

Name:

Roll Number:

Laboratory 6

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Instrumentation amplifier

Today's lab is a mini-quiz. You are allowed to discuss with your group for the design & analysis of Parts A to C – get your answers checked in sequence. Circuit building & testing happens in Part D.

The term 'instrumentation amplifier' is generally used to denote an amplifier that has the following properties:

1. High gain
2. Accepts a differential input
3. Has very high input impedance
4. Produces a single ended output with reference to a user supplied V_{ref}
5. Has very small output impedance
6. Has very high CMRR

In this assignment we will build up an instrumentation amplifier in steps to satisfy each of the above criteria. Recall the diagram of a measurement system shown in Fig 1, which we discussed in the introductory lecture:

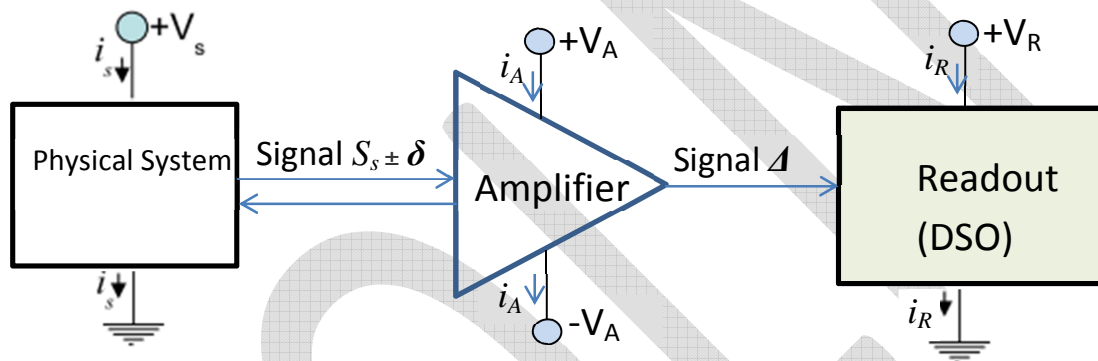


Fig 1: Typical measurement system with an instrumentation amplifier

Introduction – definition of CMRR

The steady state currents consumed by the three components: Source i_s , Amplifier i_A , Readout i_R are usually very different. Hence the steady state signals generated by the three devices S_s , S_A , S_R will also be different. These can be voltage or current signals.

The source is a transducer that converts a physical effect (eg: light shining on a photo-diode, pressure measured by a piezo sensor etc...) into a small electrical signal δ centered around the steady-state value S_s . For a *voltage* source: S_s is typically set to $(V_s/2)$ so as to maximize the 'dynamic' range: $S_s \pm \delta = V_s/2 \pm \delta$ is allowed to swing through the full range between V_s and 0.

This places a restriction on the design of the amplifier with (large) gain G : The amplifier's output $S_A = G(S_s \pm \delta)$ would normally be so large as to always keep S_A saturated.

Therefore the amplifier, which we now call an instrumentation amplifier, must operate such that the steady-state source signal S_s is rejected and only the dynamic part $\pm \delta$ is amplified: $S_A = \pm \Delta = G(\pm \delta)$

This principle is called Common Mode Rejection, and it is quantified by the Common Mode Rejection Ratio (CMRR)

Mathematical definition of CMRR: Consider a two-terminal device which produces voltages V_1 , V_2 at its terminals. The signal input to the amplifier is $V_{in} = (V_1 - V_2)$. An amplifier with differential signal gain A_D provides $V_{out} = A_D \cdot V_{in}$. The common mode signal is defined as $V_{cm} = (V_1 + V_2)/2$ and the common-mode gain is $A_{CM} = V_{out}/V_{cm}$. The CMRR is defined by the following formula. You want to have it as large as possible. The 'bare' opamp has an intrinsic CMRR (look this up in the datasheet). A feedback circuit to stabilize the gain will almost always reduce the CMRR.

$$CMRR = \frac{A_D}{A_{CM}} \text{ in dB: } \left(20 \log_{10} \frac{A_D}{A_{CM}} \right) \text{ dB}$$

Intelligent circuit design is required to keep the CMRR as high as *practically* possible.

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Part A: Difference amplifier

Consider the simple difference amplifier circuit in Fig 2(a). It has the two voltages v_1 & v_2 as input. To begin with let us consider v_1 & v_2 as two *independent voltages* – we are interested in what happens to the *difference* ($v_1 - v_2$)

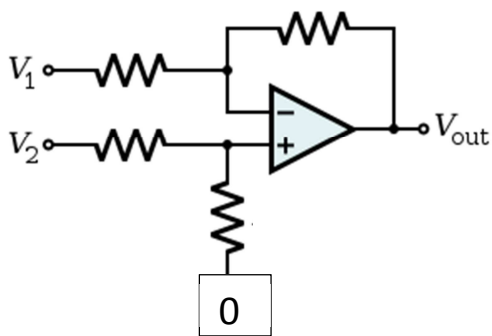


Fig 2(a): Difference amplifier – all resistors are of equal value R

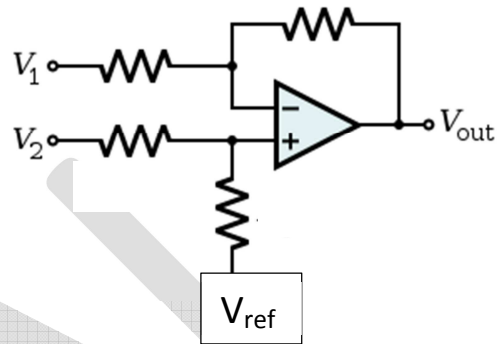


Fig 2(b): Difference amplifier – space for analysis

Q1: What is the input impedance seen by v_1 in Fig 2(a) ?

Ans: R

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Q2: What is the input impedance seen by v_2 in Fig 2(a) ?

Ans: $2R$

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Q3: Use KVL to determine the voltages at each node of the circuit in Fig 2(a) – mark your answers in the circuit of Fig 2(b)

Hint: Since the opamp draws no current, the voltages at its (+) and (-) terminal are always equal [Golden Rule 1 of opamp design!]

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Q4: Using the answers to Q3, What is the relation of v_{out} to $(v_1 - v_2)$?

Hint: As discussed in the lecture, you can use superposition – set v_1 and v_2 to zero one at a time and determine v_{out}

Ans: $v_{out} = (v_1 - v_2)$

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Q5: Suppose you have a common mode voltage $v_{cm} = (v_1 + v_2)/2$ always present, what is the relation of v_{out} to v_{cm} ?

Ans: $v_{out} = 0$

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Q6: In the above calculations, v_{out} is referenced to the 0V shown in Fig 2(a). Suppose 0V is replaced by an arbitrary user defined voltage V_{ref} in the box shown in Fig 2(b). How does your answer to Q4 change? $V_{out} = \text{function}(v_1 - v_2)$

Ans: *stays the same:* $v_{out} = v_1 - v_2$; v_{out} is now referred to V_{ref} not 0V

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Q7: Based on your answers to the above questions, list the criteria of the instrumentation amplifier design that a difference amplifier *does not* satisfy

Ans: *Low and asymmetrical input impedance.*

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Part B: Evolution of the difference amplifier design

Let us work on improving the difference amplifier of Part A by fixing its problems one at a time:

B₁: The most severe problem is obviously that the input impedance presented to V_{in} is small

Add requisite blocks to the difference amplifier so that the input terminals v_1 and v_2 look into large (equal) impedances. Draw your modified block diagram here.

Solution:

Obvious thing is to add unity gain buffers in line between v_1 and v_2 each to the inputs of the difference amplifier

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B₂: The second obvious problem is the high gain requirement for the instrumentation amplifier, which we have not gotten out of the difference amplifier yet.

Investigate ways of providing large gain to the *differential* signal $v_d = (v_1 - v_2)$

Draw your possible design of a high gain, high input impedance differential amplifier here:

Students may want to

1. Add finite gain to the unity gain blocks. This has the problem that gain of each is set by a separate set of R_f/R_0 resistors. So depending on slight variations in resistor values, v_1 and v_2 will have unequal gain in their paths.
2. Add finite gain to the final stage difference amplifier.

(1) is preferable, but both the above lead to high A_{CM} as calculated below.

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Important: For whatever design you make here, calculate *both* the differential gain A_D and the common-mode gain A_{CM} of your design. Recall that our final objective is to make A_D very high while keeping A_{CM} as low as possible for high CMRR.

Instructor's note: typically this assignment is done just before midsem. Parts A+B can be completed in one afternoon. Students may need one more session to read up references and complete Part C. Try to arrange an extra afternoon in the same week for students to complete the instrumentation amplifier design in Part C in the same week (else they will have forgotten Parts A+B by the time they come back after midsem)

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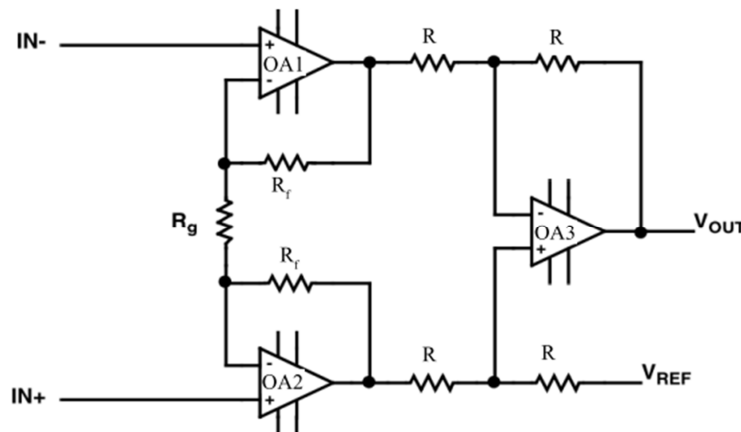
Part C₁: Final design of Instrumentation amplifier

By now, you should have solved most of the problems of the simple difference amplifier to arrive at a *nearly* good instrumentation amplifier. **Except** we still need to:

1. Minimize the common mode gain A_{cm} to get a high CMRR
2. Reduce dependence on values of discrete passive parts like resistors. Ideally, the entire circuit should use just one value of the resistor R , and the gain must be set by one gain setting resistor R_g

Make the requisite improvements to design of Part C to arrive at the final design of a 3 opamp instrumentation amplifier which satisfies all the 7 criteria listed on page 1.

Solution:



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Resistor matching not critical – need six matching R (if we use $R_f = R$), Gain is set by R_g

Part C₂: The CMRR – is it good?

Calculate the differential and common mode gains A_D and A_{CM} of your design

Hint: Use Golden Rule 1 and superposition for A_D . Determine the quantity and directions of current flow with $v_1 = v_2$ for A_{cm}

$$A_D = R/R_g$$

For $v_1 = v_2$ no current flows through R_g so each of OA1 and OA2 effectively reduce to unity gain and $A_{cm} = 1$

/1: A_D /2.5: A_{cm}

Part D: Test of Instrumentation amplifier

Build and demonstrate the operation of your 3 opamp instrumentation amplifier designed in Part C. You may set $G=10$. Use a differential sine wave signal of small magnitude as V_{in} . Demonstrate the high CMRR of your design by applying an offset to V_{in} and checking if the offset is rejected by the circuit.

Note that the three opamp instrumentation amplifier is often available as a pre-packaged IC (for example AD524). All the resistors are precision matched within the IC – only 2 external pins are provided to connect the gain setting resistor.

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