Ideal OpAmp Model

- No current flows into $V_{\text{inn}}$ or $V_{\text{inp}}$
- When operated in negative feedback, $V_{\text{inp}} - V_{\text{inn}} = 0$

Inverting Opamp Configuration

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = -\frac{R_2}{R_1}
\]

\[
V_{\text{out}} = 0 - R_2 \cdot \frac{V_{\text{in}}}{R_1}
\]
Noninverting Opamp Configuration

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

\[
V_{\text{out}} = R_2 \cdot \frac{V_{\text{in}}}{R_1}
\]

OpAmp DC Model with Imperfections

\begin{align*}
V_{\text{inn}} & \quad \text{Negative Input} \\
V_{\text{inp}} & \quad \text{Positive Input} \\
V_{\text{out}} & \quad \text{Output} \\
I_{b1}, I_{b2} & \quad \text{Input Bias Current} \\
R_{\text{in}} & \quad \text{Input Impedance} \\
R_{\text{out}} & \quad \text{Output Impedance} \\
V_{\text{os}} & \quad \text{Input Offset Voltage} \\
A_{\text{ol}} & \quad \text{Open Loop Gain}
\end{align*}
OpAmp - Typical Specs

<table>
<thead>
<tr>
<th>OpAmp Characteristics</th>
<th>OPA277 Low $V_{no}$</th>
<th>OPA129 $V_{no}$/$I_{o}$</th>
<th>OPA627 $V_{no}$/$I_{o}/BW$</th>
<th>THS4031 Hi $BW$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Loop Gain ($A_{ol}$)</td>
<td>160db</td>
<td>120db</td>
<td>120db</td>
<td>98db</td>
</tr>
<tr>
<td>Input Offset Voltage ($V_{os}$)</td>
<td>5uV</td>
<td>0.5mV</td>
<td>40uV</td>
<td>0.5mV</td>
</tr>
<tr>
<td>Input Bias Current ($I_{ib}$)</td>
<td>2.5nA</td>
<td>30fA</td>
<td>1pA</td>
<td>3uA</td>
</tr>
<tr>
<td>Input Offset Current ($I_{os}$)</td>
<td>2.5nA</td>
<td>30fA</td>
<td>0.5pA</td>
<td>30nA</td>
</tr>
<tr>
<td>Gain Bandwidth (BW)</td>
<td>8Mhz</td>
<td>1Mhz</td>
<td>16Mhz</td>
<td>100Mhz</td>
</tr>
<tr>
<td>Common Mode Rejection (CMRR)</td>
<td>138db</td>
<td>118db</td>
<td>116db</td>
<td>95db</td>
</tr>
</tbody>
</table>

* TI currently manufactures more than 1000 different opamp models!

Production Testing Strategy

**Characterization vs. High Volume Production**
- It is not cost effective to extensively test all parameters in production
- Generally a shorter test list is sufficient to guarantee performance
- Key data sheet and predictive parametric items should be selected

**AC vs. DC Testing**
- Precision Opamps have a test list dominated by DC parameters
- High speed Opamps may have mostly AC parameters tested
- This presentation focuses on DC testing

**Embedded vs. Standalone Opamps**
- Embedded Opamps generally have a more limited test list and often operate with unipolar supplies
- This presentation focuses primarily on standalone Opamps
OpAmp Servo Loop

- Set \( V_{cc} \) and \( V_{ee} \) to desired voltages
- Connect desired Load
- Set Gain and Freq Comp
- Set \( V_R \) to 0V
- Measure \( V_N \)

\[ V_{os} = \frac{V_N}{Gain} \]

The Gain should be chosen as large as possible such that worst case \( V_{os} \) will not saturate the servo amp (i.e. \( V_N \) will be saturated)

- Adjust Frequency Compensation to insure the loop does not oscillate

Input Offset Voltage (\( V_{os} \))
Achieving Low $V_{os}$ Measurements

- The 50Ω terminations are generally part of the Servo Loop instrument
- Each point of interconnect between the Servo Loop and the DUT adds to the chance of thermal EMF voltage error (i.e. relays, connectors, etc)
- Thermal EMF occurs at dissimilar metal junctions with a thermal gradient
- Locating the termination near the DUT with Low EMF or Latching Relays greatly reduces the potential for $V_{os}$ measurement error due to EMF

Open Loop Gain ($A_{ol}$)

- Set $V_{cc}$ and $V_{ee}$ to desired voltage
- Connect desired Load
- Set Gain and Freq Comp
- Set $V_R$ to $V_{R1}$
- Measure $V_{N1}$
- Set $V_R$ to $V_{R2}$
- Measure $V_{N2}$

\[
A_{ol} = \frac{V_{R2} - V_{R1}}{V_{N2} - V_{N1}} \cdot \frac{Gain}{N_{atten}}
\]

- As in the $V_{os}$ setup, it is critical to choose Gain and $V_R$ levels such that $V_N$ does not become saturated
- $A_{ol}$ is often reported in uV/V or dB units
Common Mode Rejection Ratio (CMRR)

- Set $V_{cc}$ and $V_{ee}$ to desired voltage + $V_{cmrpos}$
- Connect desired Load
- Set Gain and Freq Comp
- Set $V_R$ to $V_{cmrpos} / N_{atten}$
- Measure $V_{N1}$
- Set Vcc and Vss to desired voltage - $V_{cmrneg}$
- Set $V_R$ to $V_{cmrneg} / N_{atten}$
- Measure $V_{N2}$

$$CMRR = \frac{|V_{cmrpos} - V_{cmrneg}|}{|V_{N2} - V_{N1}|} \cdot Gain$$

- This method actually moves the power supplies and output and leaves the common mode at 0V. The net effect is the same, however.
- CMRR is often reported in uV/V or dB units

Power Supply Rejection Ratio (PSRR)

- Set $V_{cc}$ and $V_{ee}$ to minimum voltages
- Connect desired Load
- Set Gain and Freq Comp
- Set $V_R$ to 0V
- Measure $V_{N1}$
- Set $V_{cc}$ and $V_{ee}$ to maximum voltages
- Measure $V_{N2}$

$$PSRR = \left| \frac{\Delta V_{cc} + \Delta V_{ee}}{V_{N1} - V_{N2}} \right| \cdot Gain$$

- This test can be combined with the $V_{os}$ test if the given supply values and load are acceptable
- PSRR is often reported in uV/V or dB units
Input Bias Current ($I_B$) – Picoamp Meter

When $I_B > \sim 250\text{pA}$, the Picoamp Meter (PAM) is effective and efficient.

- The Servo Loop must support Inverted operation to measure $I_B$ on $V_{\text{INN}}$.
- The PAM is usually collocated with the Servo Loop.

Input Bias Current ($I_B$) – Picoamp Meter...

- U1 forms an I-to-V converter and should be a low $I_B$ opamp (OPA129).
- U2 forms a gain stage for ranging of the I-to-V output.
- The $V_{\text{INP}}$ terminal of U1 sets the Input Common Mode Voltage.
- Open Socket Measurements should be made to negate stray leakage and the compounded offsets of U1 and U2.
Picoamp Meter Limitations

Cleanliness
- Since the PAM is usually collocated with the Servo Loop, the path can be quite long. To keep stray leakage low, the entire path must be clean.
- Contamination can include: flux, finger oils, absorbed moisture, etc

Dielectric Absorption
- Interconnect dielectrics suffer from "soakage" effects where charge becomes trapped and is slowly dissipated
- This can cause mysterious readings and excessive settling time

Piezoelectric Charging
- Most coaxial cabling is susceptible to stray charging during flexure due to the piezoelectric effects of the braid rubbing against the dielectric

I-to-V Input Leakage, Offset Stability, Etc...
- U1 will ultimately limit the low end of measurement capability even in a perfect environment

Input Bias Current (I_B) – Integration Method

- K_{INTP} and K_{INTN} are closed for normal operation (i.e. V_{DS}, A_{OL}, etc)
- Opening one of the relays allows bias current to integrate into C_{INT}
- Charge Injection during switching will cause a jump in V_N (coaxially shielded relays should be used to keep this manageable)
- Integration times set to a multiple of 16.6ms will reject 60Hz noise
- A typical choice for C_{INT} is a 1000pF WIMA Film
Integration Method…

Leakage only matters on the DUT side of $C_{int}/K_{int}$

- **Cleaning** – We must now only clean around the DUT
- **Dielectric Absorption** – Only PCB Dielectric around DUT + $C_{int}$
- **Piezoelectric Charging** – Effectively a non issue
- **Environmental Noise** – We can now easily integrate out 60Hz Noise
- **Opamp Limitations** – No Opamp needed, no issue

Integration Method – Open Socket Cal…

Open Socket Calibration requires an Opamp to close the loop

- “Golden” data logged unit with known $I_B$
Relating to Small Bias Currents…

- 1 Coulomb (C) of Charge  = 6.24E18 Electrons
- 1 Ampere (A) = 1 C/sec
- 1 femto Ampere (fA) = 1E-15 A
- 1 fA = 1E-15*6.24E18 = 6240 Electrons/sec
- 1 60Hz Line Cycle = 16.6 msec
- 1 fA over 1 Line Cycle = 6240*0.0166 = ~104 Electrons
- Small Bias Current measurement is about counting Electrons!

Tips for Measuring sub 10pA I_B

- DIB should be immaculate between C_{INT}/K_{INT} and Socket
- Baking the DIB can help drive out excess absorbed moisture
- Some types of sockets can have higher background leakage and dielectric absorption
- Some types of low I_B Opamps can trap charge in their input stages if not handled carefully resulting in erratic I_B measurements
- Use an ionizer
- Keep stray unionized air flow away
- Integrate over multiple line cycles
- Data logged "Golden" unit for offset cal
Embedded Opamps

- Embedded Opamps generally do not have bipolar power supplies
- $V_{CM}$ is required to insure a legal common mode input voltage
- All measurements should be with respect to $V_{CM}$

TL1 – TI Legacy Opamp Tester

- Early 1980s era internally developed Opamp Tester
Retiring the TL1 – Emulation

- “Add On” developed for our internal low cost tester to emulate the TL1
- Existing Probe Cards and HIBs were reused
- Rapid program migration tools were developed to speed conversions

TL1 Emulator - Insides

- Servo Loops
- Pogo Stack Clamp
- Pin Mapper
- Connectors
TL1 Emulator – Connected to Handler

Increasing Throughput – Multisite Opamp Emulator (MOE)
MOE with Quad site SOIC DIB

MOE – Loop Modules
Contact Information…

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