ET 438 b Digital Control and Data Acquisition
Department of Technology

Lesson 12: Analog Signal Conditioning

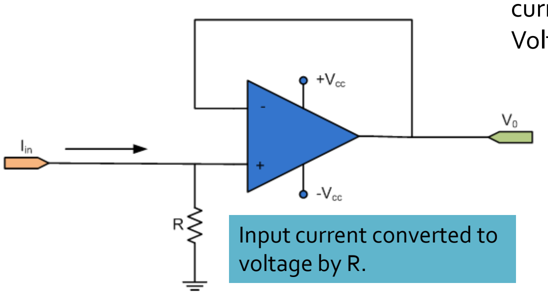
Learning Objectives

After this presentation you will be able to:

- Design a voltage-to-current interface for a transducer and simulate its operation using commonly available software
- List the modes of operation of a Wheatstone bridge circuit
- Explain how Wheatstone bridge resistor values effect linearity and sensitivity
- Design a signal conditioning circuit for a Wheatstone bridge.

Analog-to-Analog Conversion Signal Conditioning

Current-to-Voltage Converter
I-to-V Converter



Input current converted to voltage by R.

Since $V^+ = V^-$

$V_o = I_{in} \cdot R$

Example: Find a value the value of R that converts a 4 mA to 20 mA current signal into a 1 – 5 V output Voltage.

$$V_o = I_{in} \cdot R \;\Rightarrow\; R = \frac{V_o}{I_{in}}$$

$$V_o = 1\,\text{V} \;@\; I_{in} = 4\,\text{mA}$$

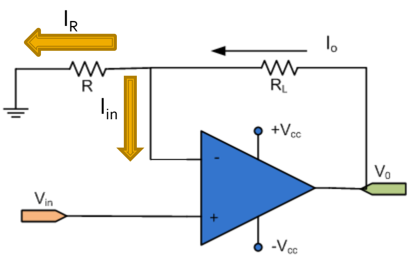
$$R = \frac{1\,\text{V}}{4\,\text{mA}} = 250\,\Omega$$

Check output at 20 mA

$$V_o = 250\,\Omega \cdot (20\,\text{mA}) = 5\,\text{V}$$

Signal Conditioning

Voltage-to-Current Converter
V-to-I Converter (Transconductance Amps)



Ungrounded load

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

So $I_o - I_R = 0$ or $I_o = I_R$

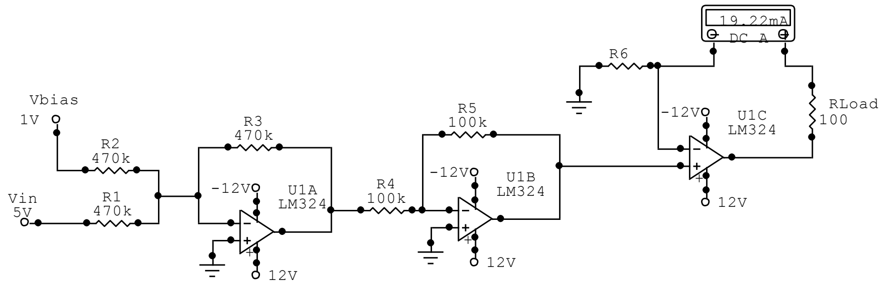
$$I_o = I_R = \frac{V^-}{R} \quad \text{but } V^- = V^+ = V_{in}$$

$$I_o = \frac{V_{in}}{R}$$

Note: $R_L < R$ for practical circuit operation. OP AMP output voltage determines magnitude of R_L for constant current

Signal Conditioning Example

Convert a 0-5 V dc voltage signal to a 4-20 mA current signal using OP AMP circuits.



Determine the ratio of spans

$$R6 = \frac{V_{in}}{I_0} = \frac{V_{in(max)} - V_{in(min)}}{I_{0max} - I_{0min}} = \frac{5\,V - 0\,V}{20\,mA - 4\,mA} = \frac{5\,V}{16\,mA} = 312.5\,\Omega$$

Signal Conditioning Example

Compute the value of Vbias to give the value of minimum output current

$$I_{0min} = 4\,mA$$
$$I_0 = \frac{V_{in}}{R} \Rightarrow I_0 \cdot R = V_{in}$$
$$V_{bias} = I_{0min} \cdot R$$
$$R = 312.5\,\Omega$$
$$V_{bias} = (4\,mA)\cdot(312.5\,\Omega)$$
$$V_{bias} = 1.25\,V$$

Check the output with $V_{in} = 5\,V$

$$I_0 = \frac{V_{in}}{R}$$
$$V_{max} = V_{in(max)} + V_{bias}$$
$$V_{max} = 5\,V + 1.25\,V$$
$$I_0 = \frac{6.25\,V}{312.5\,\Omega}$$
$$I_0 = 0.02\,A = 20\,mA$$

What in max value of R_L? Assume $V_{sat} = 10.5\,V$

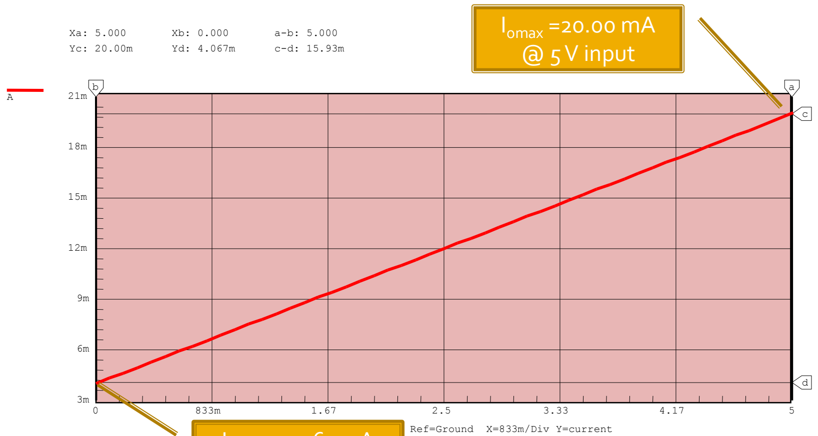
$$R_{L(max)} = \frac{V_{sat} - V_{in(max)}}{I_{o\,max}}$$
$$V_{sat} = 10.5\,V$$
$$I_{o\,max} = 0.020\,A = 20\,mA$$
$$V_{in(max)} = 6.25\,V$$
$$R_{L(max)} = \frac{10.5\,V - 6.25\,V}{0.02\,A} = 212.5\,\Omega$$

Assumes OP AMP has sufficient current output

Circuit Simulation of Example: Dc Sweep

Output Current Vs Input Voltage

I_{omax} =20.00 mA @ 5 V input



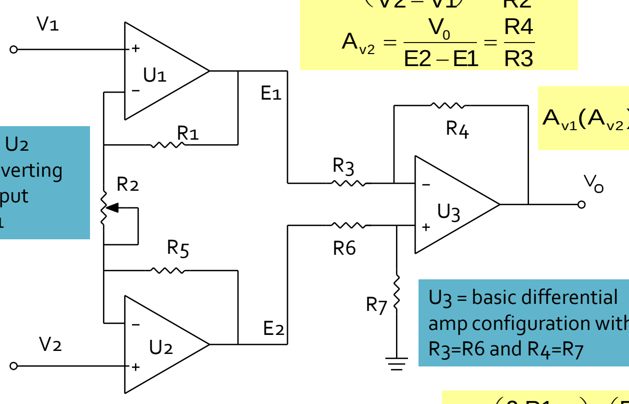
I_{omax} =4.067 mA @ 0 V input

Instrumentation Amps with High Impedance Input

Two-stage circuit

$$A_{v1} = \left(\frac{E2 - E1}{V2 - V1}\right) = \frac{2\ R1}{R2} + 1$$

$$A_{v2} = \frac{V_o}{E2 - E1} = \frac{R4}{R3}$$



U1 and U2 Non-inverting Hi-Z input R5 = R1

$$A_{v1}(A_{v2}) = \left(\frac{2\ R1}{R2} + 1\right) * \left(\frac{R4}{R3}\right)$$

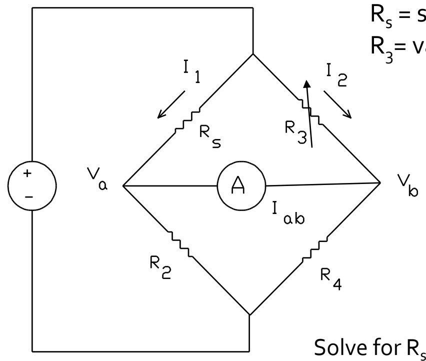
U3 = basic differential amp configuration with R3=R6 and R4=R7

Overall circuit gain

$$V_o = \left(\frac{2\ R1}{R2} + 1\right) * \left(\frac{R4}{R3}\right) * (V2 - V1)$$

Signal Conditioning-Bridge Circuits

Dc bridges (Wheatstone bridges) Used to detect small resistance changes in sensors. Typically used with sensors that measure force, temperature, and pressure.



R_s = sensor R

R_3= variable resistor used to balance bridge

When bridge is balanced:

$I_{ab} = 0$ since $V_a = V_b$

so $I_1R_s = I_2R_3$ and $I_1R_2 = I_2R_4$

$$\frac{R_s}{R_2} = \frac{R_3}{R_4}$$

Solve for R_s

$$R_s = \frac{R_3}{R_4}R_2$$

Adjust R_3 until $I_{ab} = 0$ compute R_s

Bridge Use Methods

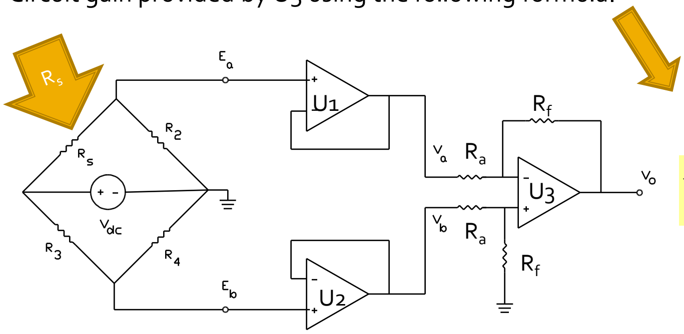
There are two operating modes for a dc bridge: balanced (null) and unbalanced

Null Mode - adjust R_3 variable resistor until $I_{ab} = 0$. Need automatic nulling circuit for automatic operation.

Unbalanced Mode - insert sensor and null bridge for sensor measurement. When initial value of sensor changes measure difference in voltage. Bridge only balanced at one point

Unbalanced Bridge Operation

Note the unbalanced bridge shown below. U1 and U2 provide high-Z input.
Circuit gain provided by U3 using the following formula.

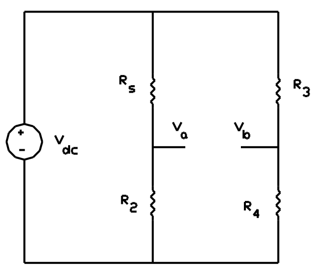


$$V_o = \frac{R_f}{R_a}(V_b - V_a)$$

Find expression for bridge equation. in terms of the change
in sensor resistance R_s.

Unbalanced Bridge Analysis

Bridge Circuit



Find the voltage V_{ba} in terms of the resistors

$$V_a = \left(\frac{R_2}{R_s + R_2}\right) \cdot V_{dc}$$

$$V_b = \left(\frac{R_4}{R_3 + R_4}\right) \cdot V_{dc}$$

$$V_b - V_a = \left(\frac{R_4}{R_3 + R_4} - \frac{R_2}{R_s + R_2}\right) \cdot V_{dc}$$

$$R_{bal} = \frac{R_2 R_3}{R_4}$$

Normalize V_{ba} by dividing by supply V.
Find common denominator

$$\frac{V_b - V_a}{V_{dc}} = \left(\frac{R_4}{R_3 + R_4} - \frac{R_2}{R_s + R_2}\right) = \frac{R_4(R_s + R_2) - R_2(R_3 + R_4)}{(R_3 + R_4)(R_s + R_2)}$$

Unbalanced Bridge Analysis

Bridge Analysis (Continued)

Expand terms and simplify

$$\frac{V_b - V_a}{V_{dc}} = \frac{R_4R_s + R_4R_2 - R_2R_3 - R_2R_4}{(R_3 + R_4)(R_s + R_2)} = \frac{R_4R_s - R_2R_3}{(R_3 + R_4)(R_s + R_2)}$$

From the previous balance equation

$$\frac{R_{bal}R_4}{R_3} = R_2$$

Substitute these equations into the above relationship

$$\frac{V_b - V_a}{V_{dc}} = \frac{R_4R_s - R_{bal}R_4}{(R_3 + R_4)(R_s + R_{bal}R_4 / R_3)}$$

$$(R_3 + R_4)(R_s + R_{bal}R_4 / R_3) = R_3R_s + R_4R_s + R_{bal}R_4 + R_{bal}R_4^2 / R_3$$

Unbalanced Bridge Analysis

Bridge Analysis (Continued)

Combine the past two equations and clear R_3 from the denominator.

$$\frac{V_b - V_a}{V_{dc}} = \frac{R_3R_4(R_s - R_{bal})}{R_3^2R_s + R_3R_4R_s + R_3R_4R_{bal} + R_{bal}R_4^2}$$

Now let R_4=R_3 and simplify further

$$\frac{V_b - V_a}{V_{dc}} = \frac{R_3^2(R_s - R_{bal})}{R_3^2(2(R_s + R_{bal})} = \frac{R_3^2(R_s - R_{bal})}{R_3^2R_s + R_3^2R_s + R_3^2R_{bal} + R_{bal}R_3^2}$$

$$\frac{V_b - V_a}{V_{dc}} = \frac{R_3^2(R_s - R_{bal})}{2R_3^2R_s + 2R_3^2R_{bal}} = \frac{R_3^2(R_s - R_{bal})}{R_3^2(2(R_s + R_{bal}))}$$

$$\frac{V_b - V_a}{V_{dc}} = \frac{(R_s - R_{bal})}{2(R_s + R_{bal})}$$

Desired Relationship

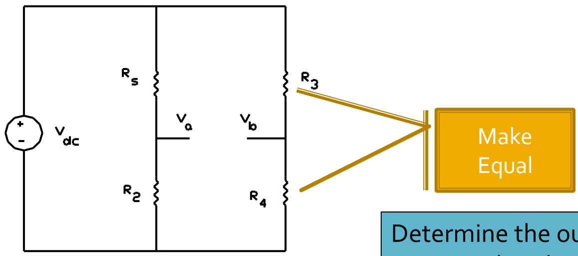
Unbalanced Bridge Analysis

Equation below relates the output voltage change (per volt of supply V) to the change in sensor resistance.

$$\frac{V_b - V_a}{V_{dc}} = \frac{(R_s - R_{bal})}{2(R_s + R_{bal})}$$

When R_3=R_4

Original Bridge



Determine the output voltage linearity compared to the sensor resistance change.

Bridge Output Linearity Analysis

Example: An unbalanced bridge circuit converts temperature sensor resistance into a differential voltage that is amplified by a instrumentation amplifier. The temperature sensor has a resistance of 120 ohms at 35 C and a resistance range of 90 to 150 ohms.

1.) Design a dc bridge circuit with a 10 V supply that will give zero output at 35 C.
 a.) Using R_3=R_4 = 1000 ohms
 b.) Using R_3 = 120, R_4= 1000 ohms

2.) Plot the output voltage over the range of operation at 5 ohm increments for both designs a.) R_3=R_4 = 1000 ohms b.) R_3=120 and R_4 = 1000 ohms

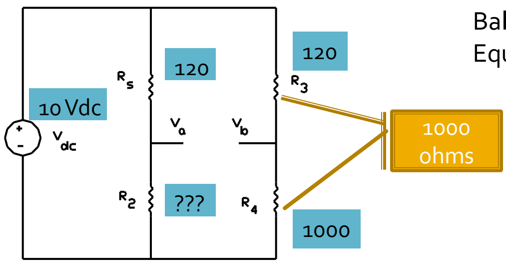
3.) Find the zero based linear approximation of the bridge output responses.

4.) Determine the maximum non-linearity for each case

5.) Determine the gain required for the instrumentation amplifier gain if a span of 15 V dc is required.

Bridge Output Linearity Analysis

Example Solution (Part 1a) Balance bridge with R_3=R_4=1000 ohms



Balance Equation

$$\frac{R_s}{R_2} = \frac{R_3}{R_4}$$

Plug in known values

$$\frac{120}{R_2} = \frac{1000}{1000}$$

$$R_2 = 120$$ Ans

Example Solution (Part 1b) Balance bridge with R_3= 120 ohms R_4=1000 ohms

$$\frac{R_s}{R_2} = \frac{R_3}{R_4}$$

$$\frac{120}{R_2} = \frac{120}{1000}$$

$$R_2 = 1000$$ Ans

Bridge Output Linearity Analysis

Example Solution (Part 2a) plot output V with R_3=R_4=1000 ohms

$$V_b - V_a = \frac{(R_s - R_{bal})}{2(R_s + R_{bal})} V_{dc}$$

$$R_{bal} = \frac{R_2 R_4}{R_3} = \frac{120(1000)}{1000} = 120$$

R_{bal} = 120

Plot values of R_s from 90 to 150 with Excel or MathCAD using the equation below

$$V_d = V_b - V_a = \frac{(R_s - 120)}{2(R_s + 120)} 10$$

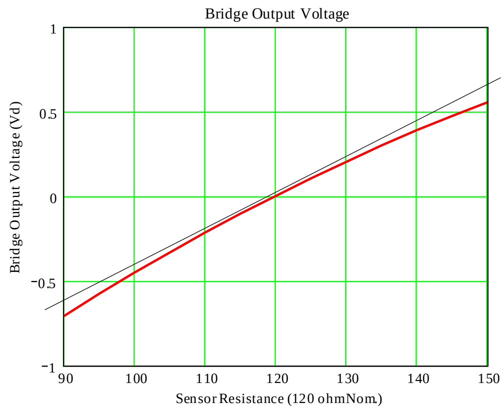
Sample calculation
R_s =90 ohms

$$V_d = \left[\frac{(90\Omega - 120\Omega)}{2\cdot(90\Omega + 120\Omega)}\right]\cdot 10\,V$$

$$V_d = -0.714V$$

Output Plot R_3=R_4= 1000 Ohms

r_s = (Ω)	$V_d(r_s)$ = (V)
90	-0.714
95	-0.581
100	-0.455
105	-0.333
110	-0.217
115	-0.106
120	0
125	0.102
130	0.2
135	0.294
140	0.385
145	0.472
150	0.556



Non-linear output

Linearity With R3 Not Equal to R4

Example Solution (Part 2b) plot output V with R_3= 120 R_4=1000 ohms

Use the alternative formula written as function of r_s, sensor resistance

$$V_{d1}(r_s) = \left[\frac{R_4 \cdot (r_s - R_{bal})}{(R_3 + R_4)\cdot\left(r_s + \dfrac{R_{bal}\cdot R_4}{R_3}\right)}\right]\cdot V_{dc}$$

Where $R_{bal} = \dfrac{R_2 \cdot R_3}{R_4} = \dfrac{(1000\,\Omega)(120\,\Omega)}{1000\,\Omega} = 120\,\Omega$

Substitute Values

$$V_d(r_s) := \frac{(1000\Omega)\cdot(r_s - 120\Omega)\cdot 10\,V}{(1120\Omega)\cdot(r_s + 1000\Omega)}$$

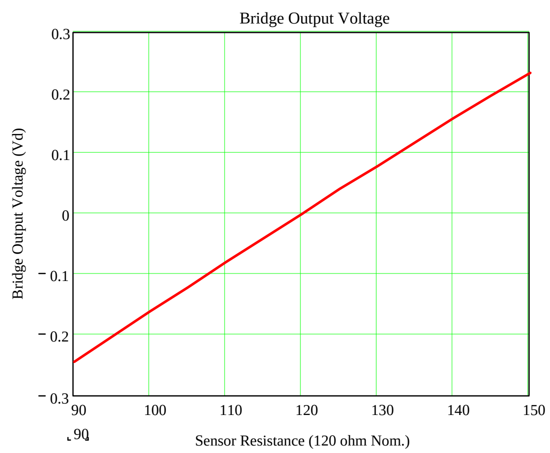
Sample Calculation

$$V_{d1} = \frac{(1000\Omega)\cdot(90\Omega - 120\Omega)\cdot 10\,V}{(1120\Omega)\cdot(90\Omega + 1000\Omega)}$$

$$V_{d1} = -0.246\,V$$

Output Plot R_3= 120 and R_4= 1000 Ohms

$V_{d1}(r_s)$ = (V)	r_s = (Ω)
-0.246	90
-0.204	95
-0.162	100
-0.121	105
-0.08	110
-0.04	115
0	120
0.04	125
0.079	130
0.118	135
0.157	140
0.195	145
0.233	150



Less output voltage than first case

Linear Approximations

Example Solution (Part 3) Find zero based linear approximation. Assume line passes through zero and the average of the end points

For bridge with R3=R4=1000 ohms

at R_s = 90 V_d = -0.714
at R_s =150 V_d = 0.556

Average max value (|-0.714|+|0.556|)/2 = 0.635

Use two data points: R_{s1}=120 V_{d1} = 0
R_{s2}=150 V_{d2}=V_{ave} =0.635

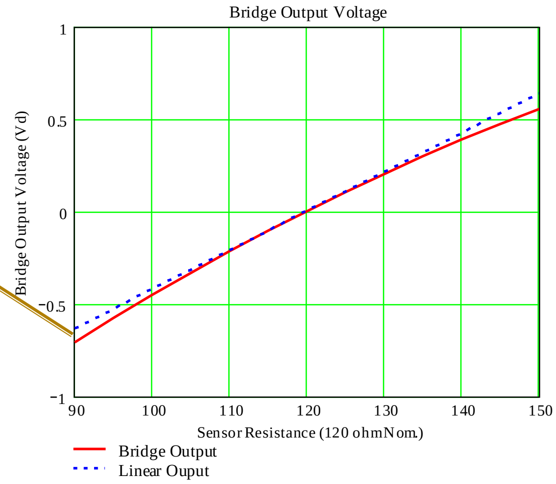
Use two-point form of line to find equation

$$(V_d - V_{d1}) = \frac{(V_{d2} - V_{d1})}{(R_{s2} - R_{s1})}(r_s - R_{s1})$$
$$(V_d - 0) = \frac{(0.635 - 0)}{(150 - 120)}(r_s - 120)$$
$$V_d = 0.021167 r_s - 2.54$$

Equation

Linear Approximations

For bridge with
R3=R4=1000 ohms



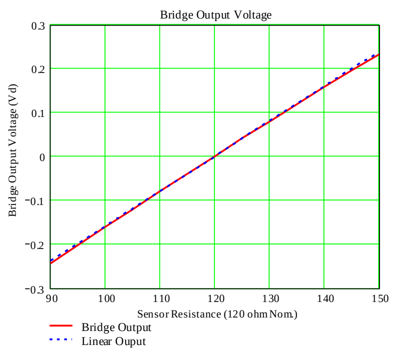
Non-linearity Increase as R_s moves from balance point

Linear Approximations

For bridge with R3= 120, R4=1000 ohms

at R_{s1} = 90 V_{d1} = -0.246
at R_{s2} =150 V_{d2} = 0.233

Average max value (|-0.246|+|0.233|)/2 = 0.2395



$$(V_d - V_{d1}) = \frac{(V_{d2} - V_{d1})}{(R_2 - R_1)}(r_s - R_1)$$

$$(V_d - 0) = \frac{(0.2395 - 0)}{(150 - 120)}(r_s - 120)$$

$$V_d = 0.007983 r_s - 0.958$$

Equation

Less output voltage but greater linearity
Dc bridge approximately linear for small deviations around balance point

Maximum Non-Linearity

Example Solution (Part 4) Determine the maximum non-linearity for each bridge.

Take difference between actual bridge output and the zero based lines. Maximum occurs at either end of the graph.

R3=1000 Ω, R4=1000 Ω

$V_d(r_s)$ = (V) Bridge	$V_{dl}(r_s)$ = (V) Linearized	$\lvert V_{dl}(r_s) - V_d(r_s)\rvert$ (V)
-0.714	-0.635	0.0793
-0.581	-0.529	0.0523
-0.455	-0.423	0.0312
-0.333	-0.317	0.0159
-0.217	-0.212	0.0058
-0.106	-0.106	0.0006
0	0	0
0.102	0.106	0.0038
0.2	0.212	0.0117
0.294	0.318	0.0234
0.385	0.423	0.0388
0.472	0.529	0.0575
0.556	0.635	0.0795

R3=120 Ω, R4=1000 Ω

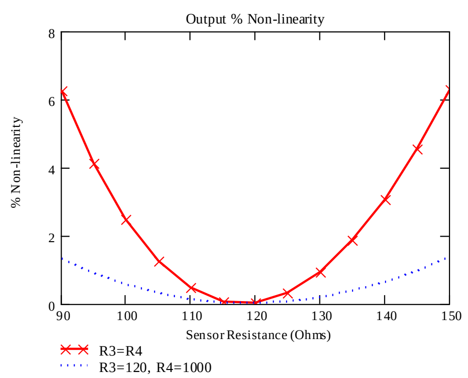
$V_{d1}(r_s)$ = (V) Bridge	$V_{dl1}(r_s)$ = (V) Linearized	$\lvert V_{dl1}(r_s) - V_{d1}(r_s)\rvert$ (V)
-0.246	-0.24	0.0062
-0.204	-0.2	0.0042
-0.162	-0.16	0.0026
-0.121	-0.12	0.0014
-0.08	-0.08	0.0006
-0.04	-0.04	0.0001
0	-0	0
0.04	0.04	0.0002
0.079	0.08	0.0008
0.118	0.12	0.0017
0.157	0.16	0.003
0.195	0.2	0.0046
0.233	0.239	0.0065

Percent Non-Linearity

Determine the percent non-linearity using the following formula

$$\%error = \frac{|V_{dl} - V_d|}{|2 \cdot V_{dl(max)}|} 100\%$$

Where $V_{dl(max)}$ = max linear output



Non-linearity greatly improved by making R_3 equal to nominal resistive sensor value

Instrumentation Amplifier Gains

Example Solution (Part 5) Determine the gain necessary for a span of 15 Vdc

Use average value of V_d to compute gain

For R3 =R4=1000 ohms

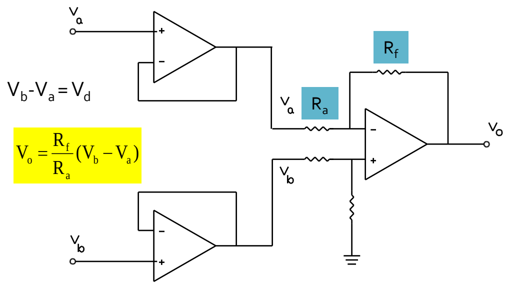
Average max value

(|-0.714|+|0.556|)/2 = **0.635 V**

For R3=120 and R4=1000 ohms

Average max value

(|-0.246|+|0.233|)/2 = **0.2395 V**



Instrumentation Amplifier Gains

Compute the Amp gains using the gain formula

For R3 =R4=1000 ohms

$$V_0 = 15\text{ V dc} \quad V_d = 0.635\text{ V}$$
$$\frac{V_0}{V_d} = \frac{R_f}{R_a} = A_V$$
$$\frac{15\text{ V}}{0.635\text{ V}} = \frac{R_f}{R_a} = A_V$$
$$23.62 = A_V$$

For R3=120 and R4=1000 ohms

$$V_0 = 15\text{ V dc} \quad V_d = 0.2395\text{ V}$$
$$\frac{V_0}{V_d} = \frac{R_f}{R_a} = A_V$$
$$\frac{15\text{ V}}{0.2395\text{ V}} = \frac{R_f}{R_a} = A_V$$
$$62.63 = A_V$$

Note that increasing linearity reduces V_d and requires higher gains

End Lesson 12: Analog Signal Conditioning

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