Lesson 11: Transducer Electrical Interfaces

ET 438b Sequential Control and Data Acquisition
Department of Technology

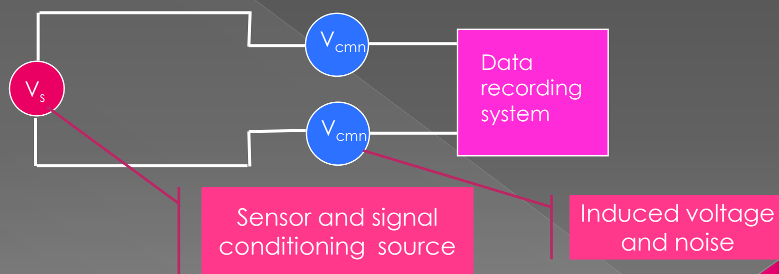
Learning Objectives

After this presentation you will be able to:

- Explain how to reject noise and undesired signal from transducer outputs using differential amplifier circuits
- List the electrical characteristics of the differential amplifier
- Analyze differential amplifier circuits
- Utilize differential amplifiers to measure voltage and current with minimal loading effects.

COMMON MODE VOLTAGES IN INSTRUMENTATION AND CONTROL

Common mode voltages are voltages that have the same magnitude and phase shift and appear at the inputs of a data acquisition system. Common mode voltages mask low level signals from low gain transducers.

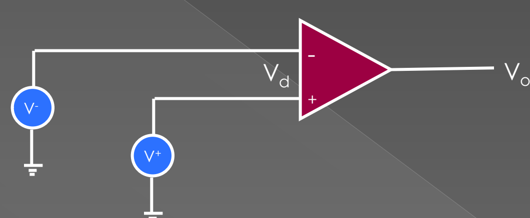


Common mode voltages also appear on shielded systems due to differences between input potentials

Common Mode Voltage Due to Inputs

Common mode voltage due to ground

Differential Amp



$$V_d = V^+ - V^-$$

$$V_{cmg} = \frac{V^+ - V^-}{2}$$

Total common mode voltage **$V_{cm} = V_{cmn} + V_{cmg}$**

OP AMP differential inputs designed to reject common mode voltages. Amplify only $V_d = V^+ - V^-$.

Common Mode Voltages and OP AMPs

Define: **A_c** = gain of OP AMP to common mode signals (designed to be low)
A_d = differential gain of OP AMP. Typically high (A_d = 200,000 for 741)

Ideal OP AMPs have infinite A_d and zero A_c

Common mode rejection ratio (CMRR) is a measure of quality for non-ideal OP AMPs. Higher values are better.

$$CMRR = \frac{A_d}{A_c}$$

Where A_d = differential gain
A_c = common mode gain

Common Mode Rejection

Common Mode Rejection (CMR) calculation

$$CMR = 20\log\left[\frac{A_d}{A_c}\right] = 20\log[CMRR]$$

CMR units are db. Higher values of CMR are better.

Example: A typical LM741 OP AMP has a differential gain of 200,000. The typical value of common mode rejection is 90 db. What is the typical value of common mode gain for this device

Common Mode Rejection Example Solution

From problem statement V_d = 200,000 CMR = 90 db

$$CMR = 20\log\left[\frac{A_d}{A_c}\right]$$

Solve for A_c by using the anitlog

$$\frac{CMR}{20} = \log\left[\frac{A_d}{A_c}\right]$$

Raise both sides to power of 10

$$10^{\frac{CMR}{20}} = \left[\frac{A_d}{A_c}\right]$$

Solve for A_c

$$\frac{A_d}{10^{\frac{CMR}{20}}} = A_c$$

Plug in values and get numerical solution

$$\frac{200{,}000}{10^{\frac{90}{20}}} = \frac{200{,}000}{10^{4.5}} = \frac{200{,}000}{31{,}623} = 6.32 = A_c$$

Common mode gain is 6.32 for typical LM741

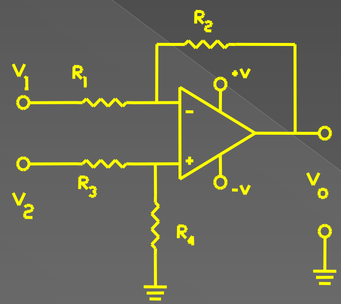
Difference Amplifier and Instrumentation Amplifiers

Characteristics of Instrumentation Amplifiers

- Amplify dc and low frequency ac (f<1000 Hz)
- Input signal may contain high noise level
- Sensors may low signal levels. Amp must have high gain.
- High input Z to minimize loading effects
- Signal may have high common mode voltage with respect to ground

Differential amplifier circuit constructed from OP AMPs are the building block of instrumentation amplifiers

Basic Difference Amplifiers



Input/output Formula

$$V_o = \left(\frac{R_2 + R_1}{R_4 + R_3}\right)\cdot\left(\frac{R_4}{R_1}\right)\cdot V_2 - \left(\frac{R_2}{R_1}\right)\cdot V_1$$

To simplify let

$R_1 = R_3$ and $R_2 = R_4$

$$V_0 = \left(\frac{R_2}{R_1}\right)\cdot(V_2 - V_1)$$

Amplifies the difference between +/ - terminals

Polarity of OP AMP input indicates order of subtraction

Basic Difference Amplifiers

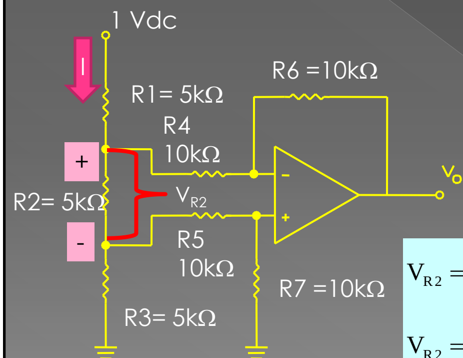
Practical considerations of basic differential amplifiers

- Resistor tolerances affect the CMRR of OP AMP circuit. Cause external unbalance that decreases overall CMRR.
- Input resistances reduce the input impedance of OP AMP
- Input offset voltages cause errors in high gain applications
- OP AMPs require bias currents to operate

Difference Amplifier Loading Effects

To minimize the loading effects of the OP AMP input resistors, their values should be at least 10x greater than the source impedance

Example: Determine the loading effects of differential amp Input on the voltage divider circuit. Compare the output predicted by differential amplifier formula to detailed analysis of circuit.



Assume no loading effects and use the OP AMP gain formula

$$V_0 = \left(\frac{R6}{R4}\right)\cdot(V_2 - V_1)$$

$$(V_2 - V_1) = (V^+ - V^-) = -V_{R2}$$

$$V_{R2} = \left[\frac{-R2}{R1+R2+R3}\right]\cdot V = \left[\frac{-5k\Omega}{5k\Omega+5k\Omega+5k\Omega}\right]\cdot 1\,V$$

$$V_{R2} = \left[\frac{-5k\Omega}{15k\Omega}\right]\cdot 1\,V = -0.3333\,V$$

Difference Amplifier Loading Effects

Find the output ignoring the loading effects that the OP AMP has on the voltage divider.

$$V_0 = \left(\frac{R6}{R4}\right)\cdot(-V_{R2})$$

$$V_0 = \left(\frac{10\,k\Omega}{10\,k\Omega}\right)\cdot(-0.333) = -0.333\,V$$

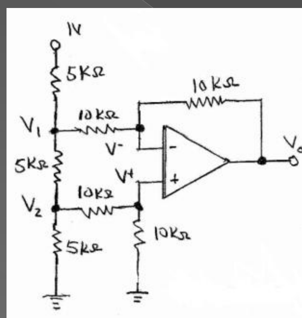
Now solve the circuit and include the loading effects of the OP AMP input resistors. Use nodal analysis and check with simulation.

Remember the rules of ideal OP AMPs:

$I_{in} = 0$ and $V^+ = V^-$

Difference Amplifier Loading Effects

Solution using nodal analysis



NODAL ANALYSIS

① $V^+ = V^-$ from OP AMP THEORY

② AT NODE V_1 (ASSUMING ALL I's LEAVE)

$$-\left[\frac{V_1-1}{5000}\right]-\left[\frac{V_1-V^-}{10,000}\right]-\left[\frac{V_1-V_2}{5000}\right]=0$$

$$0.0005V_1-0.0001V^--0.0002V_2=0.0002$$

③ AT NODE V_2

$$-\left[\frac{V_2-V_1}{5000}\right]-\left[\frac{V_2-V^+}{10,000}\right]-\left[\frac{V_2}{5000}\right]=0$$

$$0.0005V_2-0.0002V_1-0.0001V^+=0$$

④ AT NODE V^+

$$-\left[\frac{V^+-V_2}{10,000}\right]-\left[\frac{V^+}{10,000}\right]=0$$

$$2V^+-V_2=0$$

⑤ AT NODE V^-

$$-\left[\frac{V^--V_0}{10,000}\right]-\left[\frac{V^--V_1}{10,000}\right]=0$$

$$-V^-+V_0-V^-+V_1=0$$

$$2V^--V_1-V_0=0$$

Difference Amplifier Loading Effects

Solve simultaneous equations and determine percent error due to loading

5 equations and 5 unknowns

ELIMINATE V^+ FROM EQUATIONS USING ①

② $-5\times10^{-4}V_1-0.0002V_2-0.0001V^-+0V_0=0.0002$

③ $-0.0002V_1+5\times10^{-4}V_2-0.0001V^-+0V_0=0$

④ $0V_1+-1V_2+2V^-+0V_0=0$

⑤ $-1V_1+0V_2+2V^-+-1V_0=0$

SOLVE USING TI-85 CALCULATOR

$V_1=0.514\text{V}$ $V_2=0.229\text{V}$ $V^-=0.114\text{V}$

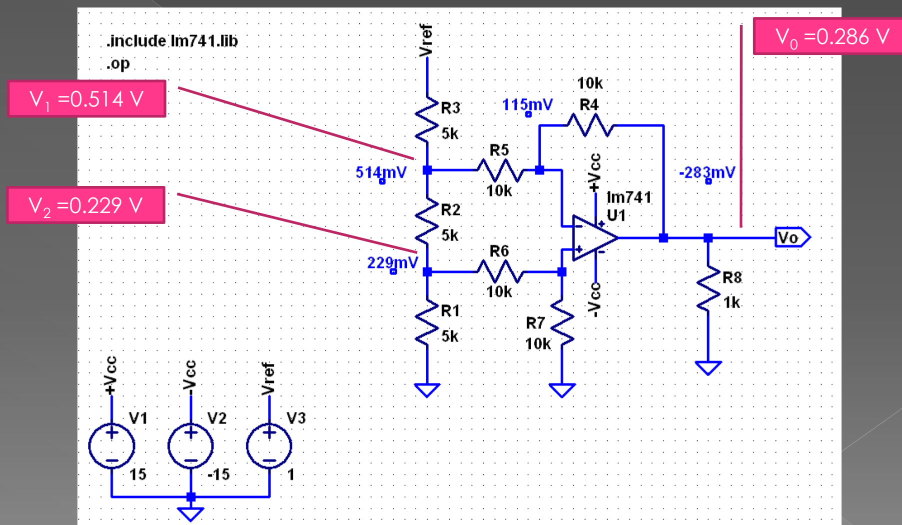
$\boxed{V_0=-0.286\text{V}}$

$$\%\text{ ERROR}=\frac{(-0.286)-(-0.333)}{(-0.286)}\times100\%$$

$\%\text{ ERROR}=-16.53\%$

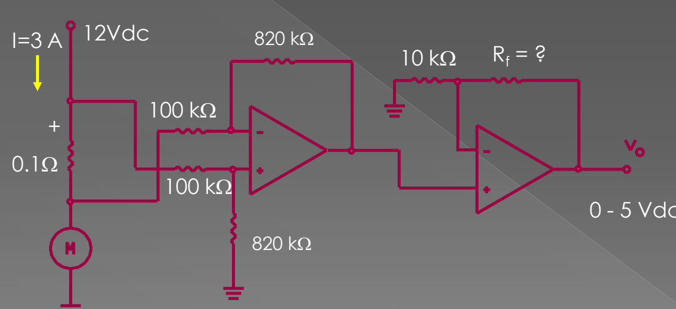
Difference Amplifier Loading Effects

Results of operating point analysis in LTSpice



Example: Measuring dc current with a current shunt

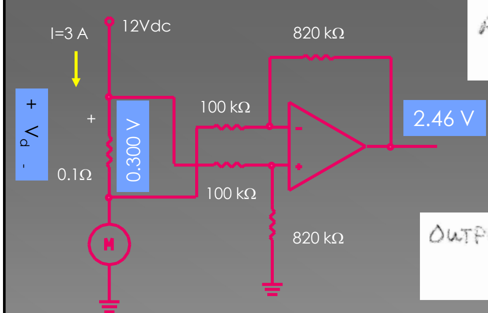
Dc motor draws a current of 3A dc when developing full mechanical power. Find the gain of the last stage of the circuit so that the output voltage is 5 volts when the motor draws full power. Also compute the power dissipation of the shunt resistor



Example: Measuring dc current with a current shunt

Example Solution

CURRENT SENSING
V_d = VOLTAGE ACROSS SHUNT
$V_d = IR$
VOLTAGE IS PROPORTIONAL TO CURRENT

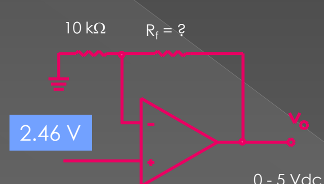


AT FULL LOAD $V_d = (3A)(0.1\Omega) = 0.3V$
$V_d = 300\ mV$

COMPUTE GAIN OF DIFF AMP.
$A_{V_d} = \frac{820\ k\Omega}{100\ k\Omega} = 8.2$

OUTPUT OF DIFF. AMP
$V_{o1} = A_{V_d} V_d = (8.2)(0.300V) = 2.46V$

Example Solution



INPUT TO NON-INVERTING AMP CIRCUIT
$V_{o1} = 2.46V \quad A_V = 1 + \frac{R_f}{R_1} \Rightarrow \frac{5.0V}{2.46V} = 2.03$

$2.03 = 1 + \frac{R_f}{R_1} \quad R_1 = 10k\Omega$
$1.03 = \frac{R_f}{10k} \Rightarrow (10k)(1.03) = 10.3\ k\Omega = R_f$

Compute power dissipation at full load I= 3 A so….

$P = I^2 R \quad R = 0.1\Omega$
$P = (3A)^2(0.1\Omega) = 0.9W$

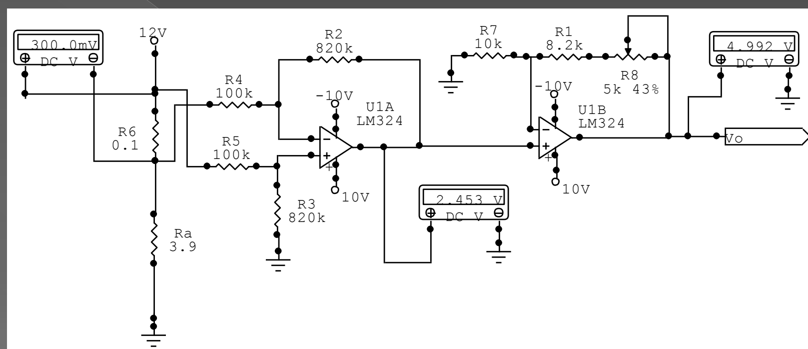
Use 1 Watt or greater Standard value

R_f is a non-standard value. Use 8.2 kΩ resistor and 5 kΩ potentiometer. Calibrate with 300 mV source Until 5.00 V output is achieved

Caution: Note the maximum differential Voltage specification of OP AMP. (30 V for LM741)

Example Solution Simulation

Simulated with Circuit Maker (Student Version)



End Lesson 11: Transducer Electrical Interfaces

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