Introduction to Analog Interfacing

- Most embedded systems include components that measure and/or control real-world parameters.
- These include position, speed, temperature, etc.
- Usually exist in a continuous, or analog, form.
- We often need to amplify, filter, and convert these signals to a digital form.
- This chapter develops analog circuit building blocks for data acquisition and control systems.
Ideal Op Amps

\[ V_{out} = K(V_y - V_x) \]

- Voltage ranges are bounded by the supply voltages, \( \pm V_s \).
- Input currents, \( I_x \) and \( I_y \), are zero.
- Negative feedback drives \( V_x \) to equal \( V_y \).
- Positive or no feedback drives \( V_{out} \) to equal \(-V_s\) or \(+V_s\).

Various Op Amps

<table>
<thead>
<tr>
<th>Op amp</th>
<th>Description</th>
<th>Open loop gain</th>
<th>( \pm V_s )</th>
<th>( \pm I_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA4227</td>
<td>High Precision</td>
<td>160 dB</td>
<td>( \pm 5 ) to ( \pm 15 ) V</td>
<td>( \pm 3.8 ) mA</td>
</tr>
<tr>
<td>OPA4132</td>
<td>High-Speed FET</td>
<td>130 dB</td>
<td>( \pm 2.5 ) to ( \pm 18 ) V</td>
<td>( \pm 4.8 ) mA</td>
</tr>
<tr>
<td>TLC2274</td>
<td>Rail-to-Rail</td>
<td>104 dB</td>
<td>0 to 5 or ( \pm 5 ) V</td>
<td>3 mA</td>
</tr>
</tbody>
</table>
Input Impedance

\[ R_{\text{cm}} = \frac{V_{\text{cm}}}{I_{\text{cm}}} \]

\[ R_{\text{diff}} = \frac{V_{\text{diff}}}{I_{\text{diff}}} \]

<table>
<thead>
<tr>
<th>Op amp</th>
<th>( R_{\text{cm}} )</th>
<th>( R_{\text{diff}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA4227</td>
<td>1 GΩ</td>
<td>10 MΩ</td>
</tr>
<tr>
<td>OPA4132</td>
<td>( 10^{13} ) Ω</td>
<td>( 10^{13} ) Ω</td>
</tr>
<tr>
<td>TLC2274</td>
<td>( 10^{12} ) Ω</td>
<td>( 10^{12} ) Ω</td>
</tr>
</tbody>
</table>

Output Impedance

\[ R_{\text{out}} = \frac{V_{\text{open}}}{I_{\text{short}}} \]
### Offset Voltage, Offset Current, and Bias Current

<table>
<thead>
<tr>
<th>Op amp</th>
<th>$V_{os}$</th>
<th>$I_{os}$</th>
<th>$I_{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA4227</td>
<td>0.075 mV</td>
<td>10 nA</td>
<td>10 nA</td>
</tr>
<tr>
<td>OPA4132</td>
<td>0.5 mV</td>
<td>50 pA</td>
<td>50 pA</td>
</tr>
<tr>
<td>TLC2274</td>
<td>3 mV</td>
<td>100 pA</td>
<td>100 pA</td>
</tr>
</tbody>
</table>

### Noise Density

<table>
<thead>
<tr>
<th>Op amp</th>
<th>$e_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA4227</td>
<td>3 nV/$\sqrt{Hz}$</td>
</tr>
<tr>
<td>OPA4132</td>
<td>23 nV/$\sqrt{Hz}$</td>
</tr>
<tr>
<td>TLC2274</td>
<td>50 nV/$\sqrt{Hz}$</td>
</tr>
</tbody>
</table>
Transient Response

![Diagram of transient response with time and voltage axes showing settling time, delay, slew, and ring]

<table>
<thead>
<tr>
<th>Op amp</th>
<th>$dV/dt$, Slew rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA4227</td>
<td>2.3 V/µs</td>
</tr>
<tr>
<td>OPA4132</td>
<td>20 V/µs</td>
</tr>
<tr>
<td>TLC2274</td>
<td>3.6 V/µs</td>
</tr>
</tbody>
</table>

Frequency Response

![Diagram of frequency response with $V_{out}/V_{in}$ ratio and frequency (KHz) axes showing $f_1$, $G$, and $G \cdot BW$]

<table>
<thead>
<tr>
<th>Op amp</th>
<th>$f_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPA4227</td>
<td>8 MHz</td>
</tr>
<tr>
<td>OPA4132</td>
<td>8 kHz</td>
</tr>
<tr>
<td>TLC2274</td>
<td>2.18 MHz</td>
</tr>
</tbody>
</table>
Power Gain ($A_{db}$)

- Combines voltage gain, input impedance, and output impedance.

\[
\begin{align*}
P_{in} &= \frac{V_{in}^2}{R_{in}} \\
P_{out} &= \frac{V_{out}^2}{R_{out}} \\
A_{db} &= 10\log_{10} \frac{P_{out}}{P_{in}} = 20\log_{10} \frac{V_{out}}{V_{in}} + 10\log_{10} \frac{R_{in}}{R_{out}}
\end{align*}
\]

Threshold Detector

[Diagram of a threshold detector circuit]
Simple Rules for Linear Op Amp Circuits

- Choose quality components.
- Negative feedback required to create linear mode circuit.

Assume no current flows into the op amp inputs.
Assume negative feedback equalizes input voltages.
Choose resistor values in the 1kΩ to 1MΩ range.
BW depends on the gain and the op amp performance.

Equalize the effective resistance to ground at the two op amp input terminals.
Input impedance is input voltage / input current.
Simple Rules for Linear Op Amp Circuits (cont)

- Match input impedances to improve common-mode rejection ratio (CMRR).

\[ G_{cm} = \frac{V_{out,cm}}{V_{cm}} \]

\[ G_{diff} = \frac{V_{out,diff}}{V_{diff}} \]

\[ CMRR = \frac{G_{diff}}{G_{cm}} \]
Inverting Amplifier with -2.5V to 2.5V Range

Noninverting Amplifier

\[ V_{out} = (1 + \frac{R_2}{R_1})V_{in} \]

\[ R_3 = \frac{R_1 \cdot R_2}{R_1 + R_2} \]
Model for Linear Circuit Design

\[ V_{out} = A_1 V_1 + A_2 V_2 + \ldots + A_n V_n + B \]

Choose a reference voltage from available reference voltage chips.

\[ V_{ref} = 5V \]

Rewrite the design equation in terms of the reference voltage, \( V_{ref} \).

\[ V_{out} = 5V_1 - 3V_2 + 2V_3 - 2V_{ref} \]

Add a ground input to the equation such that the sum of the gains is 1.

\[ V_{out} = 5V_1 - 3V_2 + 2V_3 - 2V_{ref} - V_g \]

Choose a feedback resistor, \( R_f \), in range of 10 k\( \Omega \) to 1 M\( \Omega \).

\[ R_f = 150k\Omega \quad R_1 = 30k\Omega \quad R_2 = 50k\Omega \]
\[ R_3 = 75k\Omega \quad R_{ref} = 75k\Omega \quad R_g = 150k\Omega \]

Build the circuit: connect positive gain inputs to positive terminal and negative gain inputs to the negative terminal.
Linear Op Amp Circuit

![Linear Op Amp Circuit Diagram]

Instrumentation Amplifier

![Instrumentation Amplifier Diagram]
Current-to-Voltage Circuit

Voltage-to-Current Circuit
Integrator Circuit

\[ V_{\text{out}}(t) = V_{\text{out}}(0) - \frac{1}{RC} \int_0^t V_{\text{in}}(s) \, ds \]

Derivative Circuit

\[ V_{\text{out}}(t) = -\frac{1}{RC} \frac{dV_{\text{in}}}{dt} \]
Hysteresis

Voltage Comparators with Hysteresis

[Diagram of voltage comparators with hysteresis]
Analog Isolation

Diagram of analog isolation in a medical context, showing a preamp, analog isolation, amplifier, low-pass filter, analog-to-digital converter (ADC), computer, and ground connections.