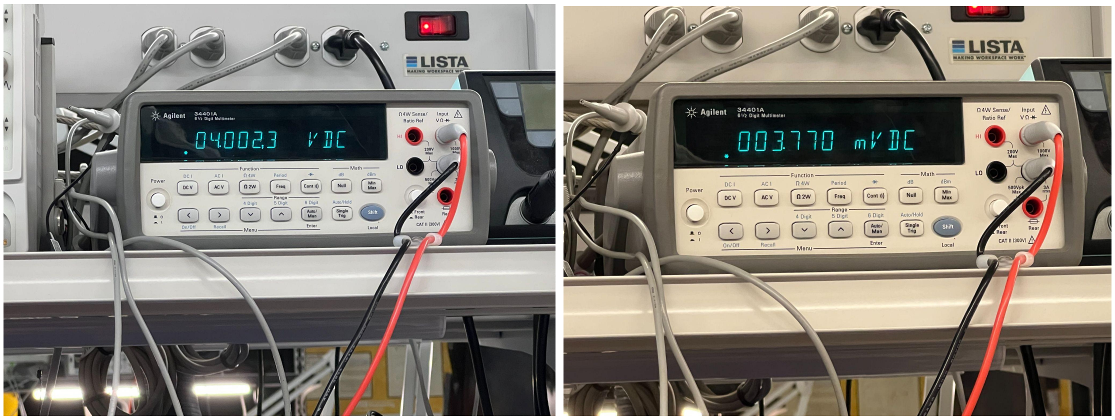


Figure 11 a & 11 b. $V_{Out}1$ and $V_{Out}2$ of CA3140 Breadboarded design.

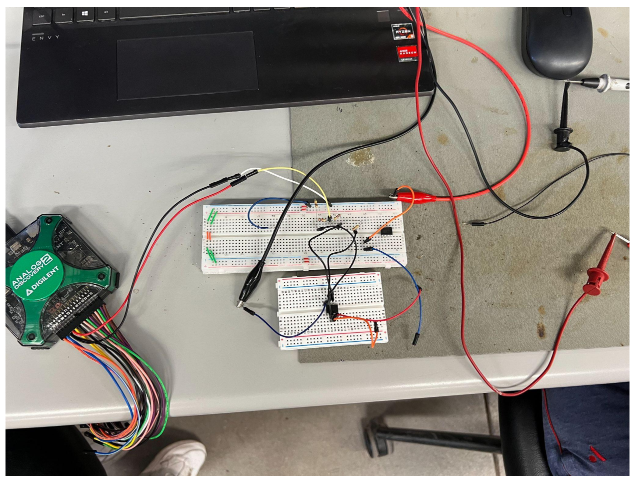


Figure 12. Breadboarded design of LM324

Calculations for Breadboard:

$$CMRR = 20log(\frac{V_{Out}1}{V_{Out}2})$$

$$CMRR = 20log(\frac{4.023}{0.003770}) = 60.51 \text{ dB}$$

LM324 Op-Amps Findings

PARAMETER		TEST CONDITIONS[1]		T_A[2]	LM124, LM224			LM324, LM324K			UNIT
					MIN	TYP[3]	MAX	MIN	TYP[3]	MAX	
V_{IO}	Input offset voltage	V_{CC} = 5 V to MAX, V_{IC} = V_{ICR}min, V_O = 1.4 V		25°C		3	5		3	7	mV
				Full range			7			9	
I_{IO}	Input offset current	V_O = 1.4 V		25°C		2	30		2	50	nA
				Full range			100			150	
I_{IB}	Input bias current	V_O = 1.4 V		25°C		–20	–150		–20	–250	nA
				Full range			–300			–500	
V_{ICR}	Common-mode input voltage range	V_{CC} = 5 V to MAX		25°C	0 to V_{CC} – 1.5			0 to V_{CC} – 1.5			V
				Full range	0 to V_{CC} – 2			0 to V_{CC} – 2			
V_{OH}	High-level output voltage	R_L = 2 kΩ		25°C	V_{CC} – 1.5			V_{CC} – 1.5			V
		R_L = 10 kΩ		25°C							
		V_{CC} = MAX	R_L = 2 kΩ	Full range	26			26			
			R_L ≥ 10 kΩ	Full range	27	28		27	28		
V_{OL}	Low-level output voltage	R_L ≤ 10 kΩ		Full range		5	20		5	20	mV
A_{VD}	Large-signal differential voltage amplification	V_{CC} = 15 V, V_O = 1 V to 11 V, R_L ≥ 2 kΩ		25°C	50	100		25	100		V/mV
				Full range	25			15			
CMRR	Common-mode rejection ratio	V_{IC} = V_{ICR}min		25°C	70	80		65	80		dB

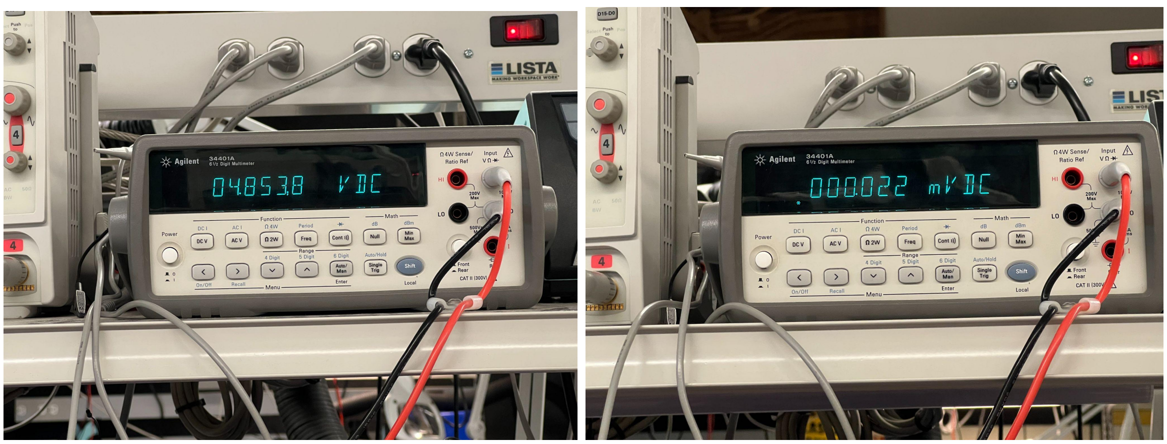


Figure 13 a & 13 b. $V_{Out}1$ and $V_{Out}2$ of LM324 Breadboarded design.

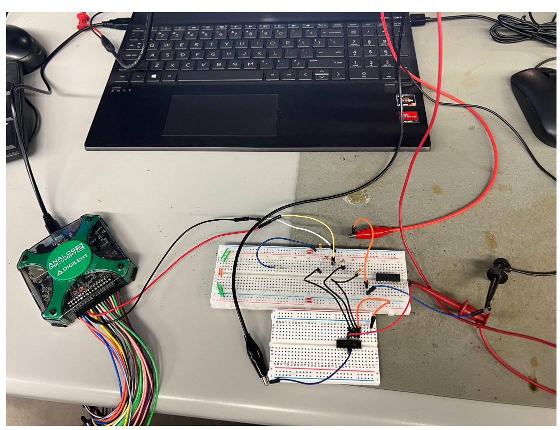


Figure 14. Breadboarded design of LM324

Calculations for Breadboard:

$$CMRR = 20log(\frac{V_{Out}1}{V_{Out}2})$$

$$CMRR = 20log(\frac{4..853}{0.02*10^{-3}}) = 106.87 \text{ dB}$$