Fundamentals of Operational Amplifiers

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Director of Technical Marketing

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Analog to Electronic Signal Processing
Analog to Electronic Signal Processing

Sensor (INPUT) -> Amp -> Converter -> Digital Processor

Actuator (OUTPUT) <- Amp <- Converter
Amplifiers and Operational Amplifiers

► Amplifiers
- Make a low-level, high-source impedance signal into a high-level, low-source impedance signal
- Op amps, power amps, RF amps, instrumentation amps, etc.
- Most complex amplifiers built up from combinations of op amps

► Operational amplifiers
- Three-terminal device (plus power supplies)
- Amplify a small signal at the input terminals to a very, very large one at the output terminal
Operational Amplifiers

Operational

- Op amps can be configured with feedback networks in multiple ways to perform ‘operations’ on input signals
- ‘Operations’ include positive or negative gain, filtering, nonlinear transfer functions, comparison, summation, subtraction, reference buffering, differential amplification, integration, differentiation, etc.

Applications

- Fundamental building block for analog design
- Sensor input amplifier
- Simple and complex filters – anti-aliasing
- ADC driver

ANALOG DEVICES
AHEAD OF WHAT’S POSSIBLE™
Original vacuum-tube op-amp from Philbrick Research in 1953 – it used +/- 300V supplies
The Relative Scale of Some Modern IC Op Amp Packages

SC-70  SOT-23  MSOP8  mSOIC  8-SOIC  14-SOIC

(ALL PACKAGES ABOVE TO SAME SCALE)

SC-70  SOT-23
AD823 JFET Input Op Amp Simplified Schematic

BIAS CURRENT = 25pA MAX @ +25°C
INPUT OFFSET VOLTAGE = 0.8mV MAX @ +25°C
INPUT VOLTAGE NOISE = 15nV/√Hz
INPUT CURRENT NOISE = 1fA/√Hz
Standard Op Amp Symbol
The Ideal Op Amp and its Attributes

**IDEAL OP AMP ATTRIBUTES:**
- Infinite Differential Gain
- Zero Common Mode Gain
- Zero Offset Voltage
- Zero Bias Current

**OP AMP INPUTS:**
- High Input Impedance
- Low Bias Current
- Respond to Differential Mode Voltages
- Ignore Common Mode Voltages

**OP AMP OUTPUT:**
- Low Source Impedance
Use of negative feedback
- The output signal, or a controlled portion of it, is fed back to the negative (-) input terminal
- The op amp will adjust the output signal until the input difference goes to zero

Example of high-gain
- Assume op amp gain of $10^6$ (one million)
- Apply signal of one volt to positive input
- Feedback directly from output to negative input
- Output will go to one volt (minus one microvolt)
- Difference at input will be one microvolt
Non-inverting Mode Op Amp Stage

\[ G = \frac{V_{\text{OUT}}}{V_{\text{IN}}} = 1 + \left(\frac{R_F}{R_G}\right) \]
Inverting Mode Op Amp Stage

\[ V_{IN} = -\frac{R_F}{R_G} \]

\[ G = \frac{V_{OUT}}{V_{IN}} = -\frac{R_F}{R_G} \]

SUMMING POINT
Non-Inverting Amplifier Gain

\[ G = \frac{V_{OUT}}{V_{IN}} = 1 + \frac{R_{FB}}{R_{IN}} \]
Op Amp Subtractor or Difference Amplifier

This configuration has signals driving both input pins

\[ V_{\text{OUT}} = (V_2 - V_1) \frac{R_2}{R_1} \]

\[ \frac{R_2}{R_1} = \frac{R_2'}{R_1'} \quad \text{CRITICAL FOR HIGH CMR} \]

EXTREMELY SENSITIVE TO SOURCE IMPEDANCE IMBALANCE

0.1% TOTAL MISMATCH YIELDS \( \approx 66\text{dB} \) CMR FOR \( R_1 = R_2 \)

\[ \text{CMR} = 20 \log_{10} \left[ 1 + \frac{R_2}{R_1} \frac{1}{K_r} \right] \]

Where \( K_r = \text{Total Fractional Mismatch of } R_1/ R_2 \text{ TO } R_1'/R_2' \)
High Common-Mode Current Sensing Using the AD629 Difference Amplifier

\[ V_{CM} = \pm 270V \text{ for } V_S = \pm 15V \]
Single Pole Op Amp Active Filters

(A) LOWPASS

(B) HIGHPASS
Key Op Amp Performance Features

► Bandwidth and slew rate
  - The speed of the op amp
  - Bandwidth is the highest operating frequency of the op amp
  - Slew rate is the maximum rate of change of the output
  - Determined by the frequency of the signal and the gain needed

► Offset voltage and current
  - The errors of the op amp
  - Determines measurement accuracy

► Noise
  - Op amp noise limits how small a signal can be amplified with good fidelity
Open Loop Gain (Bode Plot)
Gain-Bandwidth Product

OPEN LOOP GAIN, \( A(s) \)
IF GAIN BANDWIDTH PRODUCT = \( X \)
THEN \( Y \cdot f_{CL} = X \)

\[ f_{CL} = \frac{X}{Y} \]
WHERE \( f_{CL} = \) CLOSED-LOOP BANDWIDTH

\[ Y = 1 + \frac{R2}{R1} \]

NOISE GAIN = \( Y \)

GAIN dB

LOG f

\( f_{CL} \)
Noise Gain

Voltage Noise and Offset Voltage of the op amp are reflected to the output by the Noise Gain.

Noise Gain, not Signal Gain, is relevant in assessing stability.

Circuit C has unchanged Signal Gain, but higher Noise Gain, thus better stability, worse noise, and higher output offset voltage.
AD847 Open Loop Gain

The graph shows the open-loop gain of the AD847 with different supplies and load resistances. The vertical axis represents the open-loop gain in dB, while the horizontal axis represents frequency in Hz. The graph includes lines for ±15V supplies and 1kΩ load, as well as ±5V supplies and 500Ω load. The phase margin in degrees is also indicated on the graph.
AD8051 Phase Margin

- $V_S = +5V$
- $R_L = 2k\Omega$
- $C_L = 5pF$

Graph showing Open-Loop Gain (dB) and Phase Margin (Degrees) vs Frequency (Hz).
VFB and CFB Amplifiers

\[ A(s) = \text{OPEN LOOP GAIN} \]

\[ V_{\text{OUT}} = A(s) \times v \]

\[ T(s) = \text{TRANSIMPEDEANCE OPEN LOOP GAIN} \]

\[ V_{\text{OUT}} = -T(s) \times i \]
Feedback resistor fixed for optimum performance. Larger values reduce bandwidth, smaller values may cause instability.

For fixed feedback resistor, changing gain has little effect on bandwidth.

Current feedback op amps do not have a fixed gain-bandwidth product.
Standard Input Stage (Differential Pair)
PNP Input Stage
Compound Input Stage
Output Stages. Emitter Follower for Standard Configuration and Common Emitter for “Rail-to-Rail” Configuration
Offset Voltage: The differential voltage which must be applied to the input of an op amp to produce zero output.

Ranges:
- Zero-Drift Chopper Stabilized Op Amps: <1µV
- General Purpose Precision Op Amps: 50-500µV
- Best Bipolar Op Amps: 10-25µV
- Best FET Op Amps: 100-1,000µV
- High Speed Op Amps: 100-2,000µV
- Untrimmed CMOS Op Amps: 5,000-50,000µV
- DigiTrim™ CMOS Op Amps: <1,000µV
Offset Adjustment Pins

\[ +V_S \text{ OR } -V_S \]

Diagram showing the connections and labels for the offset adjustment pins.
External Offset Adjustment

\[ V_{OUT} = -\frac{R2}{R1} V_{IN} \pm \frac{R2}{R3} V_R \]

\[ \text{NOISE GAIN} = \frac{R2}{1 + \frac{R2}{R1||R3 + R_A||R_B}} \]

\[ V_{OUT} = -\frac{R2}{R1} V_{IN} \pm \left[ 1 + \frac{R2}{R1} \right] \left[ \frac{R_P}{R_P + R3} \right] V_R \]

\[ R_P = R1||R2 \quad \text{IF} \quad I_{B+} \approx I_{B-} \]

\[ R_P \leq 50\Omega \quad \text{IF} \quad I_{B+} \neq I_{B-} \]

(A) \quad (B)
Input Bias Current

\[ I_{B+} \quad I_{B-} \]
Bias Current Compensation

\[ V_O = R2 \left( I_{B^-} - I_{B^+} \right) \]
\[ = R2 I_{OS} \]
\[ = 0, \text{ IF } I_{B^+} = I_{B^-} \]

NEGLIGENCE V_{OS}
## Low Bias Current Precision BiFET Op Amps (Electrometer Grade)

<table>
<thead>
<tr>
<th>PART #</th>
<th>Vos MAX</th>
<th>TC Vos MAX</th>
<th>Ib MAX</th>
<th>P-P Noise</th>
<th>PACKAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADA4530-1</td>
<td>50μV</td>
<td>0.5μV/°C</td>
<td>20fA</td>
<td>4μV p-p</td>
<td>SOIC</td>
</tr>
<tr>
<td>ADA4665</td>
<td>1mV</td>
<td>3μV/°C</td>
<td>100fA</td>
<td>3μV p-p</td>
<td>SOIC</td>
</tr>
<tr>
<td>AD8603</td>
<td>50μV</td>
<td>1μV/°C</td>
<td>200fA</td>
<td>2.5μV p-p</td>
<td>TSOT</td>
</tr>
<tr>
<td>AD8661</td>
<td>30μV</td>
<td>3μV/°C</td>
<td>300fA</td>
<td>2.5μV p-p</td>
<td>LFSCP</td>
</tr>
</tbody>
</table>
Total Offset Voltage Calculations

\[
\text{OFFSET (RTO)} = V_{OS} \left[ 1 + \frac{R_2}{R_1} \right] + I_{B+} \cdot R_3 \left[ 1 + \frac{R_2}{R_1} \right] - I_{B-} \cdot R_2
\]

\[
\text{OFFSET (RTI)} = V_{OS} + I_{B+} \cdot R_3 - I_{B-} \left[ \frac{R_1 \cdot R_2}{R_1 + R_2} \right]
\]

FOR BIAS CURRENT CANCELLATION:

\[
\text{OFFSET (RTI)} = V_{OS} \quad \text{IF} \quad I_{B+} = I_{B-} \quad \text{AND} \quad R_3 = \frac{R_1 \cdot R_2}{R_1 + R_2}
\]
Input Impedance

\[ I_{B+} - Z_{\text{diff}} - I_{B-} \]

\[ + \text{INPUT} \quad Z_{\text{cm+}} \quad - \text{INPUT} \]

\[ Z_{\text{cm-}} \]

AHEAD OF WHAT'S POSSIBLE™
Voltage Noise

\[ V_N^- \]
Current Noise
Total Noise Calculation

\[ BW = 1.57 \times F_{CL} \]

\[ F_{CL} = \text{CLOSED LOOP BANDWIDTH} \]

\[ V_{ON} = \sqrt{BW} \times \sqrt{[(\ln^-)R_2^2][NG] + [(\ln^+)R_p^2][NG] + V_n^2[NG] + 4kTR_2[NG-1] + 4kTR_1[NG-1] + 4kTR_p[NG]} \]
ALL resistors have a voltage noise of \( V_{NR} = \sqrt{4kTBR} \)

- \( T = \) Absolute Temperature = \( T \ (°C) + 273.15 \)
- \( B = \) Bandwidth (Hz)
- \( k = \) Boltzmann’s Constant \( (1.38 \times 10^{-23}\text{J/K}) \)
- A 1000 Ω resistor generates 4 nV / \( \sqrt{\text{Hz}} \) @ 25°C
EXAMPLE: OP27
Voltage Noise = 3nV / √Hz
Current Noise = 1pA / √Hz
T = 25°C

 Neglect R1 and R2
Noise Contribution

<table>
<thead>
<tr>
<th>CONTRIBUTION FROM</th>
<th>VALUES OF R</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>AMPLIFIER VOLTAGE NOISE</td>
<td>3</td>
</tr>
<tr>
<td>AMPLIFIER CURRENT NOISE FLOWING IN R</td>
<td>0</td>
</tr>
<tr>
<td>JOHNSON NOISE OF R</td>
<td>0</td>
</tr>
</tbody>
</table>

RTI NOISE (nV / √Hz)
Dominant Noise Source is Highlighted
1/f Noise Bandwidth

- 1/f Corner Frequency is a figure of merit for op amp noise performance (the lower the better)
- Typical Ranges: 2Hz to 2kHz
- Voltage Noise and Current Noise do not necessarily have the same 1/f corner frequency

\[ e_n, i_n = k \sqrt{F_C \frac{1}{f}} \]

\[ F_C \text{ CORNER} \]

\[ 3 \text{dB/Octave} \]

\[ \text{NOISE} \]

\[ \text{nV} / \sqrt{\text{Hz}} \text{ or} \]

\[ \text{pA} / \sqrt{\text{Hz}} \]

\[ e_n, i_n \]

\[ k \]

\[ \text{WHITE NOISE} \]

\[ \text{LOG} f \]

\[ F_C \]

\[ \text{LOG} f \]
ADA4528-x World’s Most Accurate Op Amp Low Noise Zero-Drift Amplifier

► Key Features
  - Lowest noise zero-drift amp
    - 5.6 nV/√Hz noise floor
    - No 1/f noise
  - High DC accuracy
    - Low offset voltage: 2.5 µV max
    - Low offset voltage drift: 0.015 µV/°C max
  - Rail-to-rail input/output
  - Operating voltage: 2.2 V to 5.5 V

► Applications
  - Transducer applications
  - Temperature measurements
  - Electronic scales
  - Medical instrumentation
  - Battery-powered instruments

5.6 nV/√Hz

No 1/f Noise
# RMS to Peak to Peak Voltage Comparison Chart

<table>
<thead>
<tr>
<th>Nominal Peak-to-Peak</th>
<th>% of the Time Noise will Exceed Nominal Peak-to-Peak Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 × rms</td>
<td>32%</td>
</tr>
<tr>
<td>3 × rms</td>
<td>13%</td>
</tr>
<tr>
<td>4 × rms</td>
<td>4.6%</td>
</tr>
<tr>
<td>5 × rms</td>
<td>1.2%</td>
</tr>
<tr>
<td>6 × rms</td>
<td>0.27%</td>
</tr>
<tr>
<td>6.6 × rms**</td>
<td>0.10%</td>
</tr>
<tr>
<td>7 × rms</td>
<td>0.046%</td>
</tr>
<tr>
<td>8 × rms</td>
<td>0.006%</td>
</tr>
</tbody>
</table>

**Most often used conversion factor is 6.6**
The Peak-to-Peak Noise in the 0.1 Hz to 10 Hz Bandwidth ADA4528
Slew Rate

SLEW RATE = \frac{\Delta V}{\Delta T}

\Delta V
\Delta T

10%
90%
FINAL VALUE

OVERSHOOT
RINGING

VOLTAGE

TIME
Slew Rate and Full Power Bandwidth

Slew Rate = Maximum rate at which the output voltage of an op amp can change

Ranges: A few volts / \( \mu s \) to several thousand volts / \( \mu s \)

For a sinewave, \( V_{\text{out}} = V_p \sin 2\pi f t \)

\[
\frac{dV}{dt} = 2\pi f V_p \cos 2\pi f t
\]

\[
(dV/dt)_{\text{max}} = 2\pi f V_p
\]

If 2 \( V_p \) = full output span of op amp, then

\[
\text{Slew Rate} = (dV/dt)_{\text{max}} = 2\pi \times \text{FPBW} \times V_p
\]

\[
\text{FPBW} = \frac{\text{Slew Rate}}{2\pi V_p}
\]
Error band is usually defined to be a percentage of the step 0.1 \% 0.05\%, 0.01\%, etc.

Settling time is non-linear; it may take 30 times as long to settle to 0.01\% as to 0.1\%.

Manufacturers often choose an error band which makes the op amp look good.
Common Mode Rejection Ratio for the OP177

\[ CMR = 20 \log_{10} CMRR \]
Power Supply Rejection Ratio

PSR (dB) = 20 \log_{10} \text{PSRR}

FREQUENCY - Hz

0.01 0.1 1 10 100 1k 10k 100k 1M
Maximum Power Chart (from the AD8001)
Input Protection

Diagram showing input protection circuit with components labeled $R_S$, $+V_S$, and $-V_S$. The circuit includes diodes and a resistor for protection against voltage spikes.
**Typical Absolute Maximum Ratings**

**ABSOLUTE MAXIMUM RATINGS**

- **Supply Voltage**: 12.6 V
- **Internal Power Dissipation**: 1.3 W
  - Plastic DIP Package (N)
  - Small Outline Package (R)
  - SOT-23-5 Package (RT)
- **Input Voltage (Common Mode)**: ±V_S
- **Differential Input Voltage**: ±1.2 V
- **Output Short Circuit Duration**: Observe Power Derating Curves

**Storage Temperature Range**
- N, R: -65°C to +125°C

**Operating Temperature Range (A Grade)**
- -40°C to +85°C

**Lead Temperature Range (Soldering 10 sec)**
- +300°C

**NOTES**

1. Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

2. Specification is for device in free air:
   - 8-Lead Plastic DIP Package: \( \theta_{JA} = 90°C/W \)
   - 8-Lead SOIC Package: \( \theta_{JA} = 155°C/W \)
   - 8-Lead Cerdip Package: \( \theta_{JA} = 110°C/W \)
   - 5-Lead SOT-23-5 Package: \( \theta_{JA} = 260°C/W \)
Over-Voltage Protection – Discrete versus Integrated

**External Solution**

![External Solution Diagram](image)

**Integrated Solution**

![Integrated Solution Diagram](image)

- ESD (HBM) >2kV
- Current Limiting FET
- 40V Breakdown

**Typical Op Amp**

- ADA4177-2
- BAS70-4-V
- 5k Ω

**External Solution Components**

- VCC = +15V
- VEE = -15V
- D1, D2
- RFB

**Integrated Solution Components**

- VCC
- VEE
- VIN
- ESD
- OVP
- ADA4177-2
Single-Supply Op Amps

◆ Single Supply Offers:
  ● Lower Power
  ● Battery Operated Portable Equipment
  ● Requires Only One Voltage

◆ Design Tradeoffs:
  ● Reduced Signal Swing Increases Sensitivity to Errors Caused by Offset Voltage, Bias Current, Finite Open-Loop Gain, Noise, etc.
  ● Must Usually Share Noisy Digital Supply
  ● Rail-to-Rail Input and Output Needed to Increase Signal Swing
  ● Precision Less than the best Dual Supply Op Amps but not Required for All Applications
  ● Many Op Amps Specified for Single Supply, but do not have Rail-to-Rail Inputs or Outputs
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