Harold S. Black, "Stabilized Feedback Amplifiers;"
Bell System Technical Journal, Vol. 13, No. 1, January 1934
OP AMP APPLICATIONS
SEMINAR

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Many of the figures presented in this seminar book have been extracted from the following Analog Devices publication:

**Op Amp Applications**  
Walter G. Jung  
Analog Devices, 2002

A reference to the appropriate chapters in the above book is given underneath the slides in this book where appropriate.
OP AMP APPLICATIONS
SEMINAR

1. History, Basics, Design Aids, Filters

2. Specialty Amplifiers, Using Op Amps with Data Converters

3. Hardware and Housekeeping Design Techniques

4. Signal Amplifiers, Sensor Signal Conditioning
OP AMP APPLICATIONS SEMINAR
HAROLD BLACK'S FEEDBACK AMPLIFIER

Harold S. Black, "Stabilized Feedback Amplifiers,"
Bell System Technical Journal, Vol. 13, No. 1, January 1934

Op Amp Applications, Chapter H 1.1
SCHEMATIC DIAGRAM FOR "SUMMING AMPLIFIER"
(US PATENT 2,401,779, ASSIGNED TO BELL TELEPHONE LABORATORIES, INC.)


Op Amp Applications, Chapter H 1.2
SCHEMATIC DIAGRAM OF LATE M9 SYSTEM OP AMP DESIGNED AT BELL TELEPHONE LABORATORIES (1941-1945)

Op Amp Applications, Chapter H 1.3
Op Amp Applications, Chapter H
THE GAP/R MODEL PP65 POTTED MODULE
SOLID-STATE OP AMP (1962)
THE ADI HOS-050 HIGH SPEED HYBRID IC OP AMP PHOTO AND SCHEMATIC DIAGRAM (1977)

TO-8 PACKAGE

11 Transistors
16 Chip resistors
4 Chip capacitors
2 Zener diodes

33 Components

More than 60 wirebonds

Op Amp Applications, Chapter H 1.6
THE µA709 MONOLITHIC IC OP AMP (1965)

Op Amp Applications, Chapter H 1.7
THE LM101 MONOLITHIC IC OP AMP (1967)

Op Amp Applications, Chapter H 1.8
THE µA741 MONOLITHIC IC OP AMP (1968)

Op Amp Applications, Chapter H 1.9
THE OP07 MONOLITHIC IC OP AMP (1975)

*NOTE: R2A and R2B are electronically adjusted on chip at factory.
THE AD503 AND AD506 TWO CHIP HYBRID IC OP AMPS (1970)

Op Amp Applications, Chapter H

1.11
KEY ADI IC FET OP AMP CHRONOLOGY

- AD542, 1978, Low offset (500µV) trimmed precision JFET
- AD544, 1980, Medium speed (8V/µs) trimmed JFET
- AD547, 1982, High precision JFET trimmed offset (250µV) and drift (1µV/°C)
- AD711/712/713-family, 1986, low cost, general purpose, medium precision JFET
- AD515, 1976, two chip electrometer amplifier (75fA)
- AD545, 1978, two chip electrometer amplifier (1pA)
- AD549, 1987, monolithic electrometer amplifier (60fA)
- AD795, 1993, monolithic electrometer amplifier (1pA)
- AD743/745, 1990, monolithic JFETS, 1.9nV/√Hz voltage noise
- AD820/822/824, 1993, JFETs, single-supply, rail-to-rail output (3 to 36V supply)
- AD823, 1995, JFET, single-supply, rail-to-rail output (3 to 36V supply), high speed
- AD8610/8620, 2002, precision, low noise, high speed JFET
- AD8065/8066/8067, AD8033/8034, 2002, high speed FastFET™
KEY ADI HIGH SPEED COMPLEMENTARY
BIPOLAR OP AMPS

- AD840-series, 1988, high speed voltage feedback op amps
- AD846, 1988, high speed, current feedback op amp
- AD847, 1988, high speed, capacitive load stable
- AD829, 1990, high speed, decompensated
- AD9617/9618, 1990, high speed, low distortion current feedback
- AD811, 1992, high speed, high speed, low distortion, video line driver
- AD9631/9632, 1994, high speed, low distortion
- AD8001, 1994, 800MHz current feedback, first XFCB op amp
- AD8011, 1994, 1mA, 300MHz, current feedback, low distortion
- AD8009, 1997, 1GHz current feedback
- AD8038/8039, 2002, 350MHz, 1mA/amplifier supply
- AD8021, 2002, 200MHz, 16-bit, low noise (2.1nV/√Hz)

Op Amp Applications, Chapter H 1.13
VOLTAGE FEEDBACK (VFB) OP AMP MODEL

\[ \frac{V_{OUT}}{V_{IN}} = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{1}{A(s)} \left[ 1 + \frac{R_2}{R_1} \right]} \]

\[ = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{1}{A(s) \beta}} \]

Op Amp Applications, Chapter 1 1.14
GAIN-BANDWIDTH PRODUCT
FOR VOLTAGE FEEDBACK OP AMPS

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

f_{\text{CL}} = \frac{X}{Y}

WHERE f_{\text{CL}} = CLOSED-LOOP BANDWIDTH

NOISE GAIN = Y

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

Op Amp Applications, Chapter 1
CURRENT FEEDBACK (CFB) OP AMP MODEL

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

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{R_2}{T(s)} \left[ 1 + \frac{R_O}{R_1} + \frac{R_O}{R_2} \right]}
\]

ASSUME \( R_O \ll R_1 \), AND \( R_1 \leq R_2 \), THEN

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} \approx \frac{1 + \frac{R_2}{R_1}}{1 + \frac{R_2}{T(s)}}
\]

Op Amp Applications, Chapter 1
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.
SIMPLIFIED CURRENT FEEDBACK (CFB) OP AMP

Op Amp Applications, Chapter 1
A 1937 Vacuum Tube Amplifier Designed by Frederick E. Terman Using Current Feedback to the Low Impedance Input Cathode


*Op Amp Applications, Chapter 1*
A 1941 VACUUM TUBE AMPLIFIER WITH CURRENT FEEDBACK

Feedback Resistor (R2)
(151kΩ)

Adapted from: Stewart E. Miller, "Sensitive DC Amplifier with AC Operation," Electronics, November 1941, pp. 27-31, 105-109
A 1941 CIRCUIT SHOWS CHARACTERISTIC CFB GAIN - BANDWIDTH RELATIONSHIP

Adapted from: Stewart E. Miller, "Sensitive DC Amplifier with AC Operation," *Electronics*, November 1941, pp. 27-31, 105-109

*Op Amp Applications, Chapter 1*
BIPOLAR TRANSISTOR INPUT STAGE

- Low Offset: As low as 10µV
- Low Offset Drift: As low as 0.1µV/°C
- Temperature Stable $I_B$
- Well-Matched Bias Currents
- Low Voltage Noise: As low as 1nV/√Hz

- High Bias Currents: 50nA - 10µA
- (Except Super-Beta: 50pA - 5nA, More Complex and Slower)
- Medium Current Noise: 1pA/√Hz
- Matching source impedances minimize offset error due to bias current

Op Amp Applications, Chapter 1
BIAS-CURRENT COMPENSATED
BIPOLAR INPUT STAGE

- Low Offset Voltage: As low as 10µV
- Low Offset Drift: As low as 0.1µV/°C
- Temperature Stable I_{bias}
- Low Bias Currents: <0.5 - 10nA
- Low Voltage Noise: As low as 1nV/√Hz
- Poor Bias Current Match (Currents May Even Flow in Opposite Directions)
- Higher Current Noise
- Not Very Useful at HF
- Matching source impedances makes offset error due to bias current worse because of additional impedance

*Op Amp Applications, Chapter 1* 1.23
OP497 OP AMP USES SUPER-BETA TRANSISTORS AND BIAS CURRENT COMPENSATION

BIAS CURRENT FOR OP497F = ±150pA MAX @ +25°C
INPUT VOLTAGE NOISE = 15nV/√Hz
INPUT CURRENT NOISE = 20fA/√Hz

Op Amp Applications, Chapter 1
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
PNP OR N-CHANNEL JFET STAGES ALLOW INPUT SIGNAL TO GO TO THE NEGATIVE RAIL

Op Amp Applications, Chapter 1

1.26
TRUE RAIL-TO-RAIL INPUT STAGE

Op Amp Applications, Chapter 1
TRADITIONAL OUTPUT STAGES

(A) +Vs

(B) +Vs

(C) +Vs

NPN VOUT

NMOS VOUT

Op Amp Applications, Chapter 1
"ALMOST" RAIL-TO-RAIL OUTPUT STRUCTURES

(A) +V_S
PNP

NPN

- V_S

SWINGS LIMITED BY SATURATION VOLTAGE

(B) +V_S
PMOS

NMOS

- V_S

SWINGS LIMITED BY FET "ON" RESISTANCE

Op Amp Applications, Chapter 1
AD8531/8532/8534 CMOS RAIL-TO-RAIL OP AMP
SIMPLIFIED SCHEMATIC

Op Amp Applications, Chapter 1
AD8602 (1/2) CMOS OP AMP SHOWING DigiTrim™

Op Amp Applications, Chapter 1

1.31
# SUMMARY OF TRIM PROCESSES AT ANALOG DEVICES

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>TRIMMED AT:</th>
<th>SPECIAL PROCESSING</th>
<th>RESOLUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>DigiTrim™</td>
<td>Wafer or Final Test</td>
<td>None</td>
<td>Discrete</td>
</tr>
<tr>
<td>Laser Trim</td>
<td>Wafer</td>
<td>Thin Film Resistor</td>
<td>Continuous</td>
</tr>
<tr>
<td>Zener Zap Trim</td>
<td>Wafer</td>
<td>None</td>
<td>Discrete</td>
</tr>
<tr>
<td>Link Trim</td>
<td>Wafer</td>
<td>Thin Film or Poly resistor</td>
<td>Discrete</td>
</tr>
<tr>
<td>EEPROM Trim</td>
<td>Wafer or Final Test</td>
<td>EEPROM</td>
<td>Discrete</td>
</tr>
</tbody>
</table>

*Op Amp Applications, Chapter 1*
**PRECISION OP AMP (OP177F) DC ERROR BUDGET**

**SPECS @ +25°C:**
- $V_{OS} = 25\mu V$ max
- $I_{OS} = 1.5nA$ max
- $A_{VOL} = 5 \times 10^6$ min
- $A_{VOL}$ Nonlinearity = 0.07ppm
- 0.1Hz to 10Hz Noise = 200nV

**MAXIMUM ERROR CONTRIBUTION, +25°C**

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Contribution</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{OS}$</td>
<td>25µV + 100mV</td>
<td>250ppm</td>
</tr>
<tr>
<td>$I_{OS}$</td>
<td>100Ω x 1.5nA + 100mV</td>
<td>1.5ppm</td>
</tr>
<tr>
<td>$A_{VOL}$ Nonlinearity</td>
<td>(100/ 5x10^6) x 100mV</td>
<td>20ppm</td>
</tr>
<tr>
<td>0.1Hz to 10Hz 1/f Noise</td>
<td>100 x 0.07ppm</td>
<td>7ppm</td>
</tr>
<tr>
<td>Total Unadjusted Error</td>
<td>= 12 Bits Accurate</td>
<td>280.5ppm</td>
</tr>
<tr>
<td>Resolution Error</td>
<td>= 17 Bits Accurate</td>
<td>9ppm</td>
</tr>
</tbody>
</table>

**Fullscale:** $V_{IN} = 100mV$, $V_{OUT} = 10V$

---

*Op Amp Applications, Chapter 1* 1.33
# PRECISION SINGLE-SUPPLY OP AMP

**PERFORMANCE CHARACTERISTICS**

Listed in order of increasing supply current

<table>
<thead>
<tr>
<th>PART NO.</th>
<th>$V_{os}$ max</th>
<th>$V_{os}$ TC</th>
<th>$A_{vol}$min</th>
<th>NOISE (1kHz)</th>
<th>INPUT</th>
<th>OUTPUT</th>
<th>$I_{SY/AMP MAX}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OP293</td>
<td>250µV</td>
<td>2µV/°C</td>
<td>200k</td>
<td>5nV/√Hz</td>
<td>0, 4V</td>
<td>5mV, 4V</td>
<td>20µA</td>
</tr>
<tr>
<td>OP196/296/496</td>
<td>300µV</td>
<td>2µV/°C</td>
<td>150k</td>
<td>26nV/√Hz</td>
<td>R/R</td>
<td>&quot;R/R&quot;</td>
<td>60µA</td>
</tr>
<tr>
<td>OP777</td>
<td>100µV</td>
<td>1.3µV/°C</td>
<td>300k</td>
<td>15nV/√Hz</td>
<td>0, 4V</td>
<td>&quot;R/R&quot;</td>
<td>270µA</td>
</tr>
<tr>
<td>OP191/291/491</td>
<td>700µV</td>
<td>5µV/°C</td>
<td>25k</td>
<td>35nV/√Hz</td>
<td>R/R</td>
<td>&quot;R/R&quot;</td>
<td>350µA</td>
</tr>
<tr>
<td>*AD820/822/824</td>
<td>1000µV</td>
<td>20µV/°C</td>
<td>500k</td>
<td>16nV/√Hz</td>
<td>0, 4V</td>
<td>&quot;R/R&quot;</td>
<td>800µA</td>
</tr>
<tr>
<td>**AD8601/2/4</td>
<td>600µV</td>
<td>2µV/°C</td>
<td>20k</td>
<td>33nV/√Hz</td>
<td>R/R</td>
<td>&quot;R/R&quot;</td>
<td>1000µA</td>
</tr>
<tr>
<td>OP184/284/484</td>
<td>150µV</td>
<td>2µV/°C</td>
<td>50k</td>
<td>3.9nV/√Hz</td>
<td>R/R</td>
<td>&quot;R/R&quot;</td>
<td>1350µA</td>
</tr>
<tr>
<td>OP113/213/413</td>
<td>175µV</td>
<td>4µV/°C</td>
<td>2M</td>
<td>4.7nV/√Hz</td>
<td>0, 4V</td>
<td>5mV, 4V</td>
<td>3000µA</td>
</tr>
<tr>
<td>OP177F (±15V)</td>
<td>25µV</td>
<td>0.1µV/°C</td>
<td>5M</td>
<td>0nV/√Hz</td>
<td>N/A</td>
<td>N/A</td>
<td>2000µA</td>
</tr>
</tbody>
</table>

*JFET INPUT **CMOS

**NOTE:** Unless otherwise stated
Specifications are typical @ +25°C
$V_{S} = +5V$

---

*Op Amp Applications, Chapter 1* 1.34
MODERN CHOPPER STABILIZED AMPLIFIER

-S IN

+IN

A1

VOUT

NULL

C1

S

Z

A2

S = SAMPLE
Z = AUTO-ZERO

Op Amp Applications, Chapter 1 1.35
INTERMODULATION PRODUCTS:
FIXED VERSUS PSEUDORANDOM CHOPPING FREQUENCY

AD8551/52/54
FIXED CHOPPING FREQUENCY:
4kHz

AD8571/72/74
PSEUDORANDOM CHOPPING FREQUENCY:
2kHz - 4kHz

INPUT SIGNAL = 1mV RMS, 200Hz
OUTPUT SIGNAL: 1V RMS, 200Hz
GAIN = 60dB

Op Amp Applications, Chapter 1 1.36
VOLTAGE NOISE SPECTRAL DENSITY COMPARISON:
FIXED VERSUS PSEUDORANDOM CHOPPING FREQUENCY

AD8551/52/54
FIXED CHOPPING FREQUENCY:
4kHz

AD8571/72/74
PSEUDORANDOM CHOPPING FREQUENCY
2kHz - 4kHz

Op Amp Applications, Chapter 1
1.37
NOISE: BIPOLAR VERSUS CHOPPER AMPLIFIER

INPUT VOLTAGE NOISE, nV / √Hz

<table>
<thead>
<tr>
<th>NOISE BW</th>
<th>BIPOLAR (OP177)</th>
<th>CHOPPER (AD8571/72/74)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1Hz to 10Hz</td>
<td>0.238µV p-p</td>
<td>1.3 µV p-p</td>
</tr>
<tr>
<td>0.01Hz to 1Hz</td>
<td>0.135µV p-p</td>
<td>0.41µV p-p</td>
</tr>
<tr>
<td>0.001Hz to 0.1Hz</td>
<td>0.120µV p-p</td>
<td>0.130µV p-p</td>
</tr>
<tr>
<td>0.0001Hz to 0.01Hz</td>
<td>0.118µV p-p</td>
<td>0.042µV p-p</td>
</tr>
</tbody>
</table>

---

*Op Amp Applications, Chapter 1*
OP AMP PROCESS TECHNOLOGY SUMMARY

◆ BIPOLAR (NPN-BASED): This is Where it All Started!!
◆ BIPOLAR + JFET (BiFET): High Input Impedance, High Speed
◆ COMPLEMENTARY BIPOLAR + JFET (CBFET): High Input Impedance, Rail-to-Rail Output, High Speed
◆ DIELECTRICALLY ISOLATED COMPLEMENTARY BIPOLAR + JFET (XFCB, FastFET™)
◆ COMPLEMENTARY MOSFET (CMOS): Low Cost Op Amps (ADI DigiTrim™ Minimizes Offset Voltage and Drift in CMOS op amps)
◆ BIPOLAR (NPN) + CMOS (BiCMOS): Bipolar Input Stage adds Linearity, Low Power, Rail-to-Rail Output
◆ COMPLEMENTARY BIPOLAR + CMOS (CBCMOS): Rail-to-Rail Inputs, Rail-to-Rail Outputs, Good Linearity, Low Power, Higher Cost

Op Amp Applications, Chapter 1
AMPLIFIER BANDWIDTH VERSUS SUPPLY CURRENT FOR ANALOG DEVICES' PROCESSES

Op Amp Applications, Chapter 1
FOLDED CASCODE SIMPLIFIED CIRCUIT

Op Amp Applications, Chapter 1
MODEL AND BODE PLOT FOR A VFB OP AMP

\[ i = v \cdot gm \]

\[ f_o = \frac{1}{2\pi R_T C_P} \]

\[ f_u = \frac{gm}{2\pi C_P} \]

\[ f_{CL} = \frac{f_u}{1 + \frac{R_2}{R_1}} = \frac{f_u}{G} \]

\[ NOISE \ GAIN \ G = 1 + \frac{R_2}{R_1} \]

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

\[ f_u = \text{UNITY GAIN FREQUENCY} \]

\[ 6\text{dB/OCTAVE} \]
"QUAD-CORE" VFB gm STAGE FOR CURRENT-ON-DEMAND

Op Amp Applications, Chapter 1
AD8061/62/63 SINGLE-SUPPLY 300MHz VOLTAGE FEEDBACK OP AMP

Op Amp Applications, Chapter 1
AD8061 OUTPUT SETTLING TIME
\[ G = +2, \ V_S = +5V \]
AD8061 OUTPUT RESPONSE
\[ G = +2, \ V_S = +5V \]

**RAIL-TO-RAIL OUTPUT**
- \( V_S = 5V \)
- \( G = 2 \)
- \( R_P = R_L = 1k\Omega \)
- \( V_{IN} = 4V \text{ p-p} \)

**STEP OUTPUT**
- \( V_S = 5V \)
- \( G = 2 \)
- \( R_P = R_L = 1k\Omega \)
- \( V_{IN} = 2V \text{ p-p} \)

*Op Amp Applications, Chapter 1*  
1.46
SIMPLIFIED CURRENT FEEDBACK (CFB) OP AMP

Op Amp Applications, Chapter 1
CFB OP AMP MODEL AND BODE PLOT

\[ f_{CL} = \frac{1}{2\pi R2Cp \left(1 + \frac{R_O}{R_2} + \frac{R_O}{R_1}\right)} \]

FOR

\[ R_O \ll R_1 \]
\[ R_O \ll R_2 \]

Op Amp Applications, Chapter 1

1.48
SIMPLIFIED TWO-STAGE CFB OP AMP

NOTE: BIAS CIRCUITRY OMITTED

Op Amp Applications, Chapter 1

   See also ADI AN357


5. "Ray Stata Speaks Out on 'What's Wrong with Op Amp Specs',' *EEE*, July 1968.

*Op Amp Applications, Chapter 1*  

1.50
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  ◆ Sensor Signal Conditioning
  ◆ Mixed-Signal and DSP Design Techniques
◆ 1-800-ANALOGD
ADI WEB-BASED INTERACTIVE DESIGN TOOLS

- Op Amp
  - Gain/Range Error Calculator
  - Error Budget Analysis
- In-Amp
  - Gain/Range Error Calculator
  - Error Budget Analysis
- Differential Amplifiers
  - Gain/Range Error Calculator
- Ideal Single Pole Op Amp Stability Analysis
- Log Amp: Output Voltage and Impedance Matching
- ADC Tools
- DAC/DDS/PLL Tools
- Accelerometer Tools
- Transmission Line Matching Tutorial
- Filter Design

1.52
OP AMP RANGE/GAIN/ERROR CALCULATOR

SELECT TOPOLOGY:
INVERTING, NON-INVERTING SUBTRACTOR

INPUT DESIRED PARAMETERS

CHANGE GAIN (G = -5)

SUPPLY VOLTAGES

ERROR CONDITIONS FLAGGED

1.53
OP AMP RANGE/GAIN/ERROR CALCULATOR CONTINUED

DECREASE GAIN (G = -4)

OR

INCREASE SUPPLY VOLTAGES
**OP AMP ERROR BUDGET ANALYSIS FOR OP1177**

### Application Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Approx. Calculation</th>
<th>Absolute Error</th>
<th>Drift/Gain Error</th>
<th>Resolution Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temp., $T_{o}$</td>
<td>125°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Voltage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Offset Voltage Err, $V_{os1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Offset Voltage Err, $V_{os2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Voltage Drift, $V_{os1}$</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Voltage Drift, $V_{os2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Offset Voltage, $V_{os}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Voltage Drift, $V_{os}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Drift, $V_{td}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. stab. V, $V_{st}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Open Loop Gain, $A_{op}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. Open Loop Gain, $A_{ol}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Supply Rejection, $PSR$</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Differential Gain Error</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Corner freq</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total resolution error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total drift/gain error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total absolute - drift + resolution error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Error Source

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Specification</th>
<th>Approx. Calculation</th>
<th>Absolute Error</th>
<th>Drift/Gain Error</th>
<th>Resolution Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias Current, $I_{b}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source Res. Error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage noise</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current noise</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total resolution error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total drift/gain error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total absolute - drift + resolution error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### ABSOLUTE ACCURACY ERROR OVER TEMPERATURE

### RESOLUTION ERROR

1.55
AD623 SINGLE SUPPLY IN AMP RANGE/GAIN/ERROR CALCULATOR EXAMPLE

### Differential Voltage

- **Gain**: 11
- **Adaptive Voltage**: 2.15V
- **Common Mode Voltage**: 2.75V
- **Reference Voltage**: 1V

### Common Mode Voltage

- **Gain**: 11
- **Adaptive Voltage**: 2.15V
- **Common Mode Voltage**: -0.15V
- **Reference Voltage**: 0.15V

### Reference Voltage

- **Gain**: 11
- **Adaptive Voltage**: 2.15V
- **Common Mode Voltage**: 2.75V
- **Reference Voltage**: 1V

**ERROR CONDITIONS FLAGGED**

- **Positive Supply**: 8
- **Negative Supply**: 8

1.56
# AD623 ERROR BUDGET

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Specification</th>
<th>Calculation</th>
<th>Effect on Accuracy Resolution at Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>100</td>
<td>100</td>
<td>0.25 µV/V</td>
</tr>
<tr>
<td>Common Mode Voltage, VCM</td>
<td>2.5 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Temperature, TA</td>
<td>85 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source Resistance, Rs+</td>
<td>100 ohms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bias Current, Ibb</td>
<td>275 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source Impedance Error</td>
<td>5.0 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offset Current, Ios</td>
<td>2.5 µA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offset Current Drift, Ios TC</td>
<td>0.005%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common Mode Rejection, CMR</td>
<td>77 µV</td>
<td></td>
<td>353.1 ppm</td>
</tr>
<tr>
<td>Noise, 0.1 Hz to 10 Hz</td>
<td>0 ppm</td>
<td></td>
<td>200 ppm</td>
</tr>
<tr>
<td>TOTALS</td>
<td></td>
<td></td>
<td>20073.1 ppm</td>
</tr>
</tbody>
</table>

**ABSOLUTE ACCURACY ERROR OVER TEMPERATURE**

**RESOLUTION ERROR**

1.57
AD8138 DIFFERENTIAL AMPLIFIER
RANGE/GAIN/ERROR CALCULATOR

<table>
<thead>
<tr>
<th>Input</th>
<th>Single-ended</th>
<th>Positive Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td></td>
<td>V&lt;sub&gt;OUT&lt;/sub&gt; = 2.35</td>
</tr>
<tr>
<td>R&lt;sub&gt;IN&lt;/sub&gt;</td>
<td>0.3 ohms</td>
<td>V&lt;sub&gt;OUT&lt;/sub&gt; = 2.65</td>
</tr>
<tr>
<td>R&lt;sub&gt;1&lt;/sub&gt;</td>
<td>500 ohms</td>
<td>V&lt;sub&gt;OUT&lt;/sub&gt; = 2.35</td>
</tr>
<tr>
<td>R&lt;sub&gt;2&lt;/sub&gt;</td>
<td>500 ohms</td>
<td>V&lt;sub&gt;OUT&lt;/sub&gt; = 2.65</td>
</tr>
<tr>
<td>R&lt;sub&gt;3&lt;/sub&gt;</td>
<td>4.054 kohms</td>
<td>V&lt;sub&gt;OUT&lt;/sub&gt; = 2.35</td>
</tr>
<tr>
<td>R&lt;sub&gt;4&lt;/sub&gt;</td>
<td>4.054 kohms</td>
<td>V&lt;sub&gt;OUT&lt;/sub&gt; = 2.65</td>
</tr>
</tbody>
</table>

CHANGE COMMON-MODE VOLTAGE

<table>
<thead>
<tr>
<th>Input</th>
<th>Single-ended</th>
<th>Positive Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td></td>
<td>V&lt;sub&gt;OUT&lt;/sub&gt; = 0.15</td>
</tr>
<tr>
<td>R&lt;sub&gt;IN&lt;/sub&gt;</td>
<td>0.3 ohms</td>
<td>V&lt;sub&gt;OUT&lt;/sub&gt; = 0.15</td>
</tr>
<tr>
<td>R&lt;sub&gt;1&lt;/sub&gt;</td>
<td>500 ohms</td>
<td>V&lt;sub&gt;OUT&lt;/sub&gt; = 0.15</td>
</tr>
<tr>
<td>R&lt;sub&gt;2&lt;/sub&gt;</td>
<td>500 ohms</td>
<td>V&lt;sub&gt;OUT&lt;/sub&gt; = 0.15</td>
</tr>
<tr>
<td>R&lt;sub&gt;3&lt;/sub&gt;</td>
<td>4.054 kohms</td>
<td>V&lt;sub&gt;OUT&lt;/sub&gt; = 0.15</td>
</tr>
<tr>
<td>R&lt;sub&gt;4&lt;/sub&gt;</td>
<td>4.054 kohms</td>
<td>V&lt;sub&gt;OUT&lt;/sub&gt; = 0.15</td>
</tr>
</tbody>
</table>

ERROR CONDITIONS FLAGGED
SINGLE-POLE OP AMP MODEL
GAIN AND PHASE RESPONSE

GAIN PEAKING DUE TO $C_D$
KEY FILTER PARAMETERS

PASSBAND RIPPLE $A_{MAX}$

3dB POINT OR CUTOFF FREQUENCY $F_c$

STOPBAND FREQUENCY $F_s$

STOPBAND ATTENUATION $A_{MIN}$

PASS BAND

TRANSITION BAND

Op Amp Applications, Chapter 5

1.60
ANTIALIASING FILTER DESIGN EXAMPLE

◆ An Antialiasing Filter will be Designed
  • \( F_0 = 8 \text{ kHz} \) (3dB cutoff frequency)
  • \( A_{\text{MIN}} = 72 \text{ dB} \) (equal to a 12 bit system)
  • \( F_S = 50 \text{ kSPS} \) (stopband frequency)
  • Butterworth Response (Best Combination of Attenuation and Phase Response)

◆ The Ratio of \( F_0/F_S = 6.25 \)

◆ Using the Graph in Figure 5-14, We Can Determine the Required Order of the Filter is 5\(^{th}\) order.

◆ We Then Will Use ADI's Filter Design Tool to Determine the Component Values

◆ This is the First Example in Section 5-8 of \textit{Op Amp Applications}

\textit{Op Amp Applications, Chapter 5} 1.61
DETERMINING FILTER ORDER

FREQUENCY (Hz)

RESPONSE (dB)

-72 dB

Op Amp Applications, Chapter 5
FILTER DESIGN TOOL

Interactive Design Tools
OpAmps: Active Filter Synthesis

PROTOTYPE

Op Amp Applications, Chapter 5 1.63
1ST SECTION DESIGN (Sallen-Key)

Op Amp Applications, Chapter 5
2ND SECTION DESIGN (SALLEN-KEY)

Op Amp Applications, Chapter 5
3RD SECTION DESIGN (SALLEN-KEY)

Op Amp Applications, Chapter 5
1ST SECTION WITH CLOSEST STANDARD VALUES

Op Amp Applications, Chapter 5

1.67
MAGNITUDE AND PHASE PLOTS

Op Amp Applications, Chapter 5
FILTER DESIGN TOOL CAPABILITIES

◆ Up to 8th Order Filters
◆ Many Standard All-Pole Responses – and Elliptical
  ● Butterworth
  ● Bessel
  ● Chebyshev
  ● Equiripple
  ● Gaussian
◆ Lowpass, Highpass, Bandpass now
  ● Notch to be added
◆ Several Possible Topologies
  ● Sallen-Key
  ● Multiple Feedback
  ● State Variable
  ● Biquad

*Op Amp Applications, Chapter 5*
Op Amp Applications, Chapter 5
EFFECTS OF STANDARD VERSUS EXACT VALUES

\[2.0 \leq \text{FREQUENCY (kHz)} \leq 20\]

- **A**: \(c = 0.618\) REAL VALUES
- **B**: \(c = 0.618\) CALC. VALUES
- **C**: \(c = 1.618\) REAL VALUES
- **D**: \(c = 1.618\) CALC. VALUES
- **E**: SINGLE POLE REAL VALUES
- **F**: SINGLE POLE CALC. VALUES
- **G**: TOTAL FILTER REAL VALUES
- **H**: TOTAL FILTER CALC. VALUES

\[0 \leq \text{RESPONSE (dB)} \leq 5\]
OP AMP APPLICATIONS SEMINAR
OP AMP APPLICATIONS SEMINAR

1. History, Basics, Design Aids, Filters

2. Specialty Amplifiers, Using Op Amps with Data Converters

3. Hardware and Housekeeping Design Techniques

4. Signal Amplifiers, Sensor Signal Conditioning
OP AMP APPLICATIONS SEMINAR
THE GENERIC INSTRUMENTATION AMPLIFIER (IN-AMP)

COMMON MODE VOLTAGE \( V_{CM} \)

\[ COMMON\ MODE\ ERROR\ (RTI) = \frac{V_{CM}}{CMRR} \]

*Op Amp Applications, Chapter 2*  
2.1
**OP AMP SUBTRACTOR OR DIFFERENCE AMPLIFIER**

![Circuit Diagram]

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

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

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

Where \( K_r \) = Total Fractional Mismatch of \( R_1/R_2 \) TO \( R_1'/R_2' \)

- EXTREMELY SENSITIVE TO SOURCE IMPEDANCE IMBALANCE
- 0.1% TOTAL MISMATCH YIELDS \( \approx 66 \text{dB} \) CMR FOR \( R_1 = R_2 \)

*Op Amp Applications, Chapter 2* 2.2
SSM2141/SSM2143 DIFFERENCE AMPLIFIERS
(AUDIO LINE RECEIVERS)

SSM2141

SSM2143

Op Amp Applications, Chapter 2

2.3
A CURRENT SENSING CIRCUIT USING THE AD629, A HIGH COMMON-MODE INPUT VOLTAGE DIFFERENCE AMPLIFIER

\[
\begin{align*}
V_{CM} &= \pm 270V \text{ for } V_S = \pm 15V \\
\end{align*}
\]

*Op Amp Applications, Chapter 2*
TWO OP AMP INSTRUMENTATION AMPLIFIER

\[ G = 1 + \frac{R_2}{R_1} + \frac{2R_2}{R_G} \]

\[ V_{OUT} = (V_2 - V_1) \left[ 1 + \frac{R_2}{R_1} + \frac{2R_2}{R_G} \right] + V_{REF} \]

- \[ R_2 = \frac{R_2'}{R_1} \frac{R_2'}{R_1'} \]
- \[ CMR \leq 20 \log \left( \frac{GAIN \times 100}{\% MISMATCH} \right) \]

Op Amp Applications, Chapter 2

2.5
SINGLE SUPPLY RESTRICTIONS:
\( V_S = +5V, \ G = 2 \)

\[
V_{OH} = 4.9V \\
V_{OL} = 0.1V
\]

\[
V_{OH} - V_{OL} \leq 2.4V
\]

\[
V_{1,MIN} \geq \frac{1}{G} (G - 1)V_{OL} + V_{REF} \geq 1.3V
\]

\[
V_{1,MAX} \leq \frac{1}{G} (G - 1)V_{OH} + V_{REF} \leq 3.7V
\]

\[
|V_2 - V_1|_{\text{MAX}} \leq \frac{V_{OH} - V_{OL}}{G} \leq 2.4V
\]

Op Amp Applications, Chapter 2 2.6
SPECIALTY AMPLIFIERS, USING OP AMPS WITH DATA CONVERTERS

SINGLE SUPPLY RESTRICTIONS:
\( V_S = +5V, \; G = 100 \)

\[ V_{OH} = 4.9V \]
\[ V_{OL} = 0.1V \]

\[ V_{OUT} \]

\[ V_{REF} = \frac{V_{OH} + V_{OL}}{2} = 2.5V \]

\[ V_{1,MIN} \geq \frac{1}{\frac{G}{1}}(G-1)V_{OL} + V_{REF} \geq 0.124V \]

\[ V_{1,MAX} \leq \frac{1}{\frac{G}{1}}(G-1)V_{OH} + V_{REF} \leq 4.876V \]

\[ |V_2 - V_1|_{MAX} \leq \frac{V_{OH} - V_{OL}}{G} \leq 0.048V \]
THE AD627 SINGLE-SUPPLY IN-AMP ARCHITECTURE

\[ G = 5 + \frac{200k\Omega}{R_G} \]

\[ V_{OUT} = G(V_2 - V_1) + V_{REF} \]

*Op Amp Applications, Chapter 2*
THREE OP AMP INSTRUMENTATION AMPLIFIER

\[ V_{OUT} = V_{SIG} \cdot \frac{R_3}{R_2} \left[ 1 + \frac{2R_1}{R_G} \right] + V_{REF} \]

- CMR ≤ 20\log \left( \frac{\text{GAIN} \times 100}{\% \text{ MISMATCH}} \right)
- IF R2 = R3, \quad G = 1 + \frac{2R_1}{R_G}

\textit{Op Amp Applications, Chapter 2}
**Robert Demrow's 1968 "Evolution from Operational Amplifier to Data Amplifier"**

**Op Amp Applications, Chapter 2**

![Model 601 Wideband Differential DC Amplifier](image)

**Fig. 16 - Wideband differential DC amplifier Model 601 embodies many of the principles outlined in this article.**

- The input circuit based on UA726 temperature compensated monolithic pair provides high voltage & current stability, uses bootstrapping feedback to create 1000 megohms common mode and 10 megohms differential input impedance. Subsequent circuitry preserves UA726's inherently wide bandwidth by using low-value resistors, which also permit highest resistance stability, hence best long-term CMRR.
- Single resistor adjusts closed-loop gain from 20 to 2000; fixed first-stage gain of 20:1 reduces second stage's gain-inequality error: $\text{CMRR}_a = A_2 / (A_2 - A_1)$, twentyfold.

---

2.10
AD524 RELEASED IN 1982
SET THE STANDARD FOR IC IN-AMPS


*Op Amp Applications, Chapter 2* 2.11
AD620 IN-AMP SIMPLIFIED SCHEMATIC
(RELEASED IN 1992)

Op Amp Applications, Chapter 2
AD620 IN-AMP CMR VERSUS FREQUENCY (1kΩ SOURCE IMBALANCE)

Op Amp Applications, Chapter 2
AD8225 PRECISION G = 5 IN-AMP SIMPLIFIED SCHEMATIC

Op Amp Applications, Chapter 2 2.14
AD8225 IN-AMP COMMON-MODE REJECTION

Corner Frequency of AD8225 10× Corner Frequency of AD620

Op Amp Applications, Chapter 2
EKG MONITOR FRONT END USING THE AD8225 IN-AMP

PIN 1 HAS NO INTERNAL CONNECTION

Op Amp Applications, Chapter 2 2.16
GENERALIZED BRIDGE AMPLIFIER USING AN IN-AMP

\[ V_{\text{OUT}} = V_B \left( \frac{\Delta R}{R} \right) \text{GAIN} \]
AD620B BRIDGE AMPLIFIER

DC ERROR BUDGET

MAXIMUM ERROR CONTRIBUTION, +25°C
FULLSCALE: $V_{\text{IN}} = 100\text{mV}, V_{\text{OUT}} = 10\text{V}$

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{OS}}$</td>
<td>$55\mu\text{V} + 100\text{mV}$</td>
<td>$550\text{ppm}$</td>
</tr>
<tr>
<td>$I_{\text{os}}$</td>
<td>$350\Omega \times 0.5\text{nA} + 100\text{mV}$</td>
<td>$1.8\text{ppm}$</td>
</tr>
<tr>
<td>Gain Error</td>
<td>$0.15%$</td>
<td>$1500\text{ppm}$</td>
</tr>
<tr>
<td>Gain Nonlinearity</td>
<td>$40\text{ppm}$</td>
<td>$40\text{ppm}$</td>
</tr>
<tr>
<td>CMR Error</td>
<td>$120\text{dB}$</td>
<td>$0.1\text{ppm} \times 5\text{V} + 100\text{mV}$</td>
</tr>
<tr>
<td>0.1Hz to 10Hz 1/f Noise</td>
<td>$280\text{nV} + 100\text{mV}$</td>
<td>$2.8\text{ppm}$</td>
</tr>
<tr>
<td>Total Unadjusted Error</td>
<td>$= 9\text{ Bits Accurate}$</td>
<td>$2145\text{ppm}$</td>
</tr>
<tr>
<td>Resolution Error</td>
<td>$= 14\text{ Bits Accurate}$</td>
<td>$42.8\text{ppm}$</td>
</tr>
</tbody>
</table>

AD620B SPECS @ +25°C, ±15V

$V_{\text{OSI}} + V_{\text{OSO/G}} = 55\mu\text{V} \text{ max}$

$I_{\text{OS}} = 0.5\text{nA} \text{ max}$

Gain Error = 0.15%

Gain Nonlinearity = 40ppm

0.1Hz to 10Hz Noise = 280nVp-p

CMR = 120dB @ 60Hz

$350\Omega$, 100mV FS LOAD CELL

$V_{\text{CM}} = 5\text{V}$

2.18
A PRECISION SINGLE-SUPPLY COMPOSITE IN-AMP WITH RAIL-TO-RAIL OUTPUT

\[ V_{CM} = +2.5V \]

\[ V_{SIG} = +2.5V \]

A1, A2 = 1/2 AD822

Op Amp Applications, Chapter 2 2.19
THREE OP AMP IN-AMP
SINGLE +5V SUPPLY RESTRICTIONS

\[ V_{CM} + \frac{G V_{SIG}}{2} \]

\[ V_{OUT} = G V_{SIG} + V_{REF} \]

\[ V_{REF} = 2.5V \]

\[ G = 1 + \frac{2R1}{R_G} \]

\[ V_{OH} = 4.9V \]
\[ V_{OL} = 0.1V \]

\[ V_{OUT} = 4.9V \]
\[ V_{OL} = 0.1V \]

\[ \frac{G V_{SIG}}{2} \]

\[ V_{CM} \]

\[ R_G \]

\[ R_1 \]

\[ R_2 \]

\[ R_2' \]

\[ V_{CM} \]

\[ \sim \]

\[ V_{SIG} \]

\[ \sim \]

\[ \sim \]
AD623 SINGLE-SUPPLY
THREE OP-AMP IN-AMP ARCHITECTURE

Op Amp Applications, Chapter 2  2.21
PGAs in Data Acquisition Systems

- Used to increase the dynamic range of the system
- A PGA with a gain of 1 to 2 theoretically increases the dynamic range by 6dB.
- A gain of 1 to 4 gives a 12dB increase, etc.

Op Amp Applications, Chapter 2
A POORLY DESIGNED PGA

- Gain accuracy limited by switch's on-resistance $R_{ON}$ and $R_{ON}$ modulation
- $R_{ON}$ typically 100 - 500Ω for CMOS or JFET switch
- Even for $R_{ON} = 25Ω$, there is a 2.4% gain error for $G = 16$
- $R_{ON}$ drift over temperature limits accuracy
- Must use very low $R_{ON}$ switches (relays)

*Op Amp Applications, Chapter 2* 2.23
ALTERNATE PGA CONFIGURATION MINIMIZES THE EFFECTS OF $R_{ON}$

- $R_{ON}$ is not in series with gain setting resistors
- $R_{ON}$ is small compared to input impedance
- Only slight offset errors occur due to bias current flowing through the switches

*Op Amp Applications, Chapter 2*
A VERY LOW NOISE PGA USING THE AD797 AND THE ADG412

Op Amp Applications, Chapter 2
AD7730 SIGMA-DELTA MEASUREMENT
ADC WITH ON-CLOCK PGA

Op Amp Applications, Chapter 2
SPECIALTY AMPLIFIERS, USING OP AMPS WITH DATA CONVERTERS

MOTOR CONTROL CURRENT SENSING USING AN ISOLATION AMPLIFIER

High Voltage AC Input < 2500V RMS

\[ R_G = 499\Omega \text{ for } G = 100 \]

Op Amp Applications, Chapter 2

2.27
A TYPICAL SAMPLED DATA SYSTEM SHOWING APPLICATIONS OF OP AMPS

Op Amp Applications, Chapter 3
SPECIALTY AMPLIFIERS, USING OP AMPS WITH DATA CONVERTERS

GENERAL OP AMP SELECTION CRITERIA
FOR USE WITH DATA CONVERTERS

◆ The amplifier should not degrade the performance of the ADC/DAC
◆ AC specifications are usually the most important
   ● Noise
   ● Bandwidth
   ● Distortion
◆ Selection based on op amp data sheet specifications difficult due to varying conditions in actual application circuit with ADC/DAC:
   ● Power supply voltage
   ● Signal range (differential and common-mode)
   ● Loading (static and dynamic)
   ● Gain
◆ Parametric search engines may be useful
◆ ADC/DAC data sheets often recommend op amps (but may not include newly released products)

Op Amp Applications, Chapter 3 2.29
IDEAL N-BIT ADC QUANTIZATION NOISE

RMS ERROR = \( q/\sqrt{12} \)

SNR = \( 6.02N + 1.76\text{dB} + 10\log\left(\frac{f_s}{2\cdot\text{BW}}\right) \) FOR FS SINEWAVE

*Op Amp Applications, Chapter 3*  
2.30
EFFECT OF INPUT-REFERRED NOISE
ON ADC "GROUNDED INPUT" HISTOGRAM

P-P INPUT NOISE
≈ 6.6 × RMS NOISE

NUMBER OF OCCURANCES

RMS NOISE (σ)

Output Code

n-4  n-3  n-2  n-1  n  n+1  n+2  n+3  n+4

Op Amp Applications, Chapter 3 2.31
NOISE CALCULATIONS FOR AD8038 OP AMP
DRIVING AD9225 12-BIT, 25MSPS ADC

\[
V_{\text{ni}} = \frac{1}{2\pi \cdot RC} = 50\text{MHz}
\]

**Noise Bandwidth**

\[
\text{Noise Bandwidth} = 1.57 \cdot \frac{1}{2\pi \cdot RC} = 50\text{MHz}
\]

**AD8038 OP AMP SPECIFICATIONS**
- Input Voltage Noise = 8nV/√Hz
- Closed-Loop Bandwidth = 350MHz

**AD9225 ADC SPECIFICATIONS**
- Effective Input Noise = 166μV rms
- Small Signal Input BW = 105MHz

\[
V_{\text{ni}} = 8\text{nV/√Hz} \cdot \sqrt{50\text{MHz}} = 56\mu\text{V rms}
\]

*Op Amp Applications, Chapter 3* 2.32
Positioning the anti-aliasing filter to reduce the effects of the op amp noise

In general, \( f_{\text{FILTER}} < \frac{f_s}{2} \ll f_{\text{ADC}} < f_{\text{CL}} \)

Op Amp Applications, Chapter 3 2.33
POPULAR CONVERTER DYNAMIC PERFORMANCE SPECIFICATIONS

◆ Signal-to-Noise-and-Distortion Ratio (SINAD, or S/N +D)
◆ Effective Number of Bits (ENOB)
◆ Signal-to-Noise Ratio (SNR)
◆ Analog Bandwidth (Full-Power, Small-Signal)
◆ Harmonic Distortion
◆ Worst Harmonic
◆ Total Harmonic Distortion (THD)
◆ Total Harmonic Distortion Plus Noise (THD + N)
◆ Spurious Free Dynamic Range (SFDR)
◆ Two-Tone Intermodulation Distortion
◆ Multi-tone Intermodulation Distortion

Op Amp Applications, Chapter 3 2.34
TEST SETUPS FOR MEASURING ADC AND DAC PERFORMANCE

SIGNAL GEN. → ADC → BUFFER MEMORY M SAMPLES → DSP M-POINT FFT

Resolutions = \( \frac{f_s}{M} \)

DDS → DAC → ANALOG SPECTRUM ANALYZER

Op Amp Applications, Chapter 3 2.35
SINAD, ENOB, AND SNR DEFINITIONS

◆ SINAD (Signal-to-Noise-and-Distortion Ratio):
  • The ratio of the rms signal amplitude to the mean value of the
    root-sum-squares (RSS) of all other spectral components,
    including harmonics, but excluding DC.

◆ ENOB (Effective Number of Bits):
  \[
  \text{ENOB} = \frac{\text{SINAD} - 1.76\text{dB}}{6.02}
  \]

◆ SNR (Signal-to-Noise Ratio, or Signal-to-Noise Ratio Without
  Harmonics):
  • The ratio of the rms signal amplitude to the mean value of the
    root-sum-squares (RSS) of all other spectral components,
    excluding the first 5 harmonics and DC

*Op Amp Applications, Chapter 3*
AD9220 12-BIT, 10MSPS ADC SINAD AND ENOB FOR VARIOUS INPUT SIGNAL LEVELS

Op Amp Applications, Chapter 3
SPURIOUS FREE DYNAMIC RANGE (SFDR)

- FULL SCALE (FS)
- INPUT SIGNAL LEVEL (CARRIER)
- SFDR (dBc)
- SFDR (dBFS)
- WORST SPUR LEVEL

FREQUENCY

$\frac{f_s}{2}$

Op Amp Applications, Chapter 3

2.38
SPECIALTY AMPLIFIERS, USING OP AMPS WITH DATA CONVERTERS

SOME GENERAL OP AMP REQUIREMENTS IN ADC DRIVER APPLICATIONS

◆ Minimize degradation of ADC / DAC performance specifications
◆ Fast settling to ADC/DAC transient
◆ High bandwidth
◆ Low noise
◆ Low distortion
◆ Low power

◆ Note: Op amp performance must be measured under identical conditions as encountered in ADC / DAC application
  • Gain setting resistors
  • Input source impedance, output load impedance
  • Input / output signal voltage range
  • Input signal frequency
  • Input / output common-mode level
  • Power supply voltage (single or dual supply)
  • Transient loading

Op Amp Applications, Chapter 3
KEY DC AND AC OP AMP SPECIFICATIONS FOR ADC APPLICATIONS

◆ DC
  • Offset, offset drift
  • Input bias current
  • Open loop gain
  • Integral linearity
  • 1/f noise (voltage and current)

◆ AC (Highly application dependent!)
  • Wideband noise (voltage and current)
  • Small and Large Signal Bandwidth
  • Harmonic Distortion
  • Total Harmonic Distortion (THD)
  • Total Harmonic Distortion + Noise (THD + N)
  • Spurious Free Dynamic Range (SFDR)
  • Third Order Intermodulation Distortion
  • Third Order Intercept Point

Op Amp Applications, Chapter 3 2.40
**KEY SPECIFICATIONS FOR THE AD8057/8058 OP AMP, G = +1**

<table>
<thead>
<tr>
<th></th>
<th>$V_S = \pm 5V$</th>
<th>$V_S = +5V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Common Mode Voltage Range</td>
<td>$-4.0V$ to $+4.0V$</td>
<td>$+0.9V$ to $+3.4V$</td>
</tr>
<tr>
<td>Output Common Mode Voltage Range</td>
<td>$-4.0V$ to $+4.0V$</td>
<td>$+0.9V$ to $+4.1V$</td>
</tr>
<tr>
<td>Input Voltage Noise</td>
<td>$7nV/\sqrt{Hz}$</td>
<td>$7nV/\sqrt{Hz}$</td>
</tr>
<tr>
<td>Small Signal Bandwidth</td>
<td>$325MHz$</td>
<td>$300MHz$</td>
</tr>
<tr>
<td>THD @ 5MHz, $V_O = 2V$ p-p, $R_L = 1k\Omega$</td>
<td>$-85dBc$</td>
<td>$-75dBc$</td>
</tr>
<tr>
<td>THD @ 20MHz, $V_O = 2V$ p-p, $R_L = 1k\Omega$</td>
<td>$-62dBc$</td>
<td>$-54dBc$</td>
</tr>
</tbody>
</table>

*Op Amp Applications, Chapter 3*  

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---
AD8057/8058 OP AMP DISTORTION VS. FREQUENCY
FOR G = +1, V_S = ±5V, V_O = 2Vp-p, R_L = 150Ω
AD8057/8058 OP AMP DISTORTION VS. OUTPUT SIGNAL LEVEL FOR G = +1, $V_S = \pm 5V$, $R_L = 150\Omega$
CHARACTERISTICS OF AD77XX-FAMILY HIGH RESOLUTION SIGMA-DELTA MEASUREMENT ADCs

- Resolution: 16 - 24 bits
- Input signal bandwidth: <60Hz
- Effective sampling rate: <100Hz
- Generally Sigma-Delta architecture
- Designed to interface directly to sensors (< 1 kΩ) such as bridges with no external buffer amplifier (e.g., AD77XX - series)
  - On-chip PGA and high resolution ADC eliminates the need for external amplifier
- If buffer is used, it should be precision low noise (especially 1/f noise)
  - OP1177
  - OP177
  - AD797

Op Amp Applications, Chapter 3
SPECIALTY AMPLIFIERS, USING OP AMPS WITH DATA CONVERTERS

DRIVING UNBUFFERED
AD77XX-SERIES ΣΔ ADC INPUTS

- \( R_{\text{EXT}} \) Increases \( C_{\text{INT}} \) Charge Time and May Result in Gain Error
- Charge Time Dependent on the Input Sampling Rate and Internal PGA Gain Setting
- Refer to Specific Data Sheet for Allowable Values of \( R_{\text{EXT}} \) to Maintain Desired Accuracy
- Some AD77XX-Series ADCs Have Internal Buffering Which Isolates Input from Switching Circuits

Op Amp Applications, Chapter 3

2.45
MULTIPLEXED DATA ACQUISITION SYSTEM
REQUIRES FAST SETTLING OP AMP BUFFER

Op Amp Applications, Chapter 3 2.46
SPECIALTY AMPLIFIERS, USING OP AMPS WITH DATA CONVERTERS

DRIVING SINGLE-SUPPLY DATA ACQUISITION ADCs WITH SCALED INPUTS

Op Amp Applications, Chapter 3

2.47
AD9042 12-BIT, 41 MSPS ADC IS DESIGNED TO BE DRIVEN DIRECTLY FROM 50Ω SOURCE WITH NO EXTERNAL OP AMP

AD9042 Released in 1995, Breakthrough in SFDR Performance

Op Amp Applications, Chapter 3 2.48
ADCs WITH BUFFERED DIFFERENTIAL INPUTS

◆ Input buffers typical on BiMOS and bipolar processes
◆ Difficult on CMOS
◆ Simplified input interface - no transient currents
◆ Fixed common-mode level may limit flexibility

Op Amp Applications, Chapter 3 2.49
SIMPLIFIED INPUT CIRCUIT FOR A TYPICAL SWITCHED CAPACITOR CMOS SAMPLE-AND-HOLD

Switches shown in track mode

Op Amp Applications, Chapter 3
SINGLE-ENDED INPUT TRANSIENTS ON THE AD9225 12-BIT, 25MSPS CMOS ADC

- **Hold-to-Sample Mode Transition**: \( C_S \) Returned to Source for "recharging". Transient Consists of Linear, Nonlinear, and Common-Mode Components at Sample Rate.

- **Sample-to-Hold Mode Transition**: Input Signal Sampled when \( C_S \) is disconnected from Source.

![Graph showing Hold-to-Sample and Sample-to-Hold Mode Transitions](image)
OPTIMIZING A SINGLE-ENDED SWITCHED CAPACITOR ADC INPUT DRIVE CIRCUIT

Op Amp Applications, Chapter 3

2.52
DC COUPLED SINGLE-ENDED LEVEL SHIFTER AND DRIVER FOR THE AD9225 12-BIT, 25MSPS CMOS ADC

Op Amp Applications, Chapter 3

2.53
DIRECT-COUPLED SINGLE-SUPPLY LEVEL SHIFTER FOR DRIVING AD922X ADC INPUT

**Op Amp Applications, Chapter 3**
SINGLE-ENDED (A) AND DIFFERENTIAL (B) INPUT TRANSIENTS OF AD9225 12-BIT, 25MSPS CMOS SWITCHED CAPACITOR ADC

- Differential charge transient is symmetrical around mid-scale and dominated by linear component
- Common-mode transients cancel with equal source impedance

*Op Amp Applications, Chapter 3* 2.55
TRANSFORMER COUPLING INTO A DIFFERENTIAL INPUT ADC

RF TRANSFORMER: MINI-CIRCUITS T4-6T
1:2 Turns Ratio

Op Amp Applications, Chapter 3
OP AMP SINGLE-ENDED TO DIFFERENTIAL DC COUPLED DRIVER WITH LEVEL SHIFTING

Noise Gain = +2

Input: ±1V

Output: +5V

AD922X

Set for 4 Volt p-p Differential Input Span

Op Amp Applications, Chapter 3
AD813X DIFFERENTIAL ADC DRIVER
FUNCTIONAL DIAGRAM AND EQUIVALENT CIRCUIT

(A)

(B) EQUIVALENT CIRCUIT:

\[
\text{GAIN} = \frac{R_F}{R_G}
\]

Op Amp Applications, Chapter 3

2.58
SPECIALTY AMPLIFIERS, USING OP AMPS WITH DATA CONVERTERS

SINGLE-SUPPLY DIFFERENTIAL DRIVER CIRCUIT USING THE AD8132 AMPLIFIER AND THE AD9203 10-BIT, 40MSPS ADC

Op Amp Applications, Chapter 3 2.59
AD8138 DRIVING AD9226 12-BIT, 65MSPS CMOS ADC IN DIRECT-COUPLED SINGLE-SUPPLY APPLICATION

SET FOR 1V P-P DIFFERENTIAL INPUT SPAN

Op Amp Applications, Chapter 3

2.60
AD8138 DRIVING AD9226 ADC
1V DIFFERENTIAL INPUT SPAN, \( f_s = 65\text{MSPS} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAMPLING RATE</td>
<td>65MSPS</td>
</tr>
<tr>
<td>INPUT FREQ</td>
<td>30MHz</td>
</tr>
<tr>
<td>SINAD</td>
<td>65.7dBFS</td>
</tr>
<tr>
<td>SNR</td>
<td>67.1dBFS</td>
</tr>
<tr>
<td>HD2</td>
<td>-78.4dBc</td>
</tr>
<tr>
<td>HD3</td>
<td>-71.6dBc</td>
</tr>
<tr>
<td>THD</td>
<td>71.1dBFS</td>
</tr>
<tr>
<td>SFDR</td>
<td>71.6dBFS</td>
</tr>
</tbody>
</table>

FFT
AIN = -0.5 dBFS @ 30 MHz

Op Amp Applications, Chapter 3 2.61
AD8351 LOW DISTORTION DIFFERENTIAL RF/IF AMPLIFIER APPLICATION

AD8351 KEY FEATURES
- 3dB Bandwidth: 2.2GHz for gain of 12dB
- Slew rate: 11,000V/µs
- Single resistor programmable gain, 0dB to 30dB
- Input noise: 2.3nV/√Hz
- Single supply: 3.3 to 5.5V
- Adjustable output common-mode voltage

Op Amp Applications, Chapter 3 2.62
AD8351 DIFFERENTIAL ADC DRIVER
PERFORMANCE WITH AD6645 ADC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAMPLING RATE</td>
<td>80 MSPS</td>
</tr>
<tr>
<td>INPUT FREQ</td>
<td>65 MHz</td>
</tr>
<tr>
<td>SNR</td>
<td>64.8 dB</td>
</tr>
<tr>
<td>HD2</td>
<td>-79 dBc</td>
</tr>
<tr>
<td>HD3</td>
<td>-81 dBc</td>
</tr>
<tr>
<td>THD</td>
<td>-76 dBc</td>
</tr>
<tr>
<td>SFDR</td>
<td>78 dBc</td>
</tr>
</tbody>
</table>

Op Amp Applications, Chapter 3

2.63
A TRUE 16-BIT ADC REQUIRES A TRUE 16-BIT DRIVER

Op Amp Applications, Chapter 3

2.64
SAR ADCs PRESENT A DYNAMIC TRANSIENT LOAD TO THE REFERENCE

Op Amp Applications, Chapter 3
BUFFERING DAC OUTPUTS USING OP AMPS

\[ V_{\text{OUT}} = \frac{1 + \frac{R_2}{R_1}}{1 + 2 \cdot R_2} \]

\[ I_{\text{OUT}} = \frac{V_{\text{OUT}}}{R_L} \]

\[ -I_{\text{OUT}} \cdot R_2 \]

Op Amp Applications, Chapter 3
GENERALIZED MODEL OF A HIGH SPEED DAC OUTPUT
SUCH AS THE AD976X AND AD977X SERIES

- $I_{FS} - I$ - 20mA typical
- Bipolar or BiCMOS DACs sink current, $R_{OUT} < 500\Omega$
- CMOS DACs source current, $R_{OUT} > 100k\Omega$
- Output compliance voltage < ±1V for best performance

*Op Amp Applications, Chapter 3* 2.67
DIFFERENTIAL TRANSFORMER COUPLING

Op Amp Applications, Chapter 3 2.68
DIFFERENTIAL DC COUPLED USING
A DUAL SUPPLY OP AMP

\[ f_{3dB} = \frac{1}{2\pi \cdot 50\Omega \cdot C_{FILTER}} \]
DIFFERENTIAL DC COUPLED W/ SINGLE SUPPLY OP AMP

\[ f_{3dB} = \frac{1}{2\pi \cdot 50\Omega \cdot C_{\text{FILTER}}} \]

Op Amp Applications, Chapter 3

SEE TEXT
SINGLE-ENDED CURRENT-TO-VOLTAGE
OP AMP INTERFACE

For $R_{DAC} = R_F$, make $C_F = \frac{R_{DAC} (C_{DAC} + C_{IN})}{R_F}$

For $R_{DAC} >> R_F$, make $C_F = \sqrt{\frac{C_{DAC} + C_{IN}}{2\pi R_F f_u}}$

$R_F = 200\Omega$

fu = Op Amp Unity
Gain-Bandwidth Product

Op Amp Applications, Chapter 3

2.71
BUFFERING HIGH-SPEED DACs USING AD813X DIFFERENTIAL AMPLIFIER

Op Amp Applications, Chapter 3
SPECIALTY AMPLIFIERS, USING OP AMPS WITH DATA CONVERTERS

A 75kHz 4-POLE GAUSSIAN ACTIVE FILTER FOR BUFFERING THE OUTPUT OF THE AD1853 STEREO DAC

Op Amp Applications, Chapter 3
OP AMP APPLICATIONS
SEMINAR

1. History, Basics, Design Aids, Filters

2. Specialty Amplifiers, Using Op Amps with Data Converters

3. Hardware and Housekeeping Design Techniques

4. Signal Amplifiers, Sensor Signal Conditioning
WIRE AND STRIP INDUCTANCE CALCULATIONS

WIRE INDUCTANCE = 0.0002L \left[ \ln \left( \frac{2L}{R} \right) - 0.75 \right] \mu H

EXAMPLE: 1cm of 0.5mm o.d. wire has an inductance of 7.26nH
(2R = 0.5mm, L = 1cm)

STRIP INDUCTANCE = 0.0002L \left[ \ln \left( \frac{2L}{W+H} \right) + 0.2235 \left( \frac{W+H}{L} \right) + 0.5 \right] \mu H

EXAMPLE: 1cm of 0.25 mm PC track has an inductance of 9.59 nH
(H = 0.038mm, W = 0.25mm, L = 1cm)
NONIDEAL AND IMPROVED SIGNAL TRACE ROUTING

Op Amp Applications, Chapter 7
BASIC PRINCIPLES OF INDUCTIVE COUPLING

\[
V_{\text{induced}} = \omega_N M I_N = \omega_{AB}
\]

\( M = \text{MUTUAL INDUCTANCE} \)
\( B = \text{MAGNETIC REFLUX DENSITY} \)
\( A = \text{AREA OF SIGNAL LOOP} \)
\( \omega_N = 2\pi f_N = \text{FREQUENCY OF NOISE SOURCE} \)
\( V = \text{INDUCED VOLTAGE} \)

Op Amp Applications, Chapter 7
PROPER SIGNAL ROUTING AND LAYOUT CAN REDUCE INDUCTIVE COUPLING
MUTUAL INDUCTANCE AND COUPLING
WITHIN SIGNAL CABLELING

- Flat ribbon cable with single return has large mutual inductance between circuits.

- Separate and alternate signal/return lines for each circuit reduces mutual inductance.

- Twisted pairs reduce mutual inductance still further.

*Op Amp Applications, Chapter 7* 3.5
CALCULATION OF SHEET RESISTANCE AND LINEAR RESISTANCE FOR STANDARD COPPER PCB CONDUCTORS

\[
R = \frac{\rho Z}{XY} \\
\rho = \text{RESISTIVITY}
\]

SHEET RESISTANCE CALCULATION FOR 1 OZ. COPPER CONDUCTOR:

\[
\rho = 1.724 \times 10^{-6} \ \text{Ωcm}, \ Y = 0.0036 \text{cm}
\]

\[
R = 0.48 \frac{Z}{X} \ \text{mΩ}
\]

\[
\frac{Z}{X} = \text{NUMBER OF SQUARES}
\]

\[
R = \text{SHEET RESISTANCE OF 1 SQUARE (Z=X)} \\
= 0.48 \text{mΩ/SQUARE}
\]

*Op Amp Applications, Chapter 7* 3.6
HARDWARE AND HOUSEKEEPING DESIGN TECHNIQUES

OHM'S LAW PREDICTS >1 LSB OF ERROR DUE TO DROP IN PCB CONDUCTOR

SIGNAL SOURCE

16-BIT ADC, $R_{IN} = 5k\Omega$

0.25mm (10 mils) wide, 1 oz. copper PCB trace

Assume ground path resistance negligible

Op Amp Applications, Chapter 7

3.7
A MORE REALISTIC SOURCE-TO-LOAD GROUNDING SYSTEM VIEW INCLUDES CONSIDERATION OF THE IMPEDANCE BETWEEN G1-G2, PLUS THE EFFECT OF ANY NON-SIGNAL-RELATED CURRENTS

\[ \Delta V = \text{voltage differential due to signal current and/or external current flowing in ground impedance} \]

Op Amp Applications, Chapter 7
ANY CURRENT FLOWING THROUGH A COMMON GROUND IMPEDANCE CAN CAUSE ERRORS

\[ \Delta V = \text{VOLTAGE DUE TO SIGNAL CURRENT PLUS CURRENT FROM HIGH CURRENT CIRCUIT FLOWING IN COMMON GROUND IMPEDANCE} \]

*Op Amp Applications, Chapter 7* 3.9
CHARACTERISTICS OF GROUND PLANES

- ONE ENTIRE PCB SIDE (OR LAYER) IS A CONTINUOUS GROUNDED CONDUCTOR.
- THIS GIVES MINIMUM GROUND RESISTANCE AND INDUCTANCE, BUT ISN'T ALWAYS SUFFICIENT TO SOLVE ALL GROUNDING PROBLEMS.
- BREAKS IN GROUND PLANES CAN IMPROVE OR DEGRADE CIRCUIT PERFORMANCE — THERE IS NO GENERAL RULE.
- YEARS AGO GROUND PLANES WERE DIFFICULT TO FABRICATE. TODAY THEY AREN'T.
- MULTI-LAYER, GROUND AND VOLTAGE PLANE PCB DESIGNS ARE STANDARD
UNLESS CARE IS TAKEN, EVEN SMALL COMMON GROUND CURRENTS CAN DEGRADE PRECISION AMPLIFIER ACCURACY

Op Amp Applications, Chapter 7

3.11
A differential input ground isolating amplifier allows high transmission accuracy by rejecting ground noise voltage between source (G1) and measurement (G2) grounds.

\[ R5 \quad 21.1k\Omega \quad \text{(AD629 only)} \]

\[ R1 \quad 380k\Omega \quad 25k\Omega \]
\[ R2 \quad 380k\Omega \quad 25k\Omega \]
\[ R3 \quad 380k\Omega \quad 25k\Omega \]
\[ R4 \quad 20k\Omega \quad 25k\Omega \]

\[ \text{CMV(V)} \quad \text{CMR(dB)} \]
\[ \text{AD629} \quad \pm 270 \quad 88 \]
\[ \text{AMP03} \quad \pm 20 \quad 100 \]

**Op Amp Applications, Chapter 7**

3.12
A HIGH-IMPEDANCE DIFFERENTIAL INPUT ADC ALSO ALLOWS HIGH TRANSMISSION ACCURACY BETWEEN SOURCE AND LOAD

![Diagram of signal source and high-Z differential input ADC]

Op Amp Applications, Chapter 7
INVERTING MODE GUARD ENCLOSES ALL OP AMP INVERTING INPUT CONNECTIONS WITHIN A GROUNDED GUARD RING

Example application:
Photodiode Preamps

Op Amp Applications, Chapter 7

3.14
NON-INVERTING MODE GUARD ENCLES ALL OP AMP NON-INVERTING INPUT CONNECTIONS WITHIN A LOW IMPEDANCE, DRIVEN GUARD RING

NON-INVERTING MODE GUARD:
RING SURROUNDS ALL "HOT NODE" LEAD ENDS - INCLUDING INPUT TERMINAL ON THE PCB

USE SHIELDING (Y) OR UNITY-GAIN BUFFER (X) IF GUARD HAS LONG LEAD

Op Amp Applications, Chapter 7
PCB GUARD PATTERNS FOR INVERTING AND NON-INVERTING MODE OP AMPS USING 8 PIN MINIDIP (N) PACKAGE

Op Amp Applications, Chapter 7
PCB GUARD PATTERNS FOR INVERTING AND NON-INVERTING MODE OP AMPS USING 8 PIN SOIC (R) PACKAGE

NOTE: PINS 1, 5, & 8 ARE OPEN ON MANY "R" PACKAGED DEVICES

Op Amp Applications, Chapter 7
CAPACITANCE OF TWO PARALLEL PLATES

\[ C = \frac{0.00885 \times E_r \times A}{d} \text{ pF} \]

- \( A \) = plate area in mm\(^2\)
- \( d \) = plate separation in mm
- \( E_r \) = dielectric constant relative to air

- Most common PCB type uses 1.5mm glass-fiber epoxy material with \( E_r = 4.7 \)
- Capacity of PC track over ground plane is roughly 2.8pF/cm\(^2\)
CAPACITIVE COUPLING EQUIVALENT CIRCUIT MODEL

\[ Z_1 = \text{CIRCUIT IMPEDANCE} \]
\[ Z_2 = \frac{1}{j\omega C} \]
\[ V_{\text{COUPLED}} = V_N \left( \frac{Z_1}{Z_1 + Z_2} \right) \]

*Op Amp Applications, Chapter 7*
AN OPERATIONAL MODEL OF A FARADAY SHIELD

Op Amp Applications, Chapter 7
REGULATION PRIORITIES FOR OP AMP POWER SUPPLY SYSTEMS

◆ High performance analog power systems use linear regulators, with primary power derived from:
  • AC line power
  • Battery power systems
  • DC-DC power conversion systems

◆ Switching regulators should be avoided if at all possible, but if not...
  • Apply noise control techniques
  • Use quality layout and grounding
  • Be aware of EMI

*Op Amp Applications, Chapter 7* 3.21
THE ADP330X anyCAP™ LDO ARCHITECTURE
HAS BOTH DC AND AC PERFORMANCE ADVANTAGES

Op Amp Applications, Chapter 7 3.22
DUAL-SUPPLY LOW FREQUENCY RAIL BYPASS/DISTRIBUTION FILTER

Op Amp Applications, Chapter 7
A CARD-ENTRY FILTER IS USEFUL FOR LOW-MEDIUM FREQUENCY POWER LINE NOISE FILTERING IN ANALOG SYSTEMS

3-5V NOISY INPUT FROM SWITCHING SUPPLY OR DC-DC CONVERTER

+-----------------------------+-----------------------------+
| 100µH                      | C1 100µF/20V TANTALUM       |
|                             | * Fastron MESC series or equivalent |
|                             | R1 1Ω                        |
+-----------------------------+-----------------------------+

3-5V CLEAN OUTPUT TO 300mA LOAD ANALOG STAGE

Op Amp Applications, Chapter 7
CAPACITOR EQUIVALENT CIRCUIT
AND RESPONSE TO INPUT CURRENT PULSE

\[ V_{\text{PEAK}} = ESR \cdot I_{\text{PEAK}} = 200\text{mV} \]

\[ V_{\text{PEAK}} = ESL \cdot \frac{di}{dt} + ESR \cdot I_{\text{PEAK}} = 400\text{mV} \]

\[ C = 100\mu\text{F} \]

\[ X_C = 0.0005\Omega \text{ @ 3.5MHz} \]

\[ \text{ESR} = 0.2\Omega \]

\[ \text{ESL} = 20\text{nH} \]

\[ \frac{di}{dt} = \frac{1\text{A}}{100\text{ns}} \]

\[ \text{Equivalent } f = 3.5\text{MHz} \]

\[ I_{\text{PEAK}} = 1\text{A} \]

Op Amp Applications, Chapter 7
ELECTROLYTIC CAPACITOR
IMPEDANCE VERSUS FREQUENCY

ESR = 0.2Ω

10kHz 1MHz

Op Amp Applications, Chapter 7

3.26
LOCALIZED HIGH FREQUENCY SUPPLY FILTER(S) PROVIDES OPTIMUM FILTERING
AND DECOUPLING VIA SHORT LOW-INDUCTANCE PATH (GROUND PLANE)

CORRECT

POWER SUPPLY TRACE

DECOUPLING CAPACITOR

V+

IC

GND

OPTIONAL FERRITE BEADS

INcorrect

POWER SUPPLY TRACE

DECOUPLING CAPACITOR

V+

IC

GND

VIA TO GROUND PLANE

PCB TRACE

VIA TO GROUND PLANE

Op Amp Applications, Chapter 7  3.27
A GENERAL-PURPOSE OP AMP CM OVER-VOLTAGE PROTECTION NETWORK USING SCHOTTKY CLAMP DIODES WITH CURRENT LIMIT RESISTANCE

Op Amp Applications, Chapter 7 3.28
THE AD629 HIGH VOLTAGE IN-AMP IC OFFERS ± 500V INPUT OVER-VOLTAGE PROTECTION, ONE-COMPONENT SIMPLICITY, AND FAIL-SAFE POWER OFF OPERATION

Op Amp Applications, Chapter 7 3.29
AN OP AMP INPUT STAGE WITH D1-D2 INPUT DIFFERENTIAL OVER-VOLTAGE PROTECTION NETWORK

Op Amp Applications, Chapter 7 3.30
THE AD620 IN-AMP INPUT INTERNALLY USES D1-D2 AND SERIES RESISTORS
$R_S$ FOR PROTECTION (ADDITIONAL PROTECTION CAN BE ADDED EXTERNALLY)

Op Amp Applications, Chapter 7
A GENERALIZED DIODE PROTECTION CIRCUIT FOR THE AD620 AND OTHER IN-AMPS USES D3-D6 FOR CM CLAMPING AND SERIES RESISTORS $R_{\text{LIMIT}}$ FOR PROTECTION

---

**Op Amp Applications, Chapter 7**

3.32
SINGLE-SUPPLY IN-AMPS MAY OR MAY NOT REQUIRE EXTERNAL PROTECTION IN THE FORM OF RESISTORS AND CLAMP DIODES — IF SO, THEY CAN BE ADDED AS SHOWN

\[ G = 1 + \frac{R_2}{R_1} + \frac{2R_2}{R_G} \]
A SUMMARY OF IN-CIRCUIT OVER-VOLTAGE POINTS

- INPUT VOLTAGES MUST NOT EXCEED ABSOLUTE MAXIMUM RATINGS
  (Usually Specified With Respect to Supply Voltages)
- Requires $V_{\text{IN(CM)}}$ Stay Within a Range Extending to $\leq 0.3\text{V}$ Beyond Rails
  ($-V_S - 0.3\text{V} \geq V_{\text{IN}} \leq +V_S + 0.3\text{V}$)
- IC Input Stage Fault Currents Must Be Limited
  ($\leq 5\text{mA}$ Unless Otherwise Specified)
- Avoid Reverse-Bias Breakdown in Input Stage Junctions!
- Differential and Common Mode Ratings Often Differ
- No Two Amplifiers are Exactly the Same
- Some ICs Contain Internal Input Protection
  - Diode Voltage Clamps, Current Limiting Resistors (or both)
  - Absolute Maximum Ratings Must Still Be Observed

Op Amp Applications, Chapter 7 3.34
GROUND LOOPS IN SHIELDED TWISTED PAIR CABLE CAN CAUSE ERRORS

- $V_N$ Causes Current in Shield (Usually 50/60Hz)

- Differential Error Voltage is Produced at Input of A2 Unless:
  - A1 Output is Perfectly Balanced and
  - A2 Input is Perfectly Balanced and
  - Cable is Perfectly Balanced

*Op Amp Applications, Chapter 7* 3.35
HYBRID GROUNDING OF SHIELDED CABLE WITH PASSIVE SENSOR

Op Amp Applications, Chapter 7
IMPEDEANCE-BALANCED DRIVE OF BALANCED SHIELDED CABLE AIDS NOISE-IMMUNITY WITH EITHER BALANCED OR SINGLE-ENDED SOURCE SIGNALS

Op Amp Applications, Chapter 7
COAXIAL CABLES CAN USE EITHER BALANCED OR SINGLE-ENDED RECEIVERS

Shield Carries Signal Return Current

Op Amp Applications, Chapter 7
SOME GENERAL OBSERVATIONS ON OP AMP AND IN-AMP INPUT STAGE RFI RECTIFICATION SENSITIVITY

◆ BJT input devices \textit{rectify readily}
  - Forward-biased B-E junction
  - Exponential I-V Transfer Characteristic
◆ FET input devices \textit{less sensitive} to rectifying
  - Reversed-biased p-n junction
  - Square-law I-V Transfer Characteristic
◆ Low $I_{\text{supply}}$ devices versus High $I_{\text{supply}}$ devices
  - Low $I_{\text{supply}}$ $\Rightarrow$ \textit{Higher} rectification sensitivity
  - High $I_{\text{supply}}$ $\Rightarrow$ \textit{Lower} rectification sensitivity

\textit{Op Amp Applications, Chapter 7} 3.39
RELATIVE SENSITIVITY COMPARISON - BJT VERSUS JFET

- **BJT:**
  - Emitter area = 576 µm²
  - $I_C = 10 \mu A$
  - $V_T = 25.68 \text{mV} @ 25^\circ C$
  
  \[ \Delta I_C = \left( \frac{V_X}{V_T} \right)^2 \cdot \frac{I_C}{4} \]
  
  \[ = \frac{V_X^2}{264} \]

- **JFET:**
  - $I_{DSS} = 20 \mu A (Z/L=1)$
  - $V_P = 2V$
  - $I_D = 10 \mu A$
  
  \[ \Delta I_D = \left( \frac{V_X}{V_P} \right)^2 \cdot \frac{I_{DSS}}{2} \]
  
  \[ = \frac{V_X^2}{400 \times 10^3} \]

- Conclusion: BJTs ~1500 more sensitive than JFETs!

*Op Amp Applications, Chapter 7*
SIMPLE EMI/RFI NOISE FILTERS FOR OP AMP CIRCUITS

\[ R_1 = 2R \quad R_2 = 2R \quad R_3 \]

EMI FILTER BANDWIDTH = \( \frac{1}{2\pi R C} \) > 100\times SIGNAL BANDWIDTH

\[ R_1 = R \]

\[ R_2 \]

\[ R_3 \]

*Op Amp Applications, Chapter 7*
A GENERAL-PURPOSE COMMON-MODE/DIFFERENTIAL-MODE RC EMI/RFI FILTER FOR IN-AMPS

\[ \tau_{\text{DIFF}} = (R_1 + R_2) \left[ \frac{C_1 \cdot C_2}{C_1 + C_2} + C_3 \right] \]
\[ \tau_{\text{CM}} = R_1 \cdot C_1 = R_2 \cdot C_2 \]
\[ \tau_{\text{DIFF}} \gg \tau_{\text{CM}} \]

R1 \cdot C1 = R2 \cdot C2
R1 = R2 SHOULD BE 1% RESISTORS
C1 = C2 SHOULD BE ≤ 5% CAPACITORS

DIFFERENTIAL FILTER BANDWIDTH = \( \frac{1}{2\pi (R_1 + R_2) \left[ \frac{C_1 \cdot C_2}{C_1 + C_2} + C_3 \right]} \)

Op Amp Applications, Chapter 7 3.42
FLEXIBLE COMMON-MODE AND DIFFERENTIAL-MODE RC EMI/RFI FILTERS ARE USEFUL WITH THE AD620 SERIES, THE AD623, AD627, AND OTHER IN-AMPS

![Diagram of common-mode and differential-mode RC EMI/RFI filter circuit]

U1  | R1/R2  | C1/C2  | C3  
---|-------|-------|-----
AD620/621/622 | 4.02k  | 1nF   | 47nF 
AD623  | 10k    | 1nF   | 22nF 
AD627  | 20k    | 1nF   | 22nF 

*Op Amp Applications, Chapter 7*
FOR SIMPLICITY AS WELL AS LOWEST NOISE EMI/RFI FILTER OPERATION, A COMMON-MODE CHOKE IS USEFUL WITH THE AD620 SERIES IN-AMP DEVICES

50Ω SINEWAVE SOURCE

RF CM test
DC - 20MHz
1V p-p

COMMON MODE CHOKE:
PULSE ENGINEERING B4001
http://www.pulseeng.com

Op Amp Applications, Chapter 7
OP AMP AND IN-AMP OUTPUTS SHOULD BE PROTECTED AGAINST EMI/RFI, PARTICULARLY IF THEY DRIVE LONG CABLES

Op Amp Applications, Chapter 7

3.45
A microstrip transmission line with defined impedance is formed by a PCB trace of appropriate geometry, spaced from a ground plane.
A symmetric stripline transmission line with defined impedance is formed by a PCB trace of appropriate geometry embedded between equally spaced ground and/or power planes.

---

*Op Amp Applications, Chapter 7*
### THE PROS AND CONS OF NOT EMBEDDING VS. THE EMBEDDING OF SIGNAL TRACES IN MULTI-LAYER PCB DESIGNS

<table>
<thead>
<tr>
<th></th>
<th>NOT EMBEDDED</th>
<th></th>
<th>EMBEDDED</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Route</td>
<td></td>
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<tr>
<td>Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Route</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Advantages**
- Signal traces shielded and protected
- Lower impedance, thus lower emissions and crosstalk
- Significant improvement > 50MHz

**Disadvantages**
- Difficult prototyping and troubleshooting
- Decoupling may be more difficult
- Impedance may be too low for easy matching

*Op Amp Applications, Chapter 7*
USED WISELY, SIMULATION IS A POWERFUL DESIGN TOOL

- Understand Realistic Simulation Goals
- Evaluate Available Models Accordingly
- Know the Capabilities for Each Competing Op Amp Model
- Following Simulation, Breadboarding is Always Desirable and Necessary
- Breadboarding / prototyping may require an actual PC board layout

Op Amp Applications, Chapter 7 3.49
## DIFFERENTIATING THE MACROMODEL AND MICROMODEL

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>MACROMODEL</td>
<td>Ideal Elements Model Device Behavior</td>
<td>Fast Simulation Time, Easily Modified</td>
</tr>
<tr>
<td>MICROMODEL</td>
<td>Fully Characterized Transistor Level Circuit</td>
<td>Most Complete Model</td>
</tr>
</tbody>
</table>

*Op Amp Applications, Chapter 7*
INPUT AND GAIN/POLE STAGES OF ADSpice MACROMODEL

Op Amp Applications, Chapter 7

3.51
THE FREQUENCY SHAPING STAGES POSSIBLE WITHIN THE ADSpice MODEL

POLE STAGE
\[ \frac{\text{gm}_2}{R_8} = 1 \]

ZERO STAGE
\[ \frac{E_{1}^*}{R_9 + R_{10}} = 1 \]

ZERO/POLE STAGE
\[ \frac{\text{gm}_3}{R_{11}} = 1 \]

POLE/ZERO STAGE
\[ \frac{\text{gm}_4}{R_{13}} = 1 \]

Op Amp Applications, Chapter 7

3.52
GENERAL-PURPOSE MACROMODEL OUTPUT STAGE

![Diagram of a general-purpose macromodel output stage](image)

**Output Impedance:**

\[
\text{Output Impedance} = \frac{R_{O1} + R_{O2}}{2} + sL_o
\]

*Op Amp Applications, Chapter 7*
A PULSE RESPONSE COMPARISON OF AN OP249 FOLLOWER (LEFT) MODEL FAVORS THE ADSpice MODEL IN TERMS OF FIDELITY (CENTER), BUT NOT THE BOYLE (RIGHT).

**ACTUAL**

**ADSpice MODEL**

**BOYLE MODEL**

VERTICAL SCALE: 50mV / div.
HORIZONTAL SCALE: 200ns / div.

LOAD = 260pF

*Op Amp Applications, Chapter 7* 3.54
TOWARDS ACHIEVING LOW NOISE OPERATION, A FIRST DESIGN STEP IS THE REDUCTION OF POLE/ZERO CELL IMPEDANCES TO LOW VALUES

CASE

<table>
<thead>
<tr>
<th></th>
<th>&quot;Noisy&quot;</th>
<th>&quot;Noiseless&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>R9</td>
<td>1x10^6Ω</td>
<td>1Ω</td>
</tr>
<tr>
<td>gm2</td>
<td>1x10^-6</td>
<td>1.0</td>
</tr>
<tr>
<td>C4</td>
<td>159x10^-15F</td>
<td>159x10^-9F</td>
</tr>
<tr>
<td>Noise</td>
<td>129nV/√Hz</td>
<td>129pV/√Hz</td>
</tr>
</tbody>
</table>

Op Amp Applications, Chapter 7
A BASIC SPICE NOISE GENERATOR IS FORMED WITH
DIODES, RESISTORS, AND CONTROLLED SOURCES

Op Amp Applications, Chapter 7
HARDWARE AND HOUSEKEEPING DESIGN TECHNIQUES

INPUT AND GAIN STAGES OF CURRENT FEEDBACK OP AMP MACROMODEL

Op Amp Applications, Chapter 7
COMPARISON OF A REAL AD811 CURRENT FEEDBACK OP AMP (LEFT) WITH MACROMODEL (RIGHT) SHOWS SIMILAR CHARACTERISTICS AS FEEDBACK RESISTANCE IS VARIED.
WITH CARE AND LOW PARASITIC EFFECTS IN THE PCB LAYOUT, RESULTS OF LAB TESTING (CENTER) AND SIMULATION (RIGHT) CAN CONVERGE.

Op Amp Applications, Chapter 7
WITHOUT LOW PARASITICS, LAB TESTING RESULTS (CENTER) AND PARALLEL SIMULATION (RIGHT) STILL SHOW CONVERGENCE—WITH A POORLY DAMPED RESPONSE

Op Amp Applications, Chapter 7 3.60
THESE CIRCUITS WERE EASY TO BREADBOARD (EXCEPT FOR THE 300V DC!)

Op Amp Applications, Chapter 7
SMALL PACKAGE SIZES PRESENT MAJOR DIFFICULTIES IN BREADBOARDING

Op Amp Applications, Chapter 7
A GENERAL PURPOSE OP AMP EVALUATION BOARD ALLOWS FAST, EASY CONFIGURATION OF LOW FREQUENCY OP AMP CIRCUITS

Op Amp Applications, Chapter 7

3.63
THE AD8001 EVALUATION BOARD USES A LARGE AREA GROUND PLANE AND MINIMAL PARASITIC CAPACITANCE (TOP VIEW)
A HIGH SPEED OP AMP SUCH AS THE AD8001 REQUIRES A DEDICATED EVALUATION BOARD WITH SUITABLE GROUND PLANES AND DECOUPLING (BOTTOM VIEW)

Op Amp Applications, Chapter 7
OP AMP APPLICATIONS
SEMINAR

1. History, Basics, Design Aids, Filters
2. Specialty Amplifiers, Using Op Amps with Data Converters
3. Hardware and Housekeeping Design Techniques
4. Signal Amplifiers, Sensor Signal Conditioning
OP AMP APPLICATIONS SEMINAR
EFFECT OF CAPACITIVE LOADING ON OP AMP STABILITY

Op Amp Applications, Chapter 6
RAISING NOISE GAIN (DC OR AC) FOR FOLLOWER (A) OR INVERTER (B) STABILITY

(A) FOLLOWER

(B) INVERTER

Op Amp Applications, Chapter 6 4.2
DRIVING CAPACITIVE LOADS

Op Amp Applications, Chapter 6
VIDEO TRANSMISSION LINE DRIVERS

KEY VIDEO SPECIFICATIONS:
- Differential Gain
- Differential Phase
- Bandwidth Flatness (0.1dB)

*Op Amp Applications, Chapter 6*
AD8072/73 DUAL/TRIPLE VIDEO BUFFERS
GAIN AND GAIN FLATNESS, G = +2, R_L = 150Ω

Op Amp Applications, Chapter 6
PULSE RESPONSE OF AD8001 DRIVING 5 FEET OF LOAD-ONLY TERMINATED 50Ω COAXIAL CABLE

VERTICAL SCALE: 200mV/div
HORIZONTAL SCALE: 10ns/div

Op Amp Applications, Chapter 6
PULSE RESPONSE OF AD8001 DRIVING 5 FEET OF SOURCE AND LOAD TERMINATED 50Ω COAXIAL CABLE

Op Amp Applications, Chapter 6
PULSE RESPONSE OF AD8001 DRIVING 5 FEET OF SOURCE-ONLY TERMINATED 50Ω COAXIAL CABLE

Op Amp Applications, Chapter 6

4.8
TWO APPROACHES TO DIFFERENTIAL LINE DRIVING AND RECEIVING

Op Amp Applications, Chapter 6
DIFFERENTIAL DRIVER USING
AN INVERTER AND A FOLLOWER

NOTE: DECOUPLING NOT SHOWN

Op Amp Applications, Chapter 6

4.10
AD8138 DIFFERENTIAL DRIVER AMPLIFIER FUNCTIONAL SCHEMATIC (A) AND EQUIVALENT CIRCUIT (B)

(A) 

(B) EQUIVALENT CIRCUIT:

\[
\text{GAIN} = \frac{R_F}{R_G}
\]

Op Amp Applications, Chapter 6 4.11
AD8138 OUTPUT BALANCE ERROR VERSUS FREQUENCY

Op Amp Applications, Chapter 6

4.12
THE AD8129/AD8130
ACTIVE FEEDBACK AMPLIFIER TOPOLOGY

\[ V_{\text{IN}} \]

\[ V_{X1} \quad G_M \quad V_{X2} \]
\[ I_X \]
\[ V_{X1} \quad V_{X2} \quad I_X \quad V_{Y1} \quad V_{Y2} \]
\[ R3 = R1||R2 \]
\[ R2 \]
\[ R1 \]

Feedback Forces \( I_X = I_Y \)
\[ V_{X1} - V_{X2} = -(V_{Y1} - V_{Y2}) = V_{Y2} \]

\[ V_{\text{OUT}} = \left[ 1 + \frac{R2}{R1} \right] V_{Y2} \]
\[ V_{\text{OUT}} = \left[ 1 + \frac{R2}{R1} \right] \left[ V_{X1} - V_{X2} \right] \]

Op Amp Applications, Chapter 6
AD8130 COMMON-MODE REJECTION VERSUS FREQUENCY FOR ±2.5V, ±5V, AND ±12V SUPPLIES

Op Amp Applications, Chapter 6
SIGNAL AMPLIFIERS, SENSOR SIGNAL CONDITIONING

AD8184 4:1 VIDEO MULTIPLEXER

Op Amp Applications, Chapter 6

4.15
AD8170/8174/8180/8182 BIPOLAR VIDEO MULTIPLEXERS

Op Amp Applications, Chapter 6

4.16
AD8116 16×16 200MHz BUFFERED VIDEO CROSSPOINT SWITCH

Op Amp Applications, Chapter 6
SINGLE-SUPPLY AC COUPLED COMPOSITE VIDEO LINE DRIVER HAS $\Delta G = 0.06\%$ AND $\Delta \phi = 0.06^\circ$

$R_{\text{BIAS}}$ OPTIMIZES $V_{\text{CM}} = +2.2\text{V}$

Op Amp Applications, Chapter 6

4.18
WAVEFORM DUTY CYCLE TAXES HEADROOM IN AC COUPLED SINGLE-SUPPLY OP AMPS

(A) 50% DUTY CYCLE NO CLIPPING

(B) LOW DUTY CYCLE CLIPPED POSITIVE

(C) HIGH DUTY CYCLE CLIPPED NEGATIVE

Op Amp Applications, Chapter 6 4.19
SECOND AND THIRD ORDER INTERMODULATION DISTORTION PRODUCTS

\[ 2 = \text{SECOND ORDER IMD PRODUCTS} \]
\[ 3 = \text{THIRD ORDER IMD PRODUCTS} \]

NOTE: \( f_1 = 5\text{MHz}, f_2 = 6\text{MHz} \)

---

*Op Amp Applications, Chapter 6*
INTERCEPT POINTS AND 1dB COMPRESSION POINT

OUTPUT POWER (PER TONE), dBm

SECONDon ORDER INTERCEPT

THIRD ORDER INTERCEPT

1 dB COMPRESSION POINT

FUNDAMENTAL (SLOPE = 1)

SECOND ORDER IMD (SLOPE = 2)

THIRD ORDER IMD (SLOPE = 3)

INPUT POWER (PER TONE), dBm

Op Amp Applications, Chapter 6

4.21
THIRD ORDER INTERCEPT POINT (IP3)
VERSUS FREQUENCY FOR A LOW DISTORTION AMPLIFIER
USING IP3 TO CALCULATE THE THIRD-ORDER IMD PRODUCT AMPLITUDE

OUTPUT POWER dBm

+36dBm @ 5MHz,
3RD ORDER INTERCEPT IP3

THIRD ORDER IMD
(SLOPE = 3)

3RD ORDER IMD = -60dBm
OR -64dBc

OUTPUT SLOPE = 1

OUTPUT POWER = +4dBm

INPUT POWER (PER TONE), dBm

+30

+20

+10

0

-10

-20

-30

-40

-50

-60

-70

Op Amp Applications, Chapter 6
SPURIOUS FREE DYNAMIC RANGE (SFDR) IN COMMUNICATIONS SYSTEMS

Op Amp Applications, Chapter 6

4.24
AD8011 OUTPUT NOISE ANALYSIS

\[ \text{output noise spectral density} = 8.7 \text{nV/\(\sqrt{Hz}\)} \]

\[ \text{total noise} = 8.7 \sqrt{1.57 \times 180 \times 10^6} = 146 \mu\text{V rms} \]

*Op Amp Applications, Chapter 6* 4.25
AD8011 NOISE FIGURE FOR UNTERMINATED AND TERMINATED INPUT CONDITIONS

Unterminated

$V_{\text{no(total)}} = 8.7 \text{nV/ } \sqrt{\text{Hz}}$, from previous slide

$V_{\text{no(Rs)}} = G \sqrt{4kTR} = 1.8 \text{nV/ } \sqrt{\text{Hz}}$

$\text{NF} = 20 \log \left( \frac{8.7}{1.8} \right) = 13.7 \text{ dB}$

Terminated

$V_{\text{no(total)}} = 8.7 \text{nV/ } \sqrt{\text{Hz}}$ (See Note)

$V_{\text{no(Rs)}} = G \sqrt{kTR} = 0.9 \text{nV/ } \sqrt{\text{Hz}}$

$\text{NF} = 20 \log \left( \frac{8.7}{0.9} \right) = 19.7 \text{ dB}$

Note: Input noise current ($I_{n+}$) flows through 50Ω (unterminated case) or 25Ω (terminated case), but the overall effect of this is negligible.
AD8390 FULLY DIFFERENTIAL ADSL CENTRAL OFFICE LINE DRIVER

\[ \begin{align*}
    k &= \frac{2 \cdot R_M}{R_L} \\
    \frac{R_3}{R_2} &= 1 - k \\
    \frac{V_o}{V_{in}} &= \frac{1}{2 \cdot k} \cdot \frac{R_3}{R_1}
\end{align*} \]

Op Amp Applications, Chapter 6

20.4dBm (ref to 100Ω)
17.55V_{pp}
CF = 5.3
AD8393 ADAPTIVE LINEAR POWER™
+12V CENTRAL OFFICE ADSL LINE DRIVER

= On Chip

VCC (12V)

D1

C1

VCCP

20.4dBm (ref to 100Ω)

17.55 Vpp

CF = 5.3

Adaptive
Linear
Power™
Circuitry

Signal
Conditioning

Pumps

Drive
Amps

Voutp

Phone Line

1:1.2

Voutn

Op Amp Applications, Chapter 6
AD8393 - ADAPTIVE LINEAR POWER™ DRIVER
CIRCUIT WAVEFORMS

Op Amp Applications, Chapter 6 4.29
A HIGH EFFICIENCY VIDEO LINE DRIVER

Notes:
R1 = R2 = R3 = R4a = 1kΩ.
Loaded gain as shown w/o R3b is 3x.
For gain adjust, split and scale R3a/
R3b, maintain R3a || R3b = 1kΩ.

Op Amp Applications, Chapter 6 4.30
A SIMPLE WIDEBAND NOISE GENERATOR

Op Amp Applications, Chapter 6 4.31
PARALLELLED AMPLIFIERS DRIVE LOADS QUIETLY

(A)

(B)

Op Amp Applications, Chapter 6
TWO CROSS-COUPLED AND SIMILAR IN-AMP DEVICES FOLLOWED BY A THIRD PROVIDES MUCH INCREASED CMR WITH FREQUENCY

\[ V_{01}, V_{02} \to \text{differential input ADC} \]

**Op Amp Applications, Chapter 6**

4.33
LOW NOISE, LOW DRIFT
TWO OP AMP COMPOSITE AMPLIFIER

\[ V_{IN} \quad R3 \quad 100k\Omega \quad U2 \quad AD705 \text{ or } OP97 \quad 1nF \]

\[ U1 \quad AD843 \quad R1 \quad 100k\Omega \quad R2 \quad 100k\Omega \quad C1 \quad 1nF \]

\[ R_{IN} \quad 10\Omega \quad R_F \quad 1k\Omega \]

\[ V_{OUT} \]

Op Amp Applications, Chapter 6
CHOPPER-STABILIZED 160dB GAIN, LOW VOLTAGE SINGLE-SUPPLY 
TO HIGH OUTPUT VOLTAGE COMPOSITE AMPLIFIER

Op Amp Applications, Chapter 6
VOLTAGE BOOSTED RAIL-RAIL OUTPUT COMPOSITE OP AMP

Op Amp Applications, Chapter 6
BIPOLAR TRANSISTOR GAIN-BOOSTED
INPUT COMPOSITE OP AMP

Op Amp Applications, Chapter 6
GAIN/PHASE VERSUS FREQUENCY
FOR GAIN-BOOSTED INPUT COMPOSITE OP AMP

Op Amp Applications, Chapter 6

4.38
LOW NOISE JFET GAIN-BOOSTED
INPUT COMPOSITE AMPLIFIER

Notes:
(1) J1, J2 = 2SK389
matched pair (GR)
(2) Select J3, J4 for
I_s = 35-40µA with
R_s = 100kΩ
(3) R3 trimmed for I_s
~2.5mA

Op Amp Applications, Chapter 6
"NOSTALGIA" VACUUM TUBE
INPUT/OUTPUT COMPOSITE OP AMP

Op Amp Applications, Chapter 6 4.40
TRANSFORMER INPUT MIC PREAMPLIFIER
WITH 28 TO 50 dB GAIN

Op Amp Applications, Chapter 6
TRANSFORMER COUPLED MIC PREAMPLIFIER THD+N (%) VERSUS FREQUENCY (Hz) FOR 35dB GAIN, OUTPUTS OF 0.5, 1, 2, AND 5Vrms INTO 600Ω

Op Amp Applications, Chapter 6
LOW NOISE TRANSFORMER INPUT
20 TO 50 dB GAIN MIC PREAMP

Op Amp Applications, Chapter 6
LOW NOISE TRANSFORMER INPUT MIC PREAMP THD+N (%) VERSUS FREQUENCY (Hz) FOR 35dB GAIN, OUTPUTS OF 0.5, 1, 2, AND 5Vrms INTO 600Ω
AN AUDIO BALANCED TRANSMISSION SYSTEM

Op Amp Applications, Chapter 6
A SIMPLE LINE RECEIVER WITH OPTIONAL HF TRIM AND BUFFERED OUTPUT

\[ \begin{align*}
&\text{R1} = 25\,\text{k}\Omega \\
&\text{R2} = 25\,\text{k}\Omega \\
&\text{R3} = 25\,\text{k}\Omega \\
&\text{R4} = 25\,\text{k}\Omega \\
&\text{C1} \\
&\text{C2} \\
&\text{U1} \\
&\text{V_{OUT}} \\
&\text{G} = \frac{V_{OUT}}{V_{IN}} = \frac{R_2}{R_1} \\
&\text{FOR } \frac{R_1}{R_2} = \frac{R_3}{R_4}
\end{align*} \]

Op Amp Applications, Chapter 6 4.46
A CONCEPTUAL DRIVER/RECEIVER DIAGRAM OF A BALANCED LINE AUDIO SYSTEM WITH KEY IMPEDANCES AND CM NOISE

Op Amp Applications, Chapter 6

4.47
BALANCED LINE RECEIVER USING PUSH-PULL FEEDBACK

For $\frac{R_2}{R_1} = \frac{R_4}{R_3} \rightarrow R_5 = R_6$, $G = \frac{V_{OUT}}{V_{IN}} = \frac{R_2}{2R_1}$
A BUFFERED INPUT BALANCED LINE RECEIVER

Op Amp Applications, Chapter 6

Notes:
1) Use $R_t$ for gains above 0.5 (see text).
2) Match $R_{n1}$ to $R_{n2}$ to 1% or better.
3) Use $R_{n3}$ as optional line termination.

4.49
CM ERROR (dB) VS. FREQUENCY (Hz), FOR AD825 AND AD845 PAIRS, NOMINALLY 50Ω SOURCE IMPEDANCES MATCHED/MIS-MATCHED 10%

![Graph showing CM error vs. frequency for AD825 and AD845 pairs with matched and mismatched 10% source impedances.]

*Op Amp Applications, Chapter 6*
TEST CIRCUIT FOR AUDIO LINE DRIVER AMPLIFIERS

Op Amp Applications, Chapter 6
FOLLOWER MODE $R_s$ SENSITIVITY OF OP275 BIPOLAR/JFET INPUT OP AMP-
THD+N (%) VS. FREQUENCY (Hz), $V_{OUT} = 7$Vrms, $R_L = 500\Omega$, $V_S = \pm 18$V

---

Op Amp Applications, Chapter 6
C DRIVER GROUP, THD+N (%) VS. FREQUENCY (Hz), FOR

$V_{\text{OUT}} = 7\text{Vrms}$, $R_s = 909\Omega$, $R_L = 500\Omega$, $V_s = \pm 13\text{V}$ OR $\pm 18\text{V}$

*Op Amp Applications, Chapter 6*
COMPOSITE CURRENT BOOSTED LINE DRIVER TWO

Notes:
1) Use U2 = AD815 (or 2 AD811) and L₁ for headphone driver.
2) Use U1 = AD823, U2 = AD812 for simple realization.
3) Rs is nominal impedance of Vᵢᵣ source.

Op Amp Applications, Chapter 6
A BASIC SINGLE-ENDED MIXED FEEDBACK TRANSFORMER DRIVER

Notes:
(1) $R_4 = R_1/R_2 \times R_{PRIMARY}$
(2) $R_2/R_1 = R_{PRIMARY}/R_4$
(3) $Z_{source} < 10 \Omega$

* LUNDAHL TRANSFORMERS
Norrtälje, SWEDEN
http://www.lundahl.se

Op Amp Applications, Chapter 6 4.55
LUNDAHL LL1517 TRANSFORMER AND DRIVER (WITHOUT FEEDBACK), THD+N (%) VS. FREQUENCY (Hz), FOR $V_{out} = 0.5, 1, 2, 5\text{Vrms}$, $R_L = 600\Omega$
FIG. 6-61 DRIVER WITH LUNDAHL LL2811 TRANSFORMER AND AD845, THD+N (%) VS. FREQUENCY (Hz), FOR $V_{\text{out}} = 0.5, 1, 2, 5\text{Vrms}$, $R_L = 600\Omega$

*Op Amp Applications, Chapter 6*
LUNDAHL LL1517 TRANSFORMER WITH MIXED FEEDBACK AD8610 DRIVER, THD+N (%) VS. FREQUENCY (Hz) FOR VARIOUS NULL ACCURACIES
SENSOR RESISTANCES USED IN BRIDGE CIRCUITS SPAN A WIDE DYNAMIC RANGE

- Strain Gages 120Ω, 350Ω, 3500Ω
- Weigh-Scale Load Cells 350Ω - 3500Ω
- Pressure Sensors 350Ω - 3500Ω
- Relative Humidity 100kΩ - 10MΩ
- Resistance Temperature Devices (RTDs) 100Ω, 1000Ω
- Thermistors 100Ω - 10MΩ
A BEAM FORCE SENSOR
USING A STRAIN GAGE BRIDGE

Op Amp Applications, Chapter 4
A LOAD CELL COMPRised OF 4 STRAIN GAGES IS SHOWN IN PHYSICAL (TOP) AND ELECTRICAL (BOTTOM) REPRESENTATIONS.
A NUMBER OF BRIDGE CONSIDERATIONS
IMPACT DESIGN CHOICES

◆ Selecting Configuration (1, 2, 4 - Element Varying)
◆ Selection of Voltage or Current Excitation
◆ Stability of Excitation Voltage or Current
◆ Bridge Sensitivity: FS Output / Excitation Voltage
   1mV / V to 10mV / V Typical
◆ Fullscale Bridge Outputs: 10mV - 100mV Typical
◆ Precision, Low Noise Amplification / Conditioning
   Techniques Required
◆ Linearization Techniques May Be Required
◆ Remote Sensors Present Challenges

Op Amp Applications, Chapter 4    4.62
KELVIN SENSING SYSTEM WITH A 6-WIRE VOLTAGE-DRIVEN BRIDGE CONNECTION AND PRECISION OP AMPS MINIMIZES ERRORS DUE TO WIRE LEAD RESISTANCE

\[+\text{FORCE}\]
\[\text{+SENSE}\]
\[\text{R}_{\text{LEAD}}\]
\[\text{SENSE}\]
\[-\text{FORCE}\]

\[\text{+V}_{\text{B}}\]

\[v_{\text{O}}\]

*Op Amp Applications, Chapter 4*
4-WIRE CURRENT-DRIVEN BRIDGE SCHEME ALSO MINIMIZES ERRORS DUE TO WIRE LEAD RESISTANCES, PLUS ALLOWS SIMPLER CABLING
TYPICAL SOURCES OF OFFSET VOLTAGE WITHIN BRIDGE MEASUREMENT SYSTEMS

THERMOCOUPLE VOLTAGE
= 35µV/ °C \times (T1 - T2)

Op Amp Applications, Chapter 4

4.65
AC BRIDGE EXCITATION MINIMIZES
SYSTEM OFFSET VOLTAGES

NORMAL DRIVE VOLTAGES

V_B +

E_{OS} = \text{SUM OF ALL OFFSET ERRORS}

V_O -

V_A = V_O + E_{OS}

REVERSE DRIVE VOLTAGES

V_B -

V_A - V_B = (V_O + E_{OS}) - (-V_O + E_{OS}) = 2V_O

V_O +

V_B = -V_O + E_{OS}
RATIOMETRIC DC OR AC OPERATION WITH KELVIN SENSING CAN BE IMPLEMENTED USING THE AD7730 ADC

Op Amp Applications, Chapter 4

4.67
GENERALIZED MODEL FOR HIGH SPEED PHOTODIODE PREAMP

\[ f_2 = \text{SIGNAL BW} \]

\[ G \]

\[ \text{Total Input Capacitance} \]

\[ f_1 = \frac{1}{2\pi R_2 C_1} \]

\[ f_2 = \frac{1}{2\pi R_2 C_2} \]

\[ f_2 = \sqrt{f_1 \times f_u} \]

\[ C_2 = \frac{C_1}{2\pi R_2 f_u} \]

\[ f_2 = \frac{f_u}{2\pi R_2 C_1} \]

Op Amp Applications, Chapter 4
PHOTODIODE PREAMP USING THE AD8065

\[ C_D = 4 \text{pF}, \quad C_{IN} = 6.6 \text{pF} \]
\[ C_1 = C_D + C_{IN} \]

\[ C_1 = 10.6 \text{pF} \]

\[ C_3 = 0.75 \text{pF} \]

\[ f_u = 65 \text{MHz} \]

Bandwidth: 2.7MHz

Output Noise:
- 260µV RMS, 10MHz
- 200µV RMS, 4MHz

Op Amp Applications, Chapter 4

4.69
PHOTODIODE PREAMP USING THE AD8033

\[ C \text{\textsubscript{D}} = 4\text{pF}, \quad C \text{\textsubscript{IN}} = 4\text{pF} \]
\[ C \text{\textsubscript{1}} = C \text{\textsubscript{D}} + C \text{\textsubscript{IN}} \]

\[ C \text{\textsubscript{1}} = 8\text{pF} \]
\[ C \text{\textsubscript{3}} = 0.57\text{pF} \]

\[ f_\text{u} = 40\text{MHz} \]

Bandwidth: 2.8MHz
Output Noise: 325\text{µV RMS, 10MHz}
250\text{µV RMS, 7MHz}

Op Amp Applications, Chapter 4
PHOTODIODE PREAMP USING THE AD8067

C₀ = 4pF, Cᵢᵣ = 4pF
C₁ = C₀ + Cᵢᵣ

C₁ = 8pF

C₂ = 0.35pF

33.2kΩ

AD8067

Bandwidth: 7MHz

Output Noise:
725µV RMS, 21MHz
550µV RMS, 10MHz

Op Amp Applications, Chapter 4

4.71
# COMPARISON OF OP AMPS FOR PHOTODIODE PREAMPS

<table>
<thead>
<tr>
<th></th>
<th>Unity GBW $f_u$, MHz</th>
<th>Input Capacitance $C_{IN}$, pF</th>
<th>$f_u/C_{IN}$ MHz/pF</th>
<th>$I_b$, pA</th>
<th>$V_n@10kHz$, nV/√Hz</th>
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<tbody>
<tr>
<td>*AD8610/20</td>
<td>25</td>
<td>23</td>
<td>1.1</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>AD8065/66</td>
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<td>6.6</td>
<td>9.85</td>
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<td>7</td>
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<tr>
<td>AD8033/34</td>
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<td>AD8067 G &gt; 9 Stable</td>
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<td>4</td>
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* Ideal low frequency precision preamps for large area photodiodes operated in photovoltaic mode (zero volt bias)

*Op Amp Applications, Chapter 4* 4.72
### Precision Single Supply Amps Selection Guide

#### Communications

<table>
<thead>
<tr>
<th>Generic Part #</th>
<th>Supply Voltage</th>
<th>Rail-to-Rail</th>
<th>GBP (MHz)</th>
<th>$I_{SV}$ (mA)</th>
<th>Packages*</th>
<th>Price† 1k</th>
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<tr>
<td>AD 8541 8542 8544</td>
<td>+2.7 +4.5 +2.7 +4.5</td>
<td>+5 +16 +5 +16</td>
<td>1 3</td>
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<td>1 1.2</td>
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<tr>
<td>AD 8591 8592 8594</td>
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<td>10 12</td>
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* SOIC packages also available

** With $V_S=+5V$

#### Industrial

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<th>Generic Part #</th>
<th>Supply Voltage</th>
<th>Rail-to-Rail</th>
<th>GBP (MHz)</th>
<th>$V_{GS}$ (µV)</th>
<th>$I_{BIAS}$ (nA)</th>
<th>$e_{noise}$ (nV/Hz)</th>
<th>Slew (V/µs)</th>
<th>Price† 1k</th>
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<td>AD 711 712 713</td>
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### Computer

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<th>Generic Part #</th>
<th>Supply Voltage</th>
<th>Rail-to-Rail</th>
<th>I\text{\textsubscript{OUT}} (mA)</th>
<th>GBP (MHz)</th>
<th>Killer Price</th>
<th>Applications</th>
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<td>AD8665/66/67</td>
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<td>+16</td>
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<td>x</td>
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<td>6</td>
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<tr>
<td>OP162/262/462</td>
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<td>x</td>
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* SOIC packages also available

** With V\text{\textsubscript{SY}}=+5V

### Portable and Low Power

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<tr>
<th>Generic Part #</th>
<th>Supply Voltage</th>
<th>Rail-to-Rail</th>
<th>I\text{\textsubscript{SY}} (µA)</th>
<th>GBP (MHz)</th>
<th>Packages*</th>
<th>Price†</th>
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<td>x</td>
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* SOIC packages also available

** With V\text{\textsubscript{SY}}=+5V

### Comparators

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<th>Generic Part #</th>
<th>Supply Voltage</th>
<th>Rail-to-Rail</th>
<th>GBP (MHz)</th>
<th>THD+N (dB)</th>
<th>0\text{\textsubscript{noise}} (nV/√Hz)</th>
<th>Slew (V/µs)</th>
<th>Killer Price</th>
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<tbody>
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<td>5/14</td>
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<td>100</td>
<td>10/20</td>
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### Audio

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<th>Rail-to-Rail</th>
<th>GBP (MHz)</th>
<th>THD+N (dB)</th>
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<td>+5</td>
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<td>SSM2250</td>
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<td>x</td>
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<td>45</td>
<td>Headphones + speaker</td>
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## HIGH SPEED AMPLIFIER SELECTION GUIDE

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**Drivers**

- **AD8131**
- **AD8132**
- **AD8138**

**Receivers**

- **AD8129**
- **AD8130**

**Fast HFE**

- **AD8038**
- **AD8068**

**Low Cost, High Performance**

- **AD8039**
- **AD8059**
- **AD8091**

**Rail-to-Rail**

- **AD8032**
- **AD8062**
- **AD8092**

**Low Noise, Low Distortion**

- **AD8021**
- **AD8022**
- **AD8061**

**High Supply Voltage**

- **AD8071**
- **AD8072**
- **AD8073**

**Low Cost**

- **AD8014**
- **AD8074**
- **AD8075**

**High Performance**

- **AD8004**
- **AD8005**
- **AD8007**
- **AD8009**
- **AD8012**

**Buffers**

- **AD8074**
- **AD8075**
- **AD8079**

---

1 Spurious Free Dynamic Range - Distortion @ Worst Harmonic
2 THD - Total Harmonic Distortion
3 Product Under Development

June 2002

For more information on ADI High-Speed Amps visit our website at www.analog.com/highspeedamps
In-Amps Selection Guide

<table>
<thead>
<tr>
<th>Generic Part Number</th>
<th>Supply Current</th>
<th>Operating Voltage Range</th>
<th>Gain Setting Method</th>
<th>CMRR @ 60 Hz, G=10</th>
<th>BW @ G=10</th>
<th>Settling Time to 0.01%, G=10</th>
<th>Input Voltage Offset</th>
<th>Input Voltage Offset TC</th>
<th>Input Bias Current</th>
<th>Output Offset Voltage</th>
<th>Input Voltage Noise Density (f=1 kHz)</th>
<th>Gain Range</th>
<th>Gain Error @ G=10</th>
<th>Price @ 100</th>
<th>Comments</th>
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<td>10</td>
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<td>200</td>
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<td>35 (typ)</td>
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<td>Lowest Cost In-Amp, µSOIC Packaging</td>
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<tr>
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<td>Resistor</td>
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<td>50</td>
<td>na</td>
<td>1000</td>
<td>15</td>
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<td>1</td>
<td>300 (typ)</td>
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<td>35 (typ)</td>
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<td>24</td>
<td>500</td>
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<td>ns</td>
<td>ns</td>
<td>250 (typ)</td>
<td>10, 100</td>
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<td>$3.69</td>
<td>Excellent for High Side Current Sensing</td>
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In-Amps For New Designs

In-Amps For New Designs

Low Cost In-Amps

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<tr>
<th>Part</th>
<th>Gain Setting Method</th>
<th>BW @ G=10</th>
<th>Input Voltage Offset</th>
<th>Input Voltage Offset TC</th>
<th>Input Bias Current</th>
<th>Output Offset Voltage</th>
<th>Input Noise Density (f=1 kHz)</th>
<th>Gain Range</th>
<th>Gain Error @ G=10</th>
<th>Price @ 100</th>
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<td>5</td>
<td>1.5</td>
<td>12 (typ)</td>
<td>1 to 1000</td>
<td>0.5</td>
<td>$2.65</td>
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<tr>
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<td>90</td>
<td>200</td>
<td>2</td>
<td>25</td>
<td>1</td>
<td>35 (typ)</td>
<td>1 to 1000</td>
<td>0.35</td>
<td>$1.82</td>
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<td>1</td>
<td>300 (typ)</td>
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Single Supply In-Amps

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<th>Input Noise Density (f=1 kHz)</th>
<th>Gain Range</th>
<th>Gain Error @ G=10</th>
<th>Price @ 100</th>
<th>Comments</th>
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<td>ns</td>
<td>ns</td>
<td>250 (typ)</td>
<td>10, 100</td>
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High Accuracy In-Amps

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<th>Input Noise Density (f=1 kHz)</th>
<th>Gain Range</th>
<th>Gain Error @ G=10</th>
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<tr>
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<td>0.15</td>
<td>$4.50</td>
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In-Amps For New Designs

In-Amps For New Designs

Lowest Cost In-Amps

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<td>0.35</td>
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<tr>
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<td>300 (typ)</td>
<td>0.1 to 50</td>
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<th>ns</th>
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<th>10, 100</th>
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<th>$</th>
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<th>±250 V Input CMV Range</th>
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<td>Pin</td>
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<td>24</td>
<td>500</td>
<td>2500</td>
<td>1 (typ)</td>
<td>ns</td>
<td>ns</td>
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</table>

**In-Amps For New Designs**

**Wide Bandwidth In-Amps**

| AMP03  | 3.5 | ±4.5 to ±18 | na | 80 | 3000 | 1 (typ) | ns | ns | ns | ns | 750 (Total RTO) | 1 | 0.008 (G=1) | $3.03 |

**Vintage In-Amps**

**High Accuracy In-Amps**

| AD524  | 4 | ±6 to ±18 | Pin | 90 | 400 | 15 | 250 | 2 | ±50 | 5 | 7 | 1 to 1000 | ±0.25 | $8.55 |
| AMP01  | 4.8 | ±4.5 to ±18 | Resistor | 95 | 100 | 13 | 100 | 1 | 6 | 6 | 59 | 0.1 to 10,000 | 0.8 | $10.18 |

**Low Noise In-Amps**

| AD624  | 5 | ±6 to ±18 | Pin | 90 | 1000 (G=1) | 15 | 200 | 2 | ±50 | 5 | 4 | 1 to 1000 | ±0.05 (G=1) | $14.98 |
| AD625  | 5 | ±6 to ±18 | Resistor | 90 | 400 | 15 | 200 | 2 | ±50 | 5 | 4 (Total RTI) | 1 to 10,000 | ±0.05 | $12.58 |

**Software Programmable In-Amps**

| ADS26  | 14 | ±4.5 to ±16.5 | Software | ns | 350 (G=16) | 4.1 (G=16) | 700 | 10 | 0.15 | ns | 30 (typ) | 1,2,4,8,16 | 0.08 (G=16) | $10.39 |
