Understanding Operational Amplifiers

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Outline

- Cheng - History
- Pat - OP AMP Construction/design
- Alex - OP Amp Application Circuits
- Ken - Effect of Input offset voltage
- Nan - Effect of Slew Rate, Packaging, Conclusion
## History

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
<th>Inventor(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1941</td>
<td>First vacuum tube op-amp</td>
<td>Karl D. Swartzel Jr.</td>
</tr>
<tr>
<td>1947</td>
<td>First op-amp with non-inverting input</td>
<td>John R. Ragazzini</td>
</tr>
<tr>
<td>1949</td>
<td>First chopper-stabilized op-amp</td>
<td>Edwin A. Goldberg</td>
</tr>
<tr>
<td>1961</td>
<td>Discrete IC op-amp</td>
<td></td>
</tr>
</tbody>
</table>
### History Continued

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
<th>Designer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1963</td>
<td>First monolithic IC op-amp</td>
<td>Bob Widlar</td>
</tr>
<tr>
<td>1970</td>
<td>First high-speed, low-input current FET design</td>
<td></td>
</tr>
<tr>
<td>1972</td>
<td>Single sided supply op-amps being produced</td>
<td></td>
</tr>
</tbody>
</table>
Op Amp Construction

- Integrated Circuit (IC) Main Categories:
  - Linear ICs
    - Performs amplification or linear operations on signals.
  - Monolithic ("one stone") Circuits
    - The entire circuit is embedded upon a single piece of semiconductor.
μA741 Op-Amp

- Bias Circuit
- Input Stage
- Intermediate Stage
- Output Stage
- Short-circuit Protection

Internal Schematic from LM741 Datasheet
Monolithic Building Blocks

**Transistor**

**Diode**

**IC Diffused Resistor**

**IC Diffused Capacitor**
Biasing Circuit
Biasing Circuit

\[
I_{\text{ref}} = \frac{V_{CC} - V_{EE} - 2V_{BE}}{R_5} = 733 \mu A
\]

\[
I_{13B} = 0.75 I_{\text{ref}} = 550 \mu A
\]

\[
I_{13A} = 0.25 I_{\text{ref}} = 180 \mu A
\]

\[
I_{10} = \frac{V_t}{R_4} [\ln(I_{\text{ref}}) - \ln(I_{10})] = 19 \mu A
\]
Input Stage
Input Stage

• Q1, Q2 are emitter followers.
• Q3, Q4 in common-base configuration serve as differential amplifier, level shifters and protect Q1, Q2 against emitter-base junction breakdown.
• Q5, Q6, Q7 and R1, R2, R3 provide the load (active load) for the differential amplifier.
Intermediate Stage
Intermediate Stage

- Q16 is an emitter follower.
- Q17 is a common-emitter amplifier, loaded by Q13B.
  - $\text{GAIN} \approx (g_{m-Q17})(r_{0-Q13B})$
- $Cc$ is the internal compensation cap used to maintain stability when the op-amp is used in a feedback configuration.
Output Stage
Output Stage

- Q23 is an emitter follower.
- Q14, Q20 are a complementary push-pull, or Class AB amplifier.
- Q19, Q18 are a Darlington-pair, but act similar to diodes. They maintain a $V_{BE}$ drop to smooth out the crossover distortion of Q14, Q20.
Short-circuit Protection
Short-circuit Protection

- Q15, Q21 are normally off.
- If too much current is being output (~25mA), the voltage drop across R6, R7 will turn Q15, Q21 on to bleed off the current via Q22, Q24 current mirror.
Op-amp Design Applications

PARAMETER NAME | PARAMETERS SYMBOL | VALUE
--- | --- | ---
Input current | $I_{IN}$ | 0
Input offset voltage | $V_{OS}$ | 0
Input impedance | $Z_{IN}$ | $\infty$
Output impedance | $Z_{OUT}$ | 0
Gain | $a$ | $\infty$
Simple Buffer Circuit or Voltage Follower

Typical 8-pin Op-Amp Layout
Amplifier Circuits

Non-Inverting

\[
\frac{V_{OUT}}{V_{IN}} = \frac{R_G + R_F}{R_G} = 1 + \frac{R_F}{R_G}
\]

Inverting

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

\[ V_{\text{OUT}} = - \left( \frac{R_F}{R_1} V_1 + \frac{R_F}{R_2} V_2 + \frac{R_F}{R_N} V_N \right) \]

Differential

\[ V_{\text{OUT}} = (V_1 - V_2) \frac{R_4}{R_3} \]
Non-Inverting Summing Amplifier

\[ V_{out} = \left(1 + \frac{Rf2}{Rf1}\right) \left( V1 \cdot \frac{R2}{R1 + R2} + V2 \cdot \frac{R1}{R1 + R2} \right) \]
Integrator
Active Filter Design

Passive

Active
OP AMP Specifications

Some Specifications to be aware of when using Operational Amplifiers in your circuits.

- Input Offset Voltage - Input Offset Null Pins
- Slew Rate
### Electrical Characteristics (Note 5)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conditions</th>
<th>LM741A</th>
<th>LM741</th>
<th>LM741C</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Typ</td>
<td>Max</td>
<td>Min</td>
</tr>
</tbody>
</table>
| Input Offset Voltage               | $T_A = 25^\circ$C  
$R_S \leq 10 \text{ k}\Omega$  
$R_S \leq 50\Omega$  
$T_{\text{MIN}} \leq T_A \leq T_{\text{MAX}}$  
$R_S \leq 10 \text{ k}\Omega$ | 0.8  | 3.0   | 1.0   | 5.0   | 2.0   | 6.0   | mV    | mV    |
| Average Input Offset Voltage Drift |            | 15     |       |        |       |       |       | µV/°C |       |
| Input Offset Voltage Adjustment Range | $T_A = 25^\circ$C  
$V_S = \pm 20\text{V}$ | ±10    | ±15   | ±15   |       | µV    |
| Input Offset Current               | $T_A = 25^\circ$C  
$T_{\text{MIN}} \leq T_A \leq T_{\text{MAX}}$ | 3.0   | 30    | 20    | 200   | 20    | 200   | nA    |
| Average Input Offset Current Drift |            | 0.5    |       |        |       |       |       | nA/°C |       |
| Input Bias Current                 | $T_A = 25^\circ$C  
$T_{\text{MIN}} \leq T_A \leq T_{\text{MAX}}$ | 30    | 80    | 80    | 500   | 80    | 500   | nA    |
| Input Resistance                   | $T_A = 25^\circ$C  
$V_S = \pm 20\text{V}$ | 1.0   | 6.0   | 0.3   | 2.0   | 0.3   | 2.0   | MΩ    |
| Input Voltage Range                | $T_A = 25^\circ$C  
$T_{\text{MIN}} \leq T_A \leq T_{\text{MAX}}$ | ±12   | ±13   | ±12   | ±13   | V     | V     |
### Electrical Characteristics (Note 5) (Continued)

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<tr>
<th>Parameter</th>
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<th>LM741</th>
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<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Typ</td>
<td>Max</td>
<td></td>
</tr>
<tr>
<td>Large Signal Voltage Gain</td>
<td>$T_A = 25^\circ \text{C}$, $R_l \geq 2 \ \text{k}\Omega$</td>
<td>50</td>
<td>50</td>
<td>200</td>
<td>V/mV</td>
</tr>
<tr>
<td></td>
<td>$V_S = \pm 20 \text{V}$, $V_O = \pm 15 \text{V}$, $V_D = \pm 10 \text{V}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_{\text{MIN}} \leq T_A \leq T_{\text{MAX}}$, $R_l \geq 2 \ \text{k}\Omega$, $V_S = \pm 20 \text{V}$, $V_O = \pm 15 \text{V}$, $V_D = \pm 10 \text{V}$</td>
<td>32</td>
<td>25</td>
<td>15</td>
<td>V/mV</td>
</tr>
<tr>
<td></td>
<td>$V_S = \pm 5 \text{V}$, $V_O = \pm 2 \text{V}$</td>
<td>10</td>
<td></td>
<td></td>
<td>V/mV</td>
</tr>
<tr>
<td>Output Voltage Swing</td>
<td>$V_S = \pm 20 \text{V}$</td>
<td>±16</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>$R_l \geq 10 \ \text{k}\Omega$</td>
<td>±15</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>$R_l \geq 2 \ \text{k}\Omega$</td>
<td>±12</td>
<td>±14</td>
<td>±12</td>
<td>±14</td>
</tr>
<tr>
<td></td>
<td>$V_O = \pm 15 \text{V}$</td>
<td>±10</td>
<td>±13</td>
<td>±10</td>
<td>±13</td>
</tr>
<tr>
<td>Output Short Circuit Current</td>
<td>$T_A = 25^\circ \text{C}$</td>
<td>10</td>
<td>25</td>
<td>35</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>$T_{\text{MIN}} \leq T_A \leq T_{\text{MAX}}$</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common-Mode Rejection Ratio</td>
<td>$T_{\text{MIN}} \leq T_A \leq T_{\text{MAX}}$, $R_S \leq 10 \ \text{k}\Omega$, $V_{CM} = \pm 12 \text{V}$</td>
<td>80</td>
<td>95</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>$R_S \leq 50 \ \text{k}\Omega$, $V_{CM} = \pm 12 \text{V}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Voltage Rejection Ratio</td>
<td>$T_{\text{MIN}} \leq T_A \leq T_{\text{MAX}}$, $V_S = \pm 20 \text{V}$ to $V_S = \pm 5 \text{V}$</td>
<td>86</td>
<td>96</td>
<td>77</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>$R_S \leq 10 \ \text{k}\Omega$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transient Response</td>
<td>$T_A = 25^\circ \text{C}$, Unity Gain</td>
<td>0.25</td>
<td>0.8</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Rise Time</td>
<td></td>
<td>6.0</td>
<td>20</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Overshoot</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth (Note 6)</td>
<td>$T_A = 25^\circ \text{C}$</td>
<td>0.437</td>
<td>1.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Slew Rate</td>
<td>$T_A = 25^\circ \text{C}$, Unity Gain</td>
<td>0.3</td>
<td>0.7</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Supply Current</td>
<td>$T_A = 25^\circ \text{C}$</td>
<td>1.7</td>
<td>2.8</td>
<td>1.7</td>
<td>1.7</td>
</tr>
</tbody>
</table>
**What is Input Offset Voltage?**

In an Ideal Op Amp the output should be exactly 0v with inputs shorted.

![Ideal OP AMP](image)

\[ V_{\text{out}} = 0 \text{ V} \]

However, in a real OP Amp there will be some output voltage when the inputs are shorted due to slight differences in the internal OP Amp transistors.

![Real OP AMP](image)

\[ V_{\text{out}} = 14.7 \text{ V (saturated +)} \]
What Causes Input Offset Voltage?
The Input Offset Voltage can be modeled as a small voltage always present at one of the inputs to an Ideal Op Amp.

Typically 0 to 10 mV
Effect of Input Offset Voltage

\[
50 \text{ mV} = \frac{V_{\text{in}}}{R_1} + \frac{V_{\text{in}}}{R_2} = \frac{V_{\text{in}} * (1 + \frac{R_2}{R_1})}{R_1}
\]

\[
= 50 \text{ mV} \times (1 + 99)
\]

\[
= 5 \text{ V}
\]

\[
50 \text{ mV} = \frac{3 \text{ mV}}{R_1} + \frac{V_{\text{in}}}{R_2} = \frac{(V_{\text{in}} + 3 \text{ mV}) \times (1 + \frac{R_2}{R_1})}{R_1}
\]

\[
= 53 \text{ mV} \times (1 + 99)
\]

\[
= 5.3 \text{ V} \text{ OR } 4.7 \text{ V}
\]
LM741 Null Pins

Some Op Amps have NULL Pins which allow adjustment to compensate for Input Offset Voltage.

- LM741 Has Null Pins
- LM324 Does NOT have Null Pins
LM741 Schematic
LM741 Input

Generalized Op Amp Input - similar to LM324
LM741
Input

Offset Nulling Circuit
Slew Rate

The Slew Rate of an Op Amp is the maximum rate of change in the output voltage expressed in volts/µs.

The LM741 has a slew rate of 0.5 volts/µs.

![Diagram showing input and output signals with a slew rate of 0.5 volts/µs]
The maximum frequency input sine which can be applied before slew rate distortion is seen-

\[
\frac{dV}{dt}(\sin(2\pi ft)) = 2\pi f\cos(2\pi ft)
\]

\[
\frac{dV}{dt}(\text{max}) = 2\pi f
\]

\[
f_{max} = \frac{10^6 \times \text{Slew Rate}}{2\pi}
\]
Purchasing an Op-amp

- Package
  - DIP
  - TSSOP
  - MSOP

- Mount Type
  - Surface Mount
  - Through Hole
1. Package

- **Dual in-line-package (DIP):**
  Regular sized op amp.

- **Thin Shrink Small outline package (TSSOP):**
  Smaller body size & lead pitches (0.9mm thick).

- **Micro small outline package (MSOP):**
  Only 3mm * 3mm in size.
2. Mount type

- Surface mount
  SOPs are surface mount. Need sockets to solder on the PCB.
- Through hole
  DIPs are through hole. Sockets will help to remove or switch the op amp.
Conclusion

Cheng - History

Pat - OP AMP Construction/design

Alex - OP Amp Application Circuits

Ken - Effect of Input offset voltage

Nan - Effect of Slew Rate, Packaging, Conclusion
Thank you