2102-487
Industrial Electronics

Signal Conditioners
and Transmission
Overview

Motor/Power

Arcing

Lighting

Field

Control Room

Noise Source

Interference

4-20 mA
Instrumentation Amplifier (IA)

Instrumentation amplifiers are dedicated differential amplifiers with extremely high input impedance. Its gain can be precisely set by a single internal or external resistor. The high common-mode rejection makes IA very useful in recovering small signals buried in large common-mode offsets or noise.

• IA consists of Two stages:
  • The first stage: high input impedance and gain control
  • The second stage: differential amplifier (change differential signal to common to ground)

Bridge circuit for sensor application

Equivalent circuit for a Load cell
**IA: The First Stage**

For Ideal op amp, no voltage difference between the inverting and noninverting inputs

\[ V_1 = e_1 \quad \text{and} \quad V_2 = e_2 \]

The voltage across \( R_g \)

\[ V_{R_g} = e_1 - e_2 \]

\[ I_{R_g} = \frac{e_1 - e_2}{R_g} \]

This current must flow through all three resistors because none of the current can flow into the op amp inputs

\[ V_o = I_{R_g} \left( 2R + R_g \right) \]

\[ V_o = (e_1 - e_2) \left( 1 + \frac{2R}{R_g} \right) \]

• Changing \( R_g \) will inversely alter the output voltage.
The second stage of IA is a unit-gain differential amplifier.

Without loading effect, we can apply the direct multiplication for the cascade system:

\[ V_{o1} = (e_1 - e_2) \left( 1 + \frac{2R}{R_g} \right) \]

\[ V_o = -V_{o1} \]

\[ V_o = (e_2 - e_1) \left( 1 + \frac{2R}{R_g} \right) \]

Gain = \( 1 + \frac{2R}{R_g} \)
IA with Offset (Reference)

\[ V_{o1} = (e_1 - e_2) \left(1 + \frac{2R}{R_g}\right) \]

\[ V_o = -V_{o1} + V_{ref} \]

\[ V_o = (e_2 - e_1) \left(1 + \frac{2R}{R_g}\right) + V_{ref} \]
Commercial IA: AD524

Features:
- Low Noise: 0.3 \( \mu \text{Vp-p} \) 0.1 Hz to 10 Hz
- Low Nonlinearity: 0.03\% (G = 1)
- High CMRR: 120 dB (G = 1000)
- Low offset Voltage: 50 \( \mu \text{V} \)
- Gain Bandwidth Product: 25 MHz
- Programmable Gain of 1, 10, 100, 1000

AD524 Functional Block Diagram

\[
G = \left( 1 + \frac{4000}{R_g} \right) \pm 20\%
\]

Here \( R_g = 40, 404, 4.44 \, \Omega \) or external resistor (connect: RG\(_1\) – RG\(_2\))
Ex: For the circuit, calculate $V_a$, $V_b$, and $V_{out}$ as well as the effect on the output of the 5-V common-mode signal.

\[
V_b = \frac{1}{2} V_{\text{supply}} = 5 \text{ V}
\]

\[
V_a = \left(\frac{349\Omega}{350\Omega + 349\Omega}\right)10 \text{ V} = 4.99285 \text{ V}
\]

\[
V_{out} = G(V_a - V_b)
\]

\[
= 100(4.99285 \text{ V} - 5 \text{ V}) = -715 \text{ mV}
\]

For a gain of 100, CMRR = 100 dB

\[
CMRR = 20\log\frac{G_{dm}}{G_{cm}} \quad \rightarrow \quad G_{cm} = 0.001
\]

\[
G_{cm}V_{cm} = 0.001 \times 5 \text{ V} = 5 \text{ mV}
\]

The common mode error is

\[
\frac{5 \text{ mV}}{715 \text{ mV}} \times 100\% = 0.7\%
\]
To illustrate how instrumentation amplifier specification are applied, we will now examine a typical case where an AD524 is required to amplify the output an unbalance transducer. Figure above shows a differential transducer, unbalance by 100 Ω supplying a 0 to 20 mV signal to an AD524C. The output of the IA feeds a 14-bit A/D converter with a 0 to 2 Voltage range. The operating temperature is 25°C to 85°C. Therefore, the largest change in temperature $\Delta T$ within the operating range is from ambient to +85°C ($85°C - 25°C = 60°C$).
# Commercial IA: AD524

1000 ppm = 0.1%

Table II. Error Budget Analysis of AD524CD in Bridge Application

<table>
<thead>
<tr>
<th>Error Source</th>
<th>AD524C Specifications</th>
<th>Calculation</th>
<th>Effect on Absolute Accuracy at $T_A = 25^\circ C$</th>
<th>Effect on Absolute Accuracy at $T_A = 85^\circ C$</th>
<th>Effect on Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain Error</td>
<td>±0.25%</td>
<td>±0.25% = 2500 ppm</td>
<td>2500 ppm</td>
<td>2500 ppm</td>
<td>–</td>
</tr>
<tr>
<td>Gain Instability</td>
<td>25 ppm</td>
<td>(25 ppm/°C)(60°C) = 1500 ppm</td>
<td>–</td>
<td>1500 ppm</td>
<td>–</td>
</tr>
<tr>
<td>Gain Nonlinearity</td>
<td>±0.003%</td>
<td>±0.003% = 30 ppm</td>
<td>–</td>
<td>–</td>
<td>30 ppm</td>
</tr>
<tr>
<td>Input Offset Voltage</td>
<td>±50 µV, RTI</td>
<td>±50 µV/20 mV = ±2500 ppm</td>
<td>2500 ppm</td>
<td>2500 ppm</td>
<td>–</td>
</tr>
<tr>
<td>Input Offset Voltage Drift</td>
<td>±0.5 µV/°C</td>
<td>(±0.5 µV/°C)(60°C) = 30 µV</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Output Offset Voltage(^1)</td>
<td>±2.0 mV</td>
<td>±2.0 mV/20 mV = ±1000 ppm</td>
<td>1000 ppm</td>
<td>1000 ppm</td>
<td>–</td>
</tr>
<tr>
<td>Output Offset Voltage Drift(^1)</td>
<td>±25 µV/°C</td>
<td>(±25 µV/°C)(60°C) = 1500 µV</td>
<td>–</td>
<td>–</td>
<td>750 ppm</td>
</tr>
<tr>
<td>Bias Current-Source</td>
<td>±15 nA</td>
<td>(±15 nA)(100 Ω) = 1.5 µV</td>
<td>75 ppm</td>
<td>75 ppm</td>
<td>–</td>
</tr>
<tr>
<td>Imbalance Error</td>
<td></td>
<td>1.5 µV/20 mV = 75 ppm</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Bias Current-Source</td>
<td>±100 pA/°C</td>
<td>(±100 pA/°C)(100 Ω)(60°C) = 0.6 µV</td>
<td>–</td>
<td>–</td>
<td>30 ppm</td>
</tr>
<tr>
<td>Imbalance Drift</td>
<td></td>
<td>0.6 µV/20 mV = 30 ppm</td>
<td>–</td>
<td>–</td>
<td>30 ppm</td>
</tr>
<tr>
<td>Offset Current-Source</td>
<td>±10 nA</td>
<td>(±10 nA)(100 Ω) = 1 µV</td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>–</td>
</tr>
<tr>
<td>Imbalance Drift</td>
<td></td>
<td>1 µV/20 mV = 50 ppm</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Offset Current-Source</td>
<td>±100 pA/°C</td>
<td>(100 pA/°C)(100 Ω)(60°C) = 0.6 µV</td>
<td>–</td>
<td>–</td>
<td>30 ppm</td>
</tr>
<tr>
<td>Imbalance Drift</td>
<td></td>
<td>0.6 µV/20 mV = 30 ppm</td>
<td>–</td>
<td>–</td>
<td>30 ppm</td>
</tr>
<tr>
<td>Offset Current-Source</td>
<td>±10 nA</td>
<td>(10 nA)(175 Ω) = 3.5 µV</td>
<td>87.5 ppm</td>
<td>87.5 ppm</td>
<td>–</td>
</tr>
<tr>
<td>Resistance-Error</td>
<td></td>
<td>3.5 µV/20 mV = 87.5 ppm</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Offset Current Source</td>
<td>±100 pA/°C</td>
<td>(100 pA/°C)(175 Ω)(60°C) = 1 µV</td>
<td>–</td>
<td>–</td>
<td>50 ppm</td>
</tr>
<tr>
<td>Resistance-Drift</td>
<td></td>
<td>1 µV/20 mV = 50 ppm</td>
<td>–</td>
<td>–</td>
<td>50 ppm</td>
</tr>
<tr>
<td>Common Mode Rejection</td>
<td>115 dB</td>
<td>115 dB = 1.8 ppm × 5 V = 8.8 µV</td>
<td>444 ppm</td>
<td>444 ppm</td>
<td>–</td>
</tr>
<tr>
<td>5 V dc</td>
<td></td>
<td>8.8 µV/20 mV = 444 ppm</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Noise, RTI (0.1 Hz–10 Hz)</td>
<td>0.3 µV p-p</td>
<td>0.3 µV p-p/20 mV = 15 ppm</td>
<td>–</td>
<td>–</td>
<td>15 ppm</td>
</tr>
<tr>
<td>Total Error</td>
<td></td>
<td></td>
<td>6656.5 ppm</td>
<td>10516.5 ppm</td>
<td>45 ppm</td>
</tr>
</tbody>
</table>

\(^1\)Output offset voltage and output offset voltage drift are given as RTI figures.
Zero and Span Circuits

The zero and span circuit adjust the output of a transducer to match the levels you want to provide to the controller or display.

Ex. You may need a 0.01 mV/lb input to a digital panel meter, while the load cell provides a 20 $\mu$V/lb reading with 18 mV output with no load.

Ex. A/D converter needs a 0- to 5-V signal, while the temperature transducer output 2.48 to 3.90 V.
Zero and Span: Inverting summer

Inverting summer

\[ e_{u1} = -\frac{R_f}{R_i} e_{in} - \frac{R_f}{R_{OS}} V \]

Inverting amplifier

\[ e_{u2} = -e_{u1} \]

Compare this to the eq. of straight line \( y = mx + b \)

Here \( y = e_{u2}, x = e_{in}, m = \frac{R_f}{R_i} \) and \( b = \frac{R_f}{R_{OS}} V \)
Zero and Span: Instrument Amplifier

When the temperature in a process is at its minimum, the sensor outputs 2.48 V. At maximum temperature, it outputs 3.90 V. The A/D converter used to input these data into a computer has the range 0 to 5 V. To provide maximum resolution, you must zero and span the signal from the transducer so that it fills the entire range of converter.

\[ V_{in} = 2.48-3.90 \text{ V} \quad \rightarrow \quad V_{out} = 0-5 \text{ V} \]

The gain, \( m \), is set by \( R_f/R_i \), \( R_f \) relatively large, so that \( R_i \) will not load down the sensors.

\[ b = V_{out} - mV_{in} = 0 - 3.52 \times 2.48 \text{ V} = -8.73 \text{ V} \]

Select \( R_s \) as a 47 kΩ fixed resistor with a series 100 kΩ potentiometer. \((m \sim 2.25-7.02)\)

\[ b \text{ is } R_f/R_{OS} \text{ V select V } = -12 \text{ V} \]

Select \( R_s \) as a 220 kΩ fixed resistor with a 500 kΩ potentiometer. \((b \sim -18 - -5.5 \text{ V})\)

The resistors in the 2nd stage should be in kΩ range, this will not load the 1st stage, pick \( R = 2.2 \text{ kΩ} \) and so \( R/2 = 1.1 \text{ kΩ} \)
Zero and Span: Instrument Amplifier

\[ V_{out} = \left(1 + \frac{40000}{R_g}\right)(e_2 - e_1) + V_{ref} \]
Zero and Span: Instrument Amplifier

The output from a load cell changes 20 $\mu$V/lb with an output of 18 mV with no load on the cell. Design a zero and span converter using an instrumentation amplifier which will output 0 Vdc when there is no load, and will change 10 mV/lb.

\[ V_{sensor} = 20 \mu V/lb \times Load + 18 \text{ mV} \]

\[ V_{out} = 10 \text{ mV/lb} \times Load = G \times V_{sensor} + V_{ref} \]

\[ V_{out} = 20 \mu V \times G \times Load + 18 \text{ mV} \times G + V_{ref} \]

\[ G = \frac{10 \text{ mV/lb}}{20 \mu V/lb} = 500 \]

\[ G = 1 + \frac{40000}{R_g} = 500 \quad \Rightarrow \quad R_g = 80.2 \Omega \]

Select \( R_g \) as a 33 $\Omega$ fixed resistor with a series 100 $\Omega$ potentiometer. (\( G \approx 301-1213 \))

\[ 0 = 18 \text{ mV} \times G + V_{ref} = 18 \text{ mV} \times 500 + V_{ref} \]

\[ V_{ref} = -9 \text{ V} \]

So tie one end of the potentiometer to ground and the other end to $-V_{supply}$. Select resistor and potentiometer values that will put approximately -10 V at one end and -8 V at the other end.
Voltage-To-Current Converters

Signal voltage transmission presents many problems. The series resistance between the output of the signal conditioner and the load depends on the distance, the wire used, temperature, conditioner.

\[ R_{wire} \propto \text{Distance, wire type, temperature} \]

![Diagram](image)

\[ V_o = \left(1 + \frac{R_f}{R}\right) e_{in} \]

\[ \left(\frac{\text{Load}}{R_{wire} + \text{Load}}\right) V_o \]
V To I: Floating Load

The most simple V to I actually is the non-inverting amplifier

Therefore, The resistance in the transmission loop \((R_{\text{loop}} = R_{\text{wire}} + R_{\text{load}})\) does not affect the transmitted current. However, the output voltage of the op amp is affected by the \(R_{\text{loop}}\)

\[
V_{\text{out}} = \left(1 + \frac{R_{\text{loop}}}{R}\right)e_{\text{in}} < V_{\text{sat}}
\]

\(R_{\text{loop}}\) must be kept small enough to keep the op amp out of the saturation.
Many transmission standard call for either 20 or 60 mA current. These values are beyond the capabilities of most general-purpose op amps. However, the transistor can be added to increase the transmission current capability.
V To I: Floating Load

The signal at the load is inherently differential. So we can use difference or instrumentation amplifier to reject any common-mode noise.

Open and short circuit in the transmission loop can be detected by checking $V_{out}$ of the non-inverting amplifier (transmission side)

- open circuit: $V_{out} = V_{sat}$
- short circuit: $V_{out} = e_{in}$

However, at the load side, with this circuit, if $e_{in} = 0$, $I_L = 0$, here it appears that the $I_L = 0$ is the valid signal. If the open or short circuit fault occurs, $I_L$ will fall to zero too. The load would respond as if $e_{in} = 0$.

Therefore, a method has been advised to allow the load to differentiate between no signal (circuit failure)

$$I_L = 0 \text{ and } e_{in} = 0$$

This can be achieved by adding an offset to $I_L$ when $e_{in} = 0$

$$e_{in} = 0: I_L > 0$$

Ex. 4-20 mA standard in current transmission
V To I: Floating Load

An example of 4-20 mA V to I converter (span + zero adjust)

\[ I = \frac{e_{in} + e_{ref}}{2R} = \frac{e_{in}}{2R} + \frac{e_{ref}}{2R} \]

\[ m = \frac{1}{2R}, \quad b = \frac{e_{ref}}{2R} \]
**Zero and Span: Instrument Amplifier**

**Ex** Design an offset voltage-to-current converter that will produce 4 mA with an input of -5 V and 20 mA with an input of 10 V.

\[
V_{in} = -5 \text{ to } 10 \text{ V} \quad \rightarrow \quad I_{out} = 4 \text{ to } 20 \text{ mA}
\]

Select a 430 ohm fixed resistor with a series 100 ohm potentiometer.

\[
\begin{align*}
I &= \frac{V_{in}}{2R} + \frac{V_{ref}}{2R} \\
V_{ref} &= 2RI - V_{in} = 2(469 \Omega)(20 \text{ mA}) - 10 \text{ V} = 8.8 \text{ V}
\end{align*}
\]
**V To I: Grounded Load**

This V to I actually is a derivative of difference amplifier

Using superposition:
- \( V_{out \ due \ to \ e_1} = -e_1 \)
- \( V_{out \ due \ to \ e_2} = e_2 \)
- \( V_{out \ due \ to \ V_L} = V_L \)

The current drive into the load is approximately equal to the current in \( R_s \) if \( R_{Load} \ll R_2 + R_4 \)

\[
I_L \approx I_{R_s} = \frac{V_{out} - V_L}{R_s} = \frac{e_2 - e_1}{R_s}
\]

As in the case of the floating load:

\[
V_{Sat} > IR_{load} + e_2 - e_1
\]
V To I: Grounded Load

An example of 4-20 mA V to I converter (span + zero adjust)

\[ I_L \approx \frac{e_{in} - e_{ref}}{R_s} = \frac{e_{in}}{R_s} - \frac{e_{ref}}{R_s} \]

- \[ m = \frac{1}{R_s} \]
- \[ b = -\frac{e_{ref}}{R_s} \]

\[ m = 1/R, \quad b = -e_{ref}/R \]
V To I: XTR110

- 4 to 20 mA Transmitter
- Selectable input/output ranges: 0-5V or 0-10V Inputs
  4-20mA, 0-20mA, 5-25mA Outputs
- Required an external MOS transistor to transmit current to load

![Precision resistive network](image)

![I to I converter (current mirror)](image)
The current $I_{R6}$ is approximately equal to $I_{R8}$

$$I_{R8} \approx I_{R6}$$

Since there is no voltage difference between the op amp inputs

$$V_{R8} = V_{R9}$$

$$I_o = I_{R9} = \frac{I_{R8} R_8}{R_9} = 10I_{R8}$$

$$I_o = \frac{10V_a}{R_6}$$
The voltage at $V_{a}$ is defined by precision divider network and the voltage at $V_{in1}$, $V_{in2}$ and $V_{ref}$. Using superposition

$V_{a}$ due to $V_{in1} = V_{in1}/4$

$V_{a}$ due to $V_{in2} = V_{in2}/2$

$V_{a}$ due to $V_{ref} = V_{ref}/16$

$$V_{a} = V_{in1}/4 + V_{in2}/2 + V_{ref}/16$$

Therefore, the relation of the output current can be shown as

$$I_{o} = \frac{10(V_{in1}/4 + V_{in2}/2 + V_{ref}/16)}{R_{span}}$$

This IC allows us to change the value of $R_{span}$ by using $R_{6}$, $R_{7}$ and external resistors so therefore the $I_{o}$ span can be set to 16mA, 4mA or arbitrary value.

Ex if $V_{in2} = 0$, $V_{ref} = 10$ V, $V_{in1}$ varies from 0-10V and Use $R_{span} = R_{6} = 1562.5\Omega$

At $V_{in1} = 0$ V; $I_{o} = 4$ mA at zero $V_{in1}$  \hspace{1cm} Zero = 4 mA

At $V_{in1} = 0$ V; $I_{o} = 20$ mA at $V_{in1} = 10$ V \hspace{1cm} Zero+span = 4mA + 16 mA
V To I: XTR110

\[ V_a = \frac{R_a}{(R_5 + R_1) // (R_3 + R_2)} V_{IN1} = \frac{1}{4} V_{IN1} \]

\[ V_a = \frac{R_a}{(R_5 + R_1) // (R_3 + R_2)} V_{IN2} = \frac{1}{2} V_{IN2} \]

\[ V_a = \frac{R_a}{(R_5 + R_1) // (R_3 + R_2)} V_{REF} = \frac{1}{16} V_{REF} \]
V To I: XTR110

Pin connections for standard XTR110 input voltage/output current ranges

<table>
<thead>
<tr>
<th>INPUT RANGE (V)</th>
<th>OUTPUT RANGE (mA)</th>
<th>PIN 3</th>
<th>PIN 4</th>
<th>PIN 5</th>
<th>PIN 9</th>
<th>PIN 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>0-20</td>
<td>Com</td>
<td>Input</td>
<td>Com</td>
<td>Com</td>
<td>Com</td>
</tr>
<tr>
<td>2-10</td>
<td>4-20</td>
<td>Com</td>
<td>Input</td>
<td>Com</td>
<td>Com</td>
<td>Com</td>
</tr>
<tr>
<td>0-10</td>
<td>4-20</td>
<td>+10V Ref</td>
<td>Input</td>
<td>Com</td>
<td>Com</td>
<td>Open</td>
</tr>
<tr>
<td>0-10</td>
<td>5-25</td>
<td>+10V Ref</td>
<td>Input</td>
<td>Com</td>
<td>Com</td>
<td>Com</td>
</tr>
<tr>
<td>0-5</td>
<td>0-20</td>
<td>Com</td>
<td>Com</td>
<td>Input</td>
<td>Com</td>
<td>Com</td>
</tr>
<tr>
<td>1-5</td>
<td>4-20</td>
<td>Com</td>
<td>Com</td>
<td>Input</td>
<td>Com</td>
<td>Com</td>
</tr>
<tr>
<td>0-5</td>
<td>4-20</td>
<td>+10V Ref</td>
<td>Com</td>
<td>Input</td>
<td>Com</td>
<td>Open</td>
</tr>
<tr>
<td>0-5</td>
<td>5-25</td>
<td>+10V Ref</td>
<td>Com</td>
<td>Input</td>
<td>Com</td>
<td>Com</td>
</tr>
</tbody>
</table>

A basic 4 to 20 mA transmitter
$V_{out} = 400V_{in} + 6\,\text{V}$

$V_{sensor} = \pm 10\,\text{mV}$

$V_{sensor} = 2 - 10\,\text{V}$

$I_{out} = \frac{10(V_{in} / 4)}{1250\,\Omega}$

$I_{out} = 4 - 20\,\text{mA}$

Figure 4-23  Full instrumentation channel. (Courtesy of Burr-Brown Corporation.)

$I_{out} = \frac{10(400V_{sensor} + 6) / 4}{1250\,\Omega}$
Current-To-Voltage Converters

Grounded Load I to V converter

Current is converted into a voltage by $R_L$

Voltage follower is inserted to avoid the loading effect

$$V_{out} = \frac{R_f}{R_i} IR_L + \frac{R_f}{R_{OS}} V$$

$m = \frac{R_f}{R_i} R_L$, $b = \frac{R_f}{R_{OS}} V$

The grounded load converter has many problems with the common ground (use by many device) especially the noise source. To reduce this problem, we use a floating load.
I To V Converters: Floating Load

\[ V_{out} = \frac{R_f}{R_i} IR_{span} + V_{ref} \]

\[ m = \frac{R_f R_L}{R_p}, \quad b = V_{ref} \]

To prevent the loading effect be sure that \( R_{span} \ll R_i \) or Instrumentation amplifier can be used in stead.
Ex Design a floating current-to-voltage converter that will convert a 4- to 20-mA current signal into 0- to 10-V ground-referenced voltage signal. If voltage-to-current converter, has \( V = 12 \text{ V} \), \( R_{\text{span V-I}} = 312 \Omega \), \( I_{\text{max}} = 20 \text{ mA} \) What is the maximum allowable \( R_{\text{span I-V}} \)

\[
V_{\text{out}} = \frac{R_f}{R_i} IR_{\text{span}} + V_{\text{ref}}
\]

\[
\frac{R_f}{R_i} R_{\text{span V-I}} = \frac{V_{\text{out}}(\text{max}) - V_{\text{out}}(\text{min})}{I_{\text{in}}(\text{max}) - I_{\text{in}}(\text{min})} = \frac{10 \text{ V} - 0 \text{ V}}{20 \text{ mA} - 4 \text{ mA}} = 625 \Omega
\]

Choose \( R_f/R_i = 10 \) This seem arbitrary now, but we’ll come to check it again

\( R_{\text{span V-I}} = 62.5 \Omega \)

Since \( R_i \gg R_{\text{span V-I}} \), pick \( R_i = 2.2 \text{ k}\Omega \)

\( R_f = 22 \text{ k}\Omega \)

Find \( V_{\text{ref}} : \)

\[
V_{\text{ref}} = V_{\text{out}} - \frac{R_f}{R_i} R_{\text{span I}} = 0 - \frac{22 \text{ k}\Omega}{2.2 \text{ k}\Omega} (4 \text{ mA})(62.5 \Omega) = -2.5 \text{ V}
\]
Therefore, $62.5 \, \Omega$ resistor would work. However, if we had chosen $R_f/R_i=1$ then $R_{span\,I-V} = 625 \, \Omega$, which is too large. The op Amp in the voltage-to-current converter would saturate before 20 mA would be reached.
Voltage-To-Frequency Converters

To provide the high noise immunity, digital transmission must be used.

V to F will convert the analog voltage from the sensor or signal conditioner to a pulse train. The pulse width is constant but the frequency varies linearly with the applied voltage.

\[ f \propto V_{in} \]

\[ V_{in} \quad \rightarrow \quad \text{V to F} \quad \rightarrow \quad f_{out} \]

Ideal V to F characteristics
V-To-F: LM131

Suitable for various applications:
- precision V to F converter
- simple low-cost circuits for A/D conversion
- precision F to V converter
- long-term integration
- linear frequency modulation and demodulation
Voltage-To-Frequency Converters

Basic V to F block diagram

![Block Diagram](image)

\[ f_o = \frac{V_{in}}{2.09 V R_L R_t C_t} \]

Input voltage: \( V_{in} \)

Switched current source: \( R_S \)

Comparator: \( V_x \)

One shot timer: \( V_{logic} \)

Frequency output: \( V_{out} \)

- High \( V_{in} \rightarrow \) high \( V_{out} \)
- Adjustment
- Low \( V_{in} \rightarrow \) low \( V_{out} \)
- Adjust
- High \( V_{in} \rightarrow \) high \( V_{out} \)
Voltage-To-Frequency Converters

Determine the timer of one shot

\[ T_{OS} = 1.1 R_i C_i \]

Phase I: Charge \( C_L \) with \( I_{ref} \) within the specific time \( T_{OS} \) from the one shot timer. At the end of this phase, \( V_C \) reaches the value assigned as \( V_x \)

Phase II: \( C_L \) discharge through \( I_{ref} \) until \( V_C \) is equal to \( V_{in} \). The time in this phase is defined as \( T_{II} \)

We can found that \( \frac{1}{(T_{OS} + T_{II})} = f \propto V_{in} \)
Voltage-To-Frequency Converters

Phase I: Charge $C_L$ with $I_{ref}$ within the specific time $T_{OS}$ determined from the one shot timer. At the end of this phase, $V_C$ reaches the value assigned as $V_x$.

Initial condition: $V_C(0) = V_{in}$

$$V_C(t) = (V_{in} - I_{ref} R_L) e^{-t/\tau} + I_{ref} R_L \quad \tau = R_L C_L$$

Assume $R_L C_L >> T_{OS}$

$$e^{-T_{OS}/\tau} \approx 1 - T_{OS}/\tau$$

$$V_x = V_C(T_{OS}) = V_{in} + (I_{ref} R_L - V_{in}) \frac{T_{OS}}{\tau}$$

Phase II: $C_L$ discharge through $I_{ref}$ until $V_C$ is equal to $V_{in}$. The time in this phase is defined as $T_{II}$

Initial condition: $V_C(0) = V_x$

$$V_C(t) = V_x e^{-t/\tau} \quad \tau = R_L C_L$$

$$V_{in} = V_C(T_{II}) = V_x e^{-T_{II}/\tau} \quad T_{II} = \tau \ln \frac{V_x}{V_{in}}$$

Since $R_L C_L >> T_{OS}$, Therefore $V_x/V_{in} \sim 1$

$$\ln \frac{V_x}{V_{in}} \approx \frac{V_x}{V_{in}} - 1$$

$$T_{II} = \tau \left( \frac{V_x}{V_{in}} - 1 \right)$$
Voltage-To-Frequency Converters

Combine eq.(1) and (2)

\[ T = T_{OS} + T_{II} = \frac{I_{ref} R_L T_{OS}}{V_{in}} \]

\[ f = \frac{1}{T} = \frac{V_{in}}{I_{ref} R_L T_{OS}} \]

Substitute \( I_{ref} = 1.9 \, \text{V} / R_s, T_{OS} = 1.1 R_t C_t \)

\[ f = \frac{V_{in} R_s}{1.9 \, \text{V} R_L (1.1 R_t C_t)} = \frac{V_{in} R_s}{2.09 \, \text{V} R_L R_t C_t} \]
**V To F Converters**

**Ex** Design a voltage-to-frequency converter that will output 20 kHz when the input is 5 V.

At maximum frequency, the minimum period is

\[ T_{\text{min}} = \frac{1}{f_{\text{max}}} = \frac{1}{20 \text{ kHz}} = 50 \, \mu\text{s} \]

We have to set the pulse width no wider than about 80% of the minimum period, otherwise, at the higher frequencies the pulse width may approach or exceed the period, which will not work.

\[ t_{\text{low}} = 1.1R_tC_t \]

pick \( C_t = 0.0047 \, \mu\text{F} \) (somewhat arbitrary, but suggested by manufacturer)

\[ R_t = \frac{t_{\text{low}}}{1.1C_t} = \frac{(0.8)(50 \, \mu\text{s})}{(1.1)(0.0047 \, \mu\text{F})} = 7.7 \, \text{k}\Omega \]

pick \( R_t = 6.8 \, \text{k}\Omega \), since this is not a critical parameter, as long as it is not too big. This give \( t_{\text{low}} = 35 \, \mu\text{s} \). Pick \( R_L = 100 \, \text{K}\Omega \).

\[ R_s = \frac{(2 \, \text{V})f_0R_tC_t}{V_{\text{in}}} = \frac{(2 \, \text{V})(20 \, \text{kHz})(100 \, \text{k}\Omega)(6.8 \, \text{k}\Omega)(0.0047 \, \mu\text{F})}{5 \, \text{V}} = 25.6 \, \text{k}\Omega \]

Select a 22 k\( \Omega \) fixed resistor with a series 10 k\( \Omega \) potentiometer.
Voltage-To-Frequency Converters

From

\[ f_o = \frac{V_{in}}{2.09 V} \frac{R_S}{R_L R_t C_t} \quad I = \frac{1.9 V}{R_S} < 200 \mu A \]

Manufacturer's recommended, \( R_L = 100 \text{ k\Omega} \), \( R_t = 6.8 \text{ k\Omega} \), \( C_t = 0.01 \mu \text{F} \) and \( R_S = 14.2 \text{ k\Omega} \)

\[ f_o = \frac{1 \text{ kHz}}{V_{in}} \text{ Volt} \]
**Ex** Design a voltage-to-frequency converter that will output 20 kHz when the input is 5 V.

At maximum frequency, the minimum period is

\[ T_{\text{min}} = \frac{1}{f_{\text{max}}} = \frac{1}{20 \text{ kHz}} = 50 \text{ } \mu\text{s} \]

We have to set the pulse width no wider than about 80% of the minimum period, otherwise, at the higher frequencies the pulse width may approach or exceed the period, which will not work.

\[ t_{\text{low}} = 1.1 R_t C_t \]

pick \( C_t = 0.0047 \mu\text{F} \) (somewhat arbitrary, but suggested by manufacturer)

\[ R_t = \frac{t_{\text{low}}}{1.1 C_t} = \frac{(0.8)(50 \mu\text{s})}{(1.1)(0.0047 \mu\text{F})} = 7.7 \text{ k}\Omega \]

pick \( R_t = 6.8 \text{ k}\Omega \), since this is not a critical parameter, as long as it is not too big. This gives \( t_{\text{low}} = 35 \mu\text{s} \). Pick \( R_L = 100 \text{ K}\Omega \).

\[ R_s = \frac{(2 \text{ V})f_0 R_t R_t C_t}{V_{\text{in}}} = \frac{(2 \text{ V})(20 \text{ kHz})(100 \text{ k}\Omega)(6.8 \text{ k}\Omega)(0.0047 \mu\text{F})}{5 \text{ V}} = 25.6 \text{ k}\Omega \]

Select a 22 kΩ fixed resistor with a series 10 kΩ potentiometer.
Frequency-To-Voltage Converters

Connect to low pass filter

The amplitude of pulse current output is

The average voltage output is

The average current output is

\[ V_{ave} = I_{ave} R_L = 1.9 \times 1.1 R_t C_t \frac{R_L}{R_s} f_{in} \]
Frequency-To-Voltage Converters

Simple F to V converter

\[ V_{\text{ave}} = 1.9 \times 1.1 R_L C_t \frac{R_L}{R_S} f_{\text{in}} \]

From

\[ R_L = 100 \, \text{k}\Omega, \quad R_I = 6.8 \, \text{k}\Omega, \quad C_t = 0.01 \, \mu\text{F} \quad \text{and} \quad R_S = 14.2 \, \text{k}\Omega \]

\[ V_{\text{ave}} = \frac{1 \, \text{V}}{\text{kHz}} f_{\text{in}} \]
Ex: A reflective optical sensor is used to encode the velocity of a shaft. There are six pieces of reflective tape. They are sized and positioned to produce a 50% duty cycle wave. The maximum shaft speed is 3000 r/min. Design the frequency-to-voltage converter necessary to output 10 V at maximum shaft speed. Provide filtering adequate to assure no more than 10% ripple at 100 r/min

The maximum frequency is

\[ f_{\text{max}} = \frac{6 \text{ counts}}{\text{rev}} \times \frac{3000 \text{ rev}}{\text{min}} \times \frac{1 \text{ min}}{60 \text{ s}} = 300 \text{ Hz} \]

\[ T_{\text{min}} = \frac{1}{300 \text{ Hz}} = 3.33 \text{ ms} \quad \rightarrow \quad T_{\text{pulse}} = 0.5T_{\text{min}} = 1.67 \text{ ms} \]

Select

\[ T_{\text{out(high)}} \leq 0.8T_{\text{min}} = (0.8)(3.33 \text{ ms}) = 2.664 \text{ ms} \]

Select \( C_t = 0.33 \ \mu\text{F} \)

\[ R_t = \frac{t_{\text{low}}}{1.1C_t} = \frac{(0.8)(50 \mu\text{s})}{(1.1)(0.0047 \mu\text{F})} = 7.7 \text{ k}\Omega \]

pick \( R_t = 6.8 \text{ k}\Omega \), This give \( t_{\text{out(high)}} = 2.47 \text{ ms} \). We must set \( 5R_D C_D \ll 1.67 \text{ ms} \), so pick \( R_D = 10 \text{ k}\Omega \).

\[ 5R_D C_D \leq (0.1)t_{\text{out(high)}} \quad \rightarrow \quad C_D \leq 3.3 \text{ nF} \]
F To V Converters

\[
V_{ave} = 2 \times 1.1 R_L C_F \frac{R_L}{R_s} f_{in}
\]

\[
R_s = \frac{2 \times 1.1 R_L C_F R_L f_{in}}{V_{ave}} = \frac{(2 \times 1.1)(6.8 \text{k}\Omega)(0.33 \mu\text{F})(100 \text{k}\Omega)(300 \text{Hz})}{10 \text{ V}} = 14.8 \text{k}\Omega
\]

Select \(R_s\) as a 10 k\(\Omega\) fixed resistor with a series 10 k\(\Omega\) potentiometer.

Check

\[
i = \frac{1.9 \text{ V}}{14.8 \text{ k}\Omega} = 135 \mu\text{A} < 200 \mu\text{A}
\]

At 100 r/min

\[
f = \frac{6 \text{ counts}}{100 \text{ rev}} \times \frac{1 \text{ min}}{60 \text{ s}} = 10 \text{ Hz}
\]

\[
T_{\text{min}} = \frac{1}{10 \text{ Hz}} = 0.1 \text{ s} \quad \Rightarrow \quad T_{\text{pulse}} = 0.05 \text{ ms}
\]

Filtering is accomplished by \(R_L\) and \(C_F\)

\[
\tau = R_L C_F \quad \Rightarrow \quad V_{out} = V_{pk} e^{-t/\tau}
\]

For 10% ripple,

\[
\frac{V_{out}}{V_{pk}} = 0.9 \geq e^{-t/R_L C_F}
\]

\[
C_F \geq -\frac{t}{R_L \ln(0.9)} \quad \text{and, we have} \quad t = T_{10\text{Hz}} - t_{out(\text{high})} = 100 \text{ ms} - 2.47 \text{ ms} = 97.53 \text{ ms}
\]

\[
C_F \geq -\frac{97.53 \text{ ms}}{(100 \text{k}\Omega)\ln(0.9)} = 9.25 \mu\text{F}
\]

Select \(C_F = 10 \mu\text{F}\)
Cabling

• Cables are important because they are the longest parts of the system and therefore act as efficient antennas that pick up and/or radiate noise.

• There are three coupling mechanisms that can occur between fields and cables, and between cables (crosstalk).

  • Capacitive or electric coupling (interaction of electric field and circuit)
  
  • Inductive or magnetic coupling (interaction between of the magnetic field of two circuits.
  
  • Electromagnetic coupling or radiation (RF interference)
Magnetic Coupling

• When a current flows in a closed circuit, it produces a magnetic flux, $\phi$, which is proportional to the current.

$$\phi = LI$$

• When current flow in one circuit produces a flux in a second circuit, there is a mutual inductance $M_{12}$ between circuits 1 and 2:

$$M_{12} = \frac{\phi_{12}}{I_1} \quad \phi_{12} \propto \text{the current, geometry, and orientation}$$

• The voltage $V_N$ induced in circuit 2 due to the current $I_1$:

$$V_N = M \frac{di}{dt} = j\omega M_{12}I_1 \quad \text{Assume } i \text{ varies sinusoidal with time}$$

Magnetic coupling between two circuits
Magnetic Coupling

- Separate the sensitive, input signal condition from the other portions of the electronics: Digital signal (high $f$), high power circuit, ac power (50 or 60 Hz line)
  - place low level signal on the separate card
  - board layout
  - separate low level signal conduit or race way, from ac power line, communication or digital cable conduits.

- Reduce loop area (twisted pair)

- Use magnetic shield (effective at high frequency)

**TABLE 4-6  MAGNETIC SHIELDING EFFECTIVENESS**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Thickness (in.)</th>
<th>Aluminum (dB)</th>
<th>Copper (dB)</th>
<th>Steel (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio</td>
<td>0.020</td>
<td>2</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td></td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>100 kHz</td>
<td>0.020</td>
<td>25</td>
<td>35</td>
<td>&gt;150</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td></td>
<td>130</td>
<td>&gt;150</td>
</tr>
</tbody>
</table>
Magnetic Coupling

Figure 30. Twisted Wire Pairs Reduce Magnetically Induced Errors
Capacitive Coupling

- The potential difference between two conductors generates a proportional electric field. This will result in the redistribution or movement (current) of charge by external voltage source.

\[ V_N = \frac{j \omega R C_{12}}{1 + j \omega R (C_{12} + C_{2G})} V_1 \]

*The shield must be grounded.

Capacitive coupling between two conductors

Capacitive coupling with shield
Grounding Problems

• Grounding is one of the primary ways of minimizing unwanted noise and pick up. (also bad grounding can cause the serious problem of interference)

• A well-designed system can provide the protection against unwanted interference and emission, without any addition per-unit cost to the product

• Grounds category: safety grounds (earth ground) signal grounds

A signal ground is normally defined as an equipotential point or plane that serves as a reference potential for a circuit or system (can not be realized in practical systems)

A signal ground (better definition) is a low-impedance path for current to return to the source.
Ground System can be divided into three categories:
- single-point grounds
- multipoint grounds
- hybrid grounds (frequency dependence)

Two types of single-point grounding connection:
- Series connection
- Parallel connection

Multipoint connection
A series ground system is undesirable from a noise standpoint but has the advantage of simple wiring.

A parallel ground system provides good noise performance at low frequency but is mechanical cumbersome.
Single-Point Ground System

Figure 4-49  Multistage series ground connection.

Figure 4-50  Multistage, multireturn ground connection.
Ex Calculate $V_a$ and $V_b$ resulting from the input signal and from the effects of the ground return current under the following circumstances

(a) Actuator off, $I_c = 5$ mA, $I_p = 20$ mA, $I_a = 0$;
(b) Actuator on, $I_c = 8$ mA, $I_p = 35$ mA, $I_a = 1$ A;

The voltage, $V_b$ is determined by the 40-mV input signal and any voltage developed across the 50 m$\Omega$ resistance by the ground return current.

$$V_b = -\frac{1\ \text{M}\Omega}{10\ \text{k}\Omega}(40 \text{ mV}) + \left(1 + \frac{1\ \text{M}\Omega}{10\ \text{k}\Omega}\right)V_a$$

Where $V_a = (I_c+I_p+I_a)50\text{ m}\Omega$

(a) Actuator off

$$V_a = (5 \text{ mA} + 20 \text{ mA} + 0)(50 \text{ m}\Omega) = 1.25 \text{ mV}$$

$$V_b = -100(40 \text{ mV}) + 101(1.25 \text{ mV}) = -3.87 \text{ V}$$

The error is about 3% compare to the correct value (-100)(40 mV) = -4 V

(b) Actuator on

$$V_a = (5 \text{ mA} + 20 \text{ mA} + 1 \text{ A})(50 \text{ m}\Omega) = 52 \text{ mV}$$

$$V_b = -100(40 \text{ mV}) + 101(52 \text{ mV}) = 1.25 \text{ V}$$

The large return current has raised the non-inverting input to 52 mV, and this causes the unacceptable error.
Single-Point Ground System

Figure 4-51  Ground-return signal grouping.

Figure 3-11. A printed wiring board with three separate ground systems, one for the digital logic, one for the low-level analog circuits, and one for the "noisy" circuits.
Multiple-Point Ground System

Ground loops can occur when the multiple ground points are separated by a large distance and connected to the ac power ground, or when low-level analog circuits are used.

![Diagram of multiple-point ground system](image)

Figure 4-45  Shield and signal common improperly grounded at both ends.
Multiple-Point Ground System

A ground loop between two circuits can be broken by inserting a common-mode choke
Multiple-Point Ground System

A ground loop between two circuits can be broken by inserting a transformer.

A ground loop between two circuits can be broken by inserting an optical coupler.
Isolation Amplifiers

General concepts: Isolation Amplifier provides three important advantages over normal amplifiers.

- Safety issues for some industrial and medical applications: signal common isolation and common ground can be achieved
- Extremely high common-mode voltage tolerance (in general amp this is normally less than than power supply)
- Very low failure currents

<table>
<thead>
<tr>
<th>TABLE 4–4</th>
<th>ISOLATION-INSTRUMENTATION AMPLIFIER COMPARISON</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Key specification</strong></td>
<td><strong>Isolation amplifier</strong></td>
</tr>
<tr>
<td>CMR for unity gain with 5000 Ω of source unbalance from dc to 100 Hz</td>
<td>115 dB</td>
</tr>
<tr>
<td>Common-mode voltage range</td>
<td>±2500 V dc (±7500 V, peak)</td>
</tr>
<tr>
<td>Differential input voltage range</td>
<td>±240 V rms (±6500 V, peak)</td>
</tr>
<tr>
<td>Input-to-ground leakage</td>
<td>Transformer isolated; 10^{11} Ω shunted by less than 10 pF</td>
</tr>
<tr>
<td>Bias current configuration</td>
<td>Single bias current; amplifier needs only two input conductors</td>
</tr>
<tr>
<td>Small-signal passband</td>
<td>Dc to 2 kHz</td>
</tr>
<tr>
<td>Gain nonlinearity</td>
<td>0.05%</td>
</tr>
<tr>
<td>Gain vs. temperature</td>
<td>±0.01%/°C</td>
</tr>
<tr>
<td>Offset vs. temperature (G = 1)</td>
<td>±300 μV/°C</td>
</tr>
</tbody>
</table>

*Source: Burr-Brown.*
Transformer-coupled Amplifiers

Symbol of transformer-coupled amp.

Block diagram of AD289 isolation amp
Transformer-coupled isolation amplifiers are expensive, bulky, bandwidth limited and slow response.

Optically-coupled isolation amplifiers have less non-linear and isolation.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Transformer coupling</th>
<th>Optical coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amplitude modulation</td>
<td>Pulse-width modulation</td>
</tr>
<tr>
<td>Nonlinearity, max. (%)</td>
<td>0.03–0.3</td>
<td>0.005–0.025&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Isolation voltage, test (kV)</td>
<td>Up to 7.5</td>
<td>Up to 5</td>
</tr>
<tr>
<td>Isolation-mode rejection, at 60 Hz and unity gain (dB)</td>
<td>Up to 120</td>
<td>Up to 120</td>
</tr>
<tr>
<td>Frequency response (kHz)</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Emi generated</td>
<td>Low, if shielded</td>
<td>Low, if shielded</td>
</tr>
<tr>
<td>High-frequency susceptibility</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Size (in.&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>5–10</td>
<td>6</td>
</tr>
<tr>
<td>Price in lots of 100</td>
<td>From $41</td>
<td>From $90</td>
</tr>
</tbody>
</table>

<sup>a</sup> Burr-Brown products measured at full output-voltage swing.

<sup>b</sup> Without input power supply.

*Source:* Burr-Brown.
Optically Coupled Amplifiers

Symbol of optically coupled amp.

Simplified schematic diagram

\[ I_1 = I_2 = \frac{V_{in}}{R_G} \]

\[ V_{out} = I_2 R_k = \frac{R_k}{R_G} V_{in} \]