INVESTIGATION INTO THE COMMON MODE REJECTION RATIO OF THE PHYSIOLOGICAL SIGNAL CONDITIONER CIRCUIT

Final Report

NASA/ASEE Summer Faculty Fellowship Program--1992

Johnson Space Center

Prepared By: Edward M. O'Brien, Ph.D.

Academic Rank: Associate Professor

University & Department: Mercer University
                                 Electrical and Computer
                                 Engineering Department
                                 Macon, Georgia 31207

NASA/JSC

Directorate: Space and Life Sciences

Division: Life Sciences Project

Branch: Project Engineering

JSC Colleague: Donald J. Stilwell

Date Submitted: October 30, 1992

Contract Number: NGT-44-005-803

ABSTRACT

The common mode rejection ratio (CMRR) of the single operational amplifier (op amp) differential amplifier and of the three operational amplifier differential amplifier was investigated. The three op amp differential amplifier circuit is used in the signal conditioner circuit which amplifies signals such as the electromyograph or electrocardiogram. The investigation confirmed via SPICE modeling what has been observed by others in the recent literature that the CMRR for the circuit can be maximized without precision resistor values or precisely matched op amps. This can be done if one resistor in the final stage can be adjusted either by a potentiometer or by laser trimming in the case of hybrid circuit fabrication.

INTRODUCTION

The physiological signal conditioning circuit is used to amplify various signals such as the electrocardiogram (ECG), the electromyogram (EMG), the electrooculogram (EOG), and the electroencephalogram (EEG). The electrodes used to record these signals will often see a voltage that is common to them. This will happen in the case of EEG electrodes that will also see a voltage due to the ECG. Also, 60 Hz noise is almost always capacitively coupled to the individual being monitored. Hence a differential amplifier is used to subtract out the common voltage and amplify the difference voltage between the electrodes. A measure of how well an amplifier amplifies the difference signal and attenuates the common signal is called the common mode rejection ratio (CMRR). It is important to keep this value as high as possible since some of the signals are very low in amplitude. Thus they are susceptible to being obscured by any voltage that may be in common with the transducing electrodes. This paper investigates the common mode rejection ratio of the one and three operational amplifier (op amp) differential amplifiers.

GENERAL BACKGROUND ON DIFFERENTIAL AMPLIFIERS

A detailed presentation into the theory of cascaded differential stages and differential amplifiers has been presented by Pallás-Areny and Webster (1991 a and b) and will be briefly discussed here. Figure 1 shows a single differential stage. It is assumed that each stage has two inputs and two outputs. These stages can be cascaded. The relationship between the inputs and outputs are governed by the following four terms: G_{DD}, Equation (1), is the differential mode gain assuming that there is no common mode voltage on the inputs. GCC, Equation (2), is the common mode gain assuming that Vo_1 and Vi_2 are equal. G_{DC}, Equation (3), is the common mode input to difference mode output gain. G_{CD}, Equation (4), is the difference mode input to common mode output gain. Two additional terms, C_i and D_i, are defined by Equations (5) and (6) respectively. The actual CMRR of each stage is defined in terms of the C and D values for the current stage and the preceding stages. The total $CMRR_T$ for n cascaded stages is given by Equation (7) and is the reciprocal of the individual stage CMRR's. This seems counter to the way most individuals think of cascaded stage CMRR's as being multiplicative. This intuitive concept can however be seen in Equation (8) which shows that the CMRR of each stage is the product of its own C_i term and the previous stages' D terms. A short discussion of the application of this formula to the single and three op amp differential amplifiers will be presented.
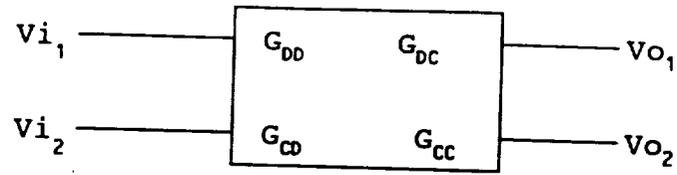
Figure 1.   Two input and two output diagram of a differential amplifier.

$$G_{DD} = \frac{Vo_1 - Vo_2}{Vi_1 - Vi_2} \qquad\qquad (1)$$

$$V_{CC} = \frac{(Vo_1 + Vo_2)/2}{(Vi_1 + Vi_2)/2} \qquad\qquad (2)$$

$$G_{DC} = \frac{Vo_1 - Vo_2}{(Vi_1 + Vi_2)/2} \qquad\qquad (3)$$

$$G_{CD} = \frac{(Vo_1 + Vo_2)/2}{Vi_1 - Vi_2} \qquad\qquad (4)$$

$$C_i = G_{DD_i}/G_{DC_i} \qquad\qquad (5)$$

$$D_i = G_{DD_i}/G_{CC_i} \qquad\qquad (6)$$

$$\frac{1}{CMRR_T} = \sum_{i=1}^{n} \frac{1}{CMRR_i} \qquad\qquad (7)$$

$$CMRR_i = C_i \prod_{1}^{i-1} D_i \qquad\qquad (8)$$

14-4

SINGLE STAGE DIFFERENTIAL AMPLIFIER

In this section the CMRR of the one op amp differential amplifier is examined. Figure 2 shows the complete schematic of all the possible circuit configurations investigated in this paper. Operational amplifier, OA1, and resistors, R1-R4, make up the single op amp differential amplifier. This is really a two stage cascaded differential amplifier. The op amp itself is the last stage and the resistive network is the first stage. The inputs for the resistive stage are V_1 and V_2 and the outputs are at the inverting and noninverting terminal of OA1. The C term for the resistive stage can be calculated to be as shown in Equation (9). The D term for this stage is 1. The C term for the OA1 is just the CMRR of the amplifier as presented in the specifications. For the LT1078AC

$$C = \frac{(2R_2R_4 + R_2R_3 + R_3R_4)/2}{R_2R_3 - R_1R_4} \qquad (9)$$

micropower op amp the typical value for the CMRR is 110 Db with a minimum value of 97 Db at 25° centigrade. This is the low frequency value. The C for this op amp actually starts to roll off with frequency with a 3 Db corner frequency of about 100 Hz. Applying Equation (8) the actual CMRR for the op amp is the product of its C term and the prior stage's D term. This yields a value 106 Db *1 or just 106 Db. Applying Equation (7) the reciprocal of the $CMRR_T$ for the one op amp differential amplifier is equal to the sum of inverses of the CMRR's for the resistive stage, i.e., the inverse of Equation (9), plus the inverse of the op amp CMRR. This would lead one to think that the $CMRR_T$ would always be less than that of lowest CMRR of the two stages just like the effective resistance of parallel resistors. However, by proper choice of resistor values, Equation (9) can actually be negative and thus, in theory, can exactly cancel the CMRR of the OA1 stage. This would result in an infinite $CMRR_T$ at least at frequencies below 100 Hz.

A PSPICE model of the one op amp differential amplifier was examined for the sensitivity of the output to the resistors R1-R4. The normalized sensitivities in units of volts/percent are shown in Table I. The common mode input voltage was 8 V dc. The nominal values of the resistors are also shown in the table. With the values shown, the stage has a differential gain of 10. A ten percent change in R4 would result in an output voltage change of .727 V. It should be noted that the magnitudes of the resistor sensitivity are the same and therefore it would not matter which one was varied. If the resistor values are exactly as indicated in Table I, the CMRR of the resistor stage would

be infinite and therefore the $CMRR_T$ for both stages would be that of the op amp used. If an LT0178 were used that had a CMRR of 106 Db, and if R1-R3 were the exactly as in Table I, then R4 would need to have a value of 199988.98 for the resistor stage to have a CMRR of -106.004 Db. This would cancel the CMRR of the op amp giving a $CMRR_T$ approximately infinite. If adjustment of the amplifier is possible after fabrication then precise resistors need not be used. Low tolerance resistors together with a fixed resistor and a trimmer pot can be used to effectively increase the $CMRR_T$ of the stage. Laser trimming of resistors can also be done in hybrid fabrication.

Table I

Resistor	Value	Normalized Sensitivity (V/percent)
R1	20 kΩ	7.27E-02
R2	200 kΩ	-7.27E-02
R3	20 kΩ	-7.27E-02
R4	200 kΩ	7.27E-02

In the laboratory, the one op amp differential amplifier was constructed using a LT1078 op amp. The values of the resistors are shown in Table II. A 5 V dc and a 5 V ac (1 Hz - 10.0 Khz) source was applied to the two inputs. A trimmer potentiometer comprising part of R4 was adjusted to achieve a minimum output voltage. The resulting value of R4 is shown in the table. The output voltage was minimized until obscured by .5 mV of noise on the output. Thus the CMRR of the stage was better than 100 Db. Equation (9) can be used to calculate the CMRR of the resistor stage and yields a value of -97.556 Db. This is certainly within the range of CMRR's specified for this op amp. The output voltage remained constant up to 1000 Hz and then started dropping. This indicates that the 3 Db point for this op amp was better than the 100 Hz which was indicated in the specification. At 10.0 Khz the CMRR of the stage dropped to 83.3 Db.

Pallás-Areny and Webster (1990) used a LM741C op amp with a specified 90 Db CMRR and obtained a $CMRR_T$ at 10 Hz and below of 126 Db (which was the limit of their measurement capabilities). This was done with nonprecision resistors and a trim pot. As expected, if the op amp was exchanged for another the potentiometer had to be readjusted to minimize $CMRR_T$.

Table II   Laboratory resistor values for one op amp differential amplifier.

Resistor	Value
R1	20.0184 kΩ
R2	191.194 kΩ
R3	20.0079 kΩ
R4	191.067 kΩ

Table III   Resistor values and sensitivities for the 3 op amp differential amplifier.

Resistor	Value	Normalized Sensitivity (V/percent)
R1	20 kΩ	7.27E-02
R2	200 kΩ	-7.27E-02
R3	20 kΩ	-7.27E-02
R4	200 kΩ	7.27E-02
R5	2 kΩ	-8.70E-10
R6	100 kΩ	5.51E-05
R7	100 kΩ	-5.51E-05

THREE OP AMP DIFFERENTIAL AMPLIFIER

The three op amp differential amplifier is shown in Figure 2 and comprises op amps OA1-OA3 and resistors R1-R7. For the present discussion OA2, OA3 and R5-R7 will be considered as one stage. The common mode rejection ration for this first stage, $CMRR_{F}$, [i.e., its C term as defined in Equation (5)] has been developed by Pallás-Areny and Webster and just the results will be reproduced here in Equation (10). In this equation the A_d's and the A_c's refer to the difference gain and common gains of the OA2 and OA3. It should be noted that R5-R7 are not involved with the CMRR of this stage. The following will indicate why this is so.
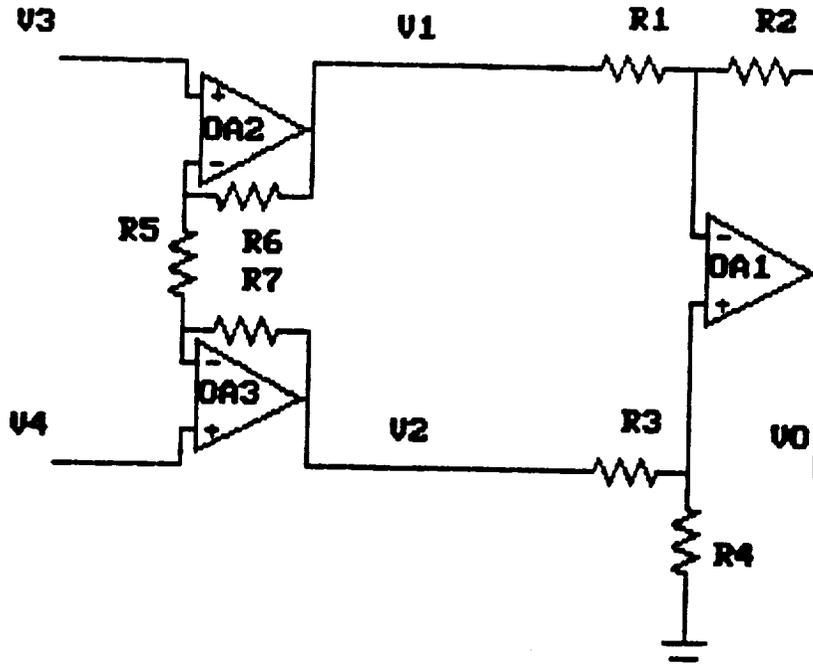
Figure 2. One and three op amp differential amplifier.

The sensitivity of the output to all resistors, R1-R7 was investigated with a PSPICE program. Again, the input common mode voltage was 8 V and the sensitivities are reported in terms of volts/percent. The results of the analysis are shown in Table III. The

$$\frac{1}{2} \frac{A_{d2}+A_{c2}/2+A_{d3}+A_{c3}/2+2A_{d2}A_{d3}-A_{c2}A_{c3}/2}{A_{d3}+A_{c3}/2-A_{d2}-A_{c2}/2+A_{d2}A_{c3}-A_{d3}A_{c2}} \qquad (10)$$

sensitivities of R1-R4 are the same as those found for the 1 op amp differential amplifier. The sensitivities of R6 and R7 are the same except for a negative sign and these sensitivities are approximately 1300 times less than for R1-R4. Thus they affect the common mode output very little. R5 has virtually no effect on the common mode voltage as seen by its very low sensitivity. From these results the maximum change in the common mode voltage gain is associated with resistors R1-R4.

From Equation (10) it is evident that for high a high $CMRR_F$ the two input op amps OA2 and OA3 must have both their common mode gains and difference mode gains matched. It is not enough to just have equal CMRR's for each.

The D term for this first stage, as defined in Equation (6), is given by Equation (11) and it can be found in many books on electronics (e.g., Horowitz and Hill, 1989 p. 425). This assumes that R6 and R7 are equal. The term $CMRR_S$ will be used for the common mode rejection ratio of the second stage of the three op amp differential amplifier. It will now consist of the CMRR found for this stage times the D term for the preceding stage as indicated by Equation (8).

$$D = 1 + \frac{2R6}{R5} \qquad (11)$$

Therefore, the $CMRR_T$ for the three op amp differential amplifier is given by equation (7) and shown more explicitly in Equation (12). If $CMRR_F$ and $CMRR_S$ have equal sign then $CMRR_T$ will be less that the lowest of the individual stage's CMRR. However, again by

$$\frac{1}{CMRR_T} = \frac{1}{CMRR_F} + \frac{1}{CMRR_S} \qquad (12)$$

adjusting one of the resistors R1-R4, $CMRR_S$ can be either positive or negative. Thus the total CMRR of the whole differential amplifier circuit can be in theory, made close to infinity. PSPICE modeling of this circuit verified this observation. Adjustment of R4 would allow the $CMRR_T$ to be driven arbitrarily close to infinity even when the A_d's and A_c's of OA2 and OA3 were greatly mismatched. Adjustment of R4 can even compensate for a mismatch of R6 and R7.

SUMMARY

In summary, if no adjustment can be made of the resistor values in the one or three op amp differential amplifier, then all resistor values should be precise and the two op amps in the first stage of the three op amp differential amplifier must have their common mode gains and their difference mode gains matched. Also each op amp should have a high CMRR. However, if one of the resistors in the last stage can be adjusted to null the overall CMRR of the amplifier then precision resistors and exactly matched operational amplifiers need not be used.

REFERENCES

Horowitz, P. and W. Hill. 1989. The Art of Electronics. Cambridge University Press, Cambridge. 1125 pp.

Pallás-Areny, R. and J.G. Webster. 1990. Composite Instrumentation Amplifier for Biopotentials. An. of Bio. Eng., vol 18, 251-262.

Pallás-Areny, R. and J.G. Webster. 1991a. Common Mode Rejection Ratio in Differential Amplifiers. IEEE Trans. Inst. and Meas., vol 40, No. 4, 669-676.

Pallás-Areny, R. and J.G. Webster. 1991b. Common Mode Rejection Ratio for Cascaded Differential Amplifier Stages. IEEE Trans. Inst. and Meas., vol 40, No. 4, 677-681.