SM73308

SM73308 Low Offset, Low Noise, RRO Operational Amplifier

Literature Number: SNOSB90A
Low Offset, Low Noise, RRO Operational Amplifier

General Description
The SM73308 is a Single low noise precision operational amplifier intended for use in a wide range of applications. Other important characteristics include: an extended operating temperature range of −40°C to 125°C, the tiny SC70-5 package, and low input bias current.

The extended temperature range of −40°C to 125°C allows the SM73308 to accommodate a broad range of applications. The SM73308 expands National Semiconductor’s Silicon Dust™ amplifier portfolio offering enhancements in size, speed, and power savings. The SM73308 is guaranteed to operate over the voltage range of 2.7V to 5.0V and has rail-to-rail output.

The SM73308 is designed for precision, low noise, low voltage, and miniature systems. This amplifier provides rail-to-rail output swing into heavy loads. The maximum input offset is 850 μV at room temperature and the input common mode voltage range includes ground.

The SM73308 is offered in the tiny SC70-5 package.

Features
(Unless otherwise noted, typical values at $V_S = 2.7V$)
- Renewable Energy Grade
- Guaranteed 2.7V and 5V specifications
- Maximum $V_{OS}$ 850μV (limit)
- Voltage noise
  - $f = 100$ Hz
  - $f = 10$ kHz
  - 12.5nV/$\sqrt{Hz}$
  - 7.5nV/$\sqrt{Hz}$
- Rail-to-Rail output swing
  - $R_L = 600\Omega$
  - $R_L = 2k\Omega$
  - 100mV from rail
  - 50mV from rail
- Open loop gain with $R_L = 2k\Omega$ 100dB
- $V_{CM}$ 0 to $V^-0.9V$
- Supply current 550μA
- Gain bandwidth product 3.5MHz
- Temperature range −40°C to 125°C

Applications
- Transducer amplifier
- Instrumentation amplifier
- Precision current sensing
- Data acquisition systems
- Active filters and buffers
- Sample and hold
- Portable/battery powered electronics
- Automotive

Connection Diagram

Instrumentation Amplifier

$V_O = -K(2a + 1)(V_1 - V_2)$
### Absolute Maximum Ratings (Note 1)
If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

ESD Tolerance (Note 2)
- Machine Model: 200V
- Human Body Model: 2000V

Differential Input Voltage: \pm Supply Voltage
Voltage at Input Pins: \( (V^+) + 0.3V, (V^-) - 0.3V \)
Current at Input Pins: \pm 10 mA
Supply Voltage (\( V^+\)–\( V^- \)): 5.75V
Output Short Circuit to \( V^+ \) (Note 3)
Output Short Circuit to \( V^- \) (Note 4)

Mounting Temperature
- Infrared or Convection (20 sec): 235°C
- Wave Soldering Lead Temp (10 sec): 260°C

Storage Temperature Range: –65°C to 150°C

### Operating Ratings (Note 1)
- Supply Voltage: 2.7V to 5.5V
- Temperature Range: –40°C to 125°C
- Thermal Resistance (\( \theta_{JA} \)): 440 °C/W

### 2.7V DC Electrical Characteristics (Note 11)
Unless otherwise specified, all limits are guaranteed for \( T_A = 25°C \). \( V^+ = 2.7V \), \( V^- = 0V \), \( V_{CM} = V^+/2 \), \( V_O = V^+/2 \) and \( R_L > 1M \Omega \). **Boldface** limits apply at the temperature extremes.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Condition</th>
<th>Min (Note 7)</th>
<th>Typ (Note 6)</th>
<th>Max (Note 7)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{OS} )</td>
<td>Input Offset Voltage</td>
<td></td>
<td>0.3</td>
<td>0.85</td>
<td>1.0</td>
<td>mV</td>
</tr>
<tr>
<td>( TCV_{OS} )</td>
<td>Input Offset Voltage Average Drift</td>
<td></td>
<td>–0.45</td>
<td></td>
<td></td>
<td>( \mu V/°C )</td>
</tr>
<tr>
<td>( I_B )</td>
<td>Input Bias Current (Note 8)</td>
<td>( V_{CM} = 1V )</td>
<td>–0.1</td>
<td>100</td>
<td>250</td>
<td>pA</td>
</tr>
<tr>
<td>( I_{OS} )</td>
<td>Input Offset Current (Note 8)</td>
<td></td>
<td>0.004</td>
<td>100</td>
<td></td>
<td>pA</td>
</tr>
<tr>
<td>( I_S )</td>
<td>Supply Current</td>
<td></td>
<td>550</td>
<td>900</td>
<td>910</td>
<td>( \mu A )</td>
</tr>
<tr>
<td>CMRR</td>
<td>Common Mode Rejection Ratio</td>
<td>( 0.5 \leq V_{CM} \leq 1.2V )</td>
<td>74</td>
<td>72</td>
<td>80</td>
<td>dB</td>
</tr>
<tr>
<td>PSSR</td>
<td>Power Supply Rejection Ratio</td>
<td>( 2.7V \leq V^+ \leq 5V )</td>
<td>82</td>
<td>76</td>
<td>90</td>
<td>dB</td>
</tr>
<tr>
<td>( V_{CM} )</td>
<td>Input Common-Mode Voltage Range</td>
<td>For CMRR ( \geq 50dB )</td>
<td>0</td>
<td>1.8</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>( A_V )</td>
<td>Large Signal Voltage Gain (Note 9)</td>
<td>( R_L = 600\Omega ) to ( 1.35V, V_O = 0.2V ) to ( 2.5V )</td>
<td>92</td>
<td>80</td>
<td>100</td>
<td>dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R_L = 2k\Omega ) to ( 1.35V, V_O = 0.2V ) to ( 2.5V )</td>
<td>98</td>
<td>86</td>
<td>100</td>
<td>dB</td>
</tr>
<tr>
<td>( V_O )</td>
<td>Output Swing</td>
<td>( R_L = 600\Omega ) to ( 1.35V, V_{IN} = \pm 100mV )</td>
<td>0.11</td>
<td>0.14</td>
<td>0.084 to 2.62</td>
<td>2.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R_L = 2k\Omega ) to ( 1.35V, V_{IN} = \pm 100mV )</td>
<td>0.05</td>
<td>0.06</td>
<td>0.026 to 2.68</td>
<td>2.65</td>
</tr>
<tr>
<td>( I_O )</td>
<td>Output Short Circuit Current</td>
<td>Sourcing, ( V_O = 0V ) ( V_{IN} = 100mV )</td>
<td>18</td>
<td>11</td>
<td>24</td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sinking, ( V_O = 2.7V ) ( V_{IN} = -100mV )</td>
<td>18</td>
<td>11</td>
<td>22</td>
<td></td>
</tr>
</tbody>
</table>
### 2.7V AC Electrical Characteristics  *(Note 11)*

Unless otherwise specified, all limits are guaranteed for $T_A = 25^\circ\text{C}$, $V^+ = 5.0\text{V}$, $V^- = 0\text{V}$, $V_{CM} = V^+/2$, $V_O = V^-/2$ and $R_L > 1\text{M} \Omega$.  **Boldface** limits apply at the temperature extremes.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conditions</th>
<th>Min <em>(Note 7)</em></th>
<th>Typ <em>(Note 6)</em></th>
<th>Max <em>(Note 7)</em></th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SR$</td>
<td>Slew Rate <em>(Note 10)</em></td>
<td>$A_V = +1$, $R_L = 10\text{ k} \Omega$</td>
<td>1.4</td>
<td></td>
<td></td>
<td>$\text{V}/\mu\text{s}$</td>
</tr>
<tr>
<td>$GBW$</td>
<td>Gain-Bandwidth Product</td>
<td></td>
<td>3.5</td>
<td></td>
<td></td>
<td>$\text{MHz}$</td>
</tr>
<tr>
<td>$\phi_m$</td>
<td>Phase Margin</td>
<td></td>
<td>79</td>
<td></td>
<td></td>
<td>$\text{Deg}$</td>
</tr>
<tr>
<td>$G_m$</td>
<td>Gain Margin</td>
<td></td>
<td>$-15$</td>
<td></td>
<td></td>
<td>$\text{dB}$</td>
</tr>
<tr>
<td>$e_n$</td>
<td>Input-Referred Voltage Noise <em>(Flatband)</em></td>
<td>$f = 10\text{kHz}$</td>
<td>7.5</td>
<td></td>
<td></td>
<td>$\text{nV}/\sqrt{\text{Hz}}$</td>
</tr>
<tr>
<td>$e_n$</td>
<td>Input-Referred Voltage Noise <em>(l/f)</em></td>
<td>$f = 100\text{Hz}$</td>
<td>12.5</td>
<td></td>
<td></td>
<td>$\text{nV}/\sqrt{\text{Hz}}$</td>
</tr>
<tr>
<td>$I_n$</td>
<td>Input-Referred Current Noise</td>
<td>$f = 1\text{kHz}$</td>
<td>0.001</td>
<td></td>
<td></td>
<td>$\text{pA}/\sqrt{\text{Hz}}$</td>
</tr>
<tr>
<td>$\text{THD}$</td>
<td>Total Harmonic Distortion</td>
<td>$f = 1\text{kHz}$, $A_V = +1$</td>
<td></td>
<td></td>
<td></td>
<td>$0.007$</td>
</tr>
</tbody>
</table>

### 5.0V DC Electrical Characteristics  *(Note 11)*

Unless otherwise specified, all limits are guaranteed for $T_A = 25^\circ\text{C}$, $V^+ = 5.0\text{V}$, $V^- = 0\text{V}$, $V_{CM} = V^+/2$, $V_O = V^-/2$ and $R_L > 1\text{M} \Omega$.  **Boldface** limits apply at the temperature extremes.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Condition</th>
<th>Min <em>(Note 7)</em></th>
<th>Typ <em>(Note 6)</em></th>
<th>Max <em>(Note 7)</em></th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{OS}$</td>
<td>Input Offset Voltage</td>
<td></td>
<td>0.25</td>
<td>0.85</td>
<td>1.0</td>
<td>$\text{mV}$</td>
</tr>
<tr>
<td>$TCV_{OS}$</td>
<td>Input Offset Voltage Average Drift</td>
<td></td>
<td></td>
<td>$-0.35$</td>
<td></td>
<td>$\mu\text{V}/\circ\text{C}$</td>
</tr>
<tr>
<td>$I_B$</td>
<td>Input Bias Current <em>(Note 8)</em></td>
<td>$V_{CM} = 1\text{V}$</td>
<td></td>
<td>$-0.23$</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>$I_{OS}$</td>
<td>Input Offset Current <em>(Note 8)</em></td>
<td></td>
<td>$0.017$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_S$</td>
<td>Supply Current</td>
<td></td>
<td>600</td>
<td>950</td>
<td>960</td>
<td>$\mu\text{A}$</td>
</tr>
<tr>
<td>$CMRR$</td>
<td>Common Mode Rejection Ratio</td>
<td>$0.5 \leq V_{CM} \leq 3.5\text{V}$</td>
<td>80</td>
<td>79</td>
<td>90</td>
<td>$\text{dB}$</td>
</tr>
<tr>
<td>$PSRR$</td>
<td>Power Supply Rejection Ratio</td>
<td>$2.7\text{V} \leq V^+ \leq 5\text{V}$</td>
<td>82</td>
<td>76</td>
<td>90</td>
<td>$\text{dB}$</td>
</tr>
<tr>
<td>$V_{CM}$</td>
<td>Input Common-Mode Voltage Range</td>
<td>For $CMRR \geq 50\text{dB}$</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>$A_V$</td>
<td>Large Signal Voltage Gain <em>(Note 9)</em></td>
<td>$R_L = 600\text{\Omega}$ to $2.5\text{V}$, $V_O = 0.2\text{V}$ to $4.8\text{V}$</td>
<td>92</td>
<td>89</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>$A_V$</td>
<td></td>
<td>$R_L = 2\text{k} \Omega$ to $2.5\text{V}$, $V_O = 0.2\text{V}$ to $4.8\text{V}$</td>
<td>98</td>
<td>95</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>$V_O$</td>
<td>Output Swing</td>
<td>$R_L = 600\text{\Omega}$ to $2.5\text{V}$, $V_{IN} = \pm 100\text{mV}$</td>
<td>0.15</td>
<td>0.23</td>
<td>0.112 to 4.9</td>
<td>4.85</td>
</tr>
<tr>
<td>$V_O$</td>
<td></td>
<td>$R_L = 2\text{k} \Omega$ to $2.5\text{V}$, $V_{IN} = \pm 100\text{mV}$</td>
<td>0.06</td>
<td>0.07</td>
<td>0.035 to 4.97</td>
<td>4.94</td>
</tr>
<tr>
<td>$I_O$</td>
<td>Output Short Circuit Current <em>(Note 8, Note 12)</em></td>
<td>Sourcing, $V_O = 0\text{V}$</td>
<td>35</td>
<td>35</td>
<td>75</td>
<td>$\text{mA}$</td>
</tr>
<tr>
<td>$I_O$</td>
<td></td>
<td>Sinking, $V_O = 2.7\text{V}$</td>
<td>35</td>
<td>35</td>
<td>66</td>
<td></td>
</tr>
</tbody>
</table>

---

*(Note 7)* This defines the minimum deviation from the typical value. *(Note 8)* This defines the nominal value. *(Note 9)* This defines the maximum deviation from the nominal value. *(Note 10)* This defines the maximum deviation from the typical value. *(Note 11)* This defines the maximum deviation from the nominal value. *(Note 12)* This defines the nominal value.
### 5.0V AC Electrical Characteristics (Note 11)

Unless otherwise specified, all limits are guaranteed for $T_A = 25\, ^\circ C$, $V^+ = 5.0V$, $V^- = 0V$, $V_{CM} = V^+/2$, $V_O = V^+/2$ and $R_L > 1\, \Omega$.

**Boldface** limits apply at the temperature extremes.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conditions</th>
<th>Min (Note 7)</th>
<th>Typ (Note 6)</th>
<th>Max (Note 7)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR</td>
<td>Slew Rate (Note 10)</td>
<td>$A_v = +1$, $R_L = 10, \Omega$</td>
<td>1.4</td>
<td></td>
<td></td>
<td>V/µs</td>
</tr>
<tr>
<td>GBW</td>
<td>Gain-Bandwidth Product</td>
<td></td>
<td></td>
<td>3.5</td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>$\Phi_m$</td>
<td>Phase Margin</td>
<td></td>
<td></td>
<td>79</td>
<td></td>
<td>Deg</td>
</tr>
<tr>
<td>$G_m$</td>
<td>Gain Margin</td>
<td></td>
<td></td>
<td>$-15$</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>$e_n$</td>
<td>Input-Reflected Voltage Noise (Flatband)</td>
<td>$f = 10kHz$</td>
<td>6.5</td>
<td></td>
<td></td>
<td>nV/√Hz</td>
</tr>
<tr>
<td>$e_{n(f)}$</td>
<td>Input-Reflected Voltage Noise (f/f)</td>
<td>$f = 100Hz$</td>
<td>12</td>
<td></td>
<td></td>
<td>nV/√Hz</td>
</tr>
<tr>
<td>$i_{n}$</td>
<td>Input-Reflected Current Noise</td>
<td>$f = 1kHz$</td>
<td>0.001</td>
<td></td>
<td></td>
<td>pA/√Hz</td>
</tr>
<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
<td>$f = 1kHz$, $A_v = +1$</td>
<td>0.007</td>
<td></td>
<td></td>
<td>%</td>
</tr>
</tbody>
</table>

**Note 1:** Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is intended to be functional, but specific performance is not guaranteed. For guaranteed specifications and the test conditions, see the Electrical Characteristics.

**Note 2:** Human Body Model is 1.5 kΩ in series with 100 pF. Machine Model is 0Ω in series with 20 pF.

**Note 3:** Shorting output to $V^+$ will adversely affect reliability.

**Note 4:** Shorting output to $V^-$ will adversely affect reliability.

**Note 5:** The maximum power dissipation is a function of $T_J(MAX)$, $\theta_{JA}$ and $T_A$. The maximum allowable power dissipation at any ambient temperature is $P_D = (T_J(MAX) - T_A) / \theta_{JA}$. All numbers apply for packages soldered directly into a PC board.

**Note 6:** Typical values represent the most likely parametric norm.

**Note 7:** All limits are guaranteed by testing or statistical analysis.

**Note 8:** Limits guaranteed by design.

**Note 9:** $R_L$ is connected to mid-supply. The output voltage is set at 200mV from the rails. $V_O = GND + 0.2V$ and $V_O = V^+ -0.2V$

**Note 10:** The number specified is the slower of positive and negative slew rates.

**Note 11:** Electrical Table values apply only for factory testing conditions at the temperature indicated. Factory testing conditions result in very limited self-heating of the device such that $T_J = T_A$.

**Note 12:** Continuous operation of the device with an output short circuit current larger than 35mA may cause permanent damage to the device.
### Connection Diagram

![SC70-5 Connection Diagram](image)

### Ordering Information

<table>
<thead>
<tr>
<th>Package</th>
<th>Part Number</th>
<th>Package Marking</th>
<th>Transport Media</th>
<th>NSC Drawing</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC70-5</td>
<td>SM73308MG</td>
<td>S08</td>
<td>1k Units Tape and Reel</td>
<td>MAA05A</td>
</tr>
<tr>
<td></td>
<td>SM73308MGX</td>
<td></td>
<td>3k Units Tape and Reel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SM73308MGE</td>
<td></td>
<td>250 Units Tape and Reel</td>
<td></td>
</tr>
</tbody>
</table>
Typical Performance Characteristics

**V\text{OS} vs. V\text{CM} Over Temperature**

- V\text{S} = 2.7V
  - 40°C
  - 25°C
  - 85°C
  - 125°C

- V\text{S} = 5V
  - 40°C
  - 25°C
  - 85°C
  - 125°C

**Output Swing vs. V\text{S}**

- NEGATIVE SWING
- POSITIVE SWING

- R\text{L} = 600Ω
- T\text{A} = 25°C

**Output Swing vs. V\text{S} Over Temperature**

- NEGATIVE SWING
- POSITIVE SWING

- R\text{L} = 100kΩ
- T\text{A} = 25°C

**I\text{S} vs. V\text{S} Over Temperature**

- 40°C
- 85°C
- 125°C

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**Sourcing Current vs. V_{OUT}**  
(Note 12)

- **Input Voltage (V_{IN})**: V_{S} = 2.7V
- **Output Voltage (V_{OUT})**: 0 to 3 V
- **Current (I_{SOURCE})**: 0 to 40 mA

- **Input Voltage (V_{IN})**: V_{S} = 5V
- **Output Voltage (V_{OUT})**: 0 to 5 V
- **Current (I_{SOURCE})**: 0 to 100 mA

**Sinking Current vs. V_{OUT}**  
(Note 12)

- **Input Voltage (V_{IN})**: V_{S} = 2.7V
- **Output Voltage (V_{OUT})**: 0 to 3 V
- **Current (I_{SINK})**: 0 to 40 mA

- **Input Voltage (V_{IN})**: V_{S} = 5V
- **Output Voltage (V_{OUT})**: 0 to 5 V
- **Current (I_{SINK})**: 0 to 100 mA

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**Notes**:
1. V_{S} = ±1.35V
2. T_{A} = 25°C
3. R_{L} = 2kΩ
4. R_{L} = 600Ω
Inverting Small Signal Pulse Response

\[ V_S = \pm 2.5V \]
\[ T_A = -40^\circ C \]
\[ R_L = 2k\Omega \]

OUTPUT SIGNAL (50 mV/div)

TIME (10 \mu s/div)

Inverting Large Signal Pulse Response

\[ V_S = \pm 2.5V \]
\[ T_A = -40^\circ C \]
\[ R_L = 2k\Omega \]

OUTPUT SIGNAL (1 V/div)

TIME (10 \mu s/div)

Inverting Small Signal Pulse Response

\[ V_S = \pm 2.5V \]
\[ T_A = 25^\circ C \]
\[ R_L = 2k\Omega \]

OUTPUT SIGNAL (50 mV/div)

TIME (10 \mu s/div)

Inverting Large Signal Pulse Response

\[ V_S = \pm 2.5V \]
\[ T_A = 25^\circ C \]
\[ R_L = 2k\Omega \]

OUTPUT SIGNAL (1 V/div)

TIME (10 \mu s/div)

Inverting Small Signal Pulse Response

\[ V_S = \pm 2.5V \]
\[ T_A = 125^\circ C \]
\[ R_L = 2k\Omega \]

OUTPUT SIGNAL (50 mV/div)

TIME (10 \mu s/div)

Inverting Large Signal Pulse Response

\[ V_S = \pm 2.5V \]
\[ T_A = 125^\circ C \]
\[ R_L = 2k\Omega \]

OUTPUT SIGNAL (1 V/div)

TIME (10 \mu s/div)
SM73308

The SM73308 is a precision amplifier with very low noise and ultra low offset voltage. SM73308’s extended temperature range of −40°C to 125°C enables the user to design a variety of applications including automotive.

The SM73308 has a maximum offset voltage of 1mV over the extended temperature range. This makes the SM73308 ideal for applications where precision is important.

**INSTRUMENTATION AMPLIFIER**

Measurement of very small signals with an amplifier requires close attention to the input impedance of the amplifier, gain of the overall signal on the inputs, and the gain on each input since we are only interested in the difference of the two inputs and the common signal is considered noise. A classic solution is an instrumentation amplifier. Instrumentation amplifiers have a finite, accurate, and stable gain. Also they have extremely high input impedances and very low output impedances. Finally they have an extremely high CMRR so that the amplifier can only respond to the differential signal. A typical instrumentation amplifier is shown in Figure 1.

![Figure 1. Instrumentation Amplifier](image)

There are two stages in this amplifier. The last stage, output stage, is a differential amplifier. In an ideal case the two amplifiers of the first stage, input stage, would be set up as buffers to isolate the inputs. However they cannot be connected as followers because of real amplifier’s mismatch.

That is why there is a balancing resistor between the two. The product of the two stages of gain will give the gain of the instrumentation amplifier. Ideally, the CMRR should be infinite. However the output stage has a small non-zero common mode gain which results from resistor mismatch.

In the input stage of the circuit, current is the same across all resistors. This is due to the high input impedance and low input bias current of the SM73308. With the node equations we have:

\[ V_{O1} - V_{O2} = (2R_1 + R_{11}) I_{R_{11}} \]

By Ohm’s Law:
\[ V_{O1} - V_{O2} = (2a + 1) R_{11} \cdot I_{R_{11}} \]
\[ = (2a + 1) V_{R_{11}} \]  \hspace{1cm} (2)

However:
\[ V_{R_{11}} = V_1 - V_2 \]  \hspace{1cm} (3)

So we have:
\[ V_{O1} - V_{O2} = (2a + 1) (V_1 - V_2) \]  \hspace{1cm} (4)

Now looking at the output of the instrumentation amplifier:
\[ V_O = \frac{KR_2}{R_2} (V_{O2} - V_{O1}) \]
\[ = -K (V_{O1} - V_{O2}) \] \hspace{1cm} (5)

Substituting from Equation 4:
\[ V_O = -K (2a + 1) (V_1 - V_2) \] \hspace{1cm} (6)

This shows the gain of the instrumentation amplifier to be:
\[ -K(2a+1) \]

Typical values for this circuit can be obtained by setting: \( a = 12 \) and \( K = 4 \). This results in an overall gain of −100.

Figure 2 shows typical CMRR characteristics of this Instrumentation amplifier over frequency. Three SM73308 amplifiers are used along with 1% resistors to minimize resistor mismatch. Resistors used to build the circuit are: \( R_1 = 21.6k\Omega, R_{11} = 1.8k\Omega, R_2 = 2.5k\Omega \) with \( K = 40 \) and \( a = 12 \). This results in an overall gain of −1000, \(-K(2a+1) = −1000\).
ACTIVE FILTER

Active filters are circuits with amplifiers, resistors, and capacitors. The use of amplifiers instead of inductors, which are used in passive filters, enhances the circuit performance while reducing the size and complexity of the filter. The simplest active filters are designed using an inverting op amp configuration where at least one reactive element has been added to the configuration. This means that the op amp will provide "frequency-dependent" amplification, since reactive elements are frequency dependent devices.

LOW PASS FILTER

The following shows a very simple low pass filter.

![Low Pass Filter Diagram](image)

The transfer function can be expressed as follows:

By KCL:

\[ \frac{-V_i}{R_1} - \frac{V_O}{R_2} - \frac{V_O}{j\omega C} = 0 \]

(7)

Simplifying this further results in:

\[ V_O = \frac{R_2}{R_1} \left( \frac{1}{j\omega C R_2} + 1 \right) V_i \]

(8)

or

\[ \frac{V_O}{V_i} = \frac{-R_2}{R_1} \left( \frac{1}{j\omega C R_2 + 1} \right) \]

(9)

Now, substituting \( \omega = 2\pi f \), so that the calculations are in f(\( \text{Hz} \)) and not \( \omega (\text{rad/s}) \), and setting the DC gain \( H_O = -R_2/R_1 \), and \( H = V_O/V_i \)

\[ H = H_O \left( \frac{1}{j\omega R_2 + 1} \right) \]

(10)

Set: \( f_0 = 1/(2\pi R_1 C) \)

\[ H = H_O \left( \frac{1}{1 + j(\omega f_0)} \right) \]

(11)

Low pass filters are known as lossy integrators because they only behave as an integrator at higher frequencies. Just by looking at the transfer function one can predict the general form of the bode plot. When the \( f/f_0 \) ratio is small, the capacitor is in effect an open circuit and the amplifier behaves at a set DC gain. Starting at \( f_0 \), −3dB corner, the capacitor will have the dominant impedance and hence the circuit will behave as an integrator and the signal will be attenuated and eventually cut. The bode plot for this filter is shown in the following picture:

![Lowpass Filter Bode Plot](image)
HIGH PASS FILTER

In a similar approach, one can derive the transfer function of a high pass filter. A typical first order high pass filter is shown below:

![High Pass Filter Circuit](image)

**FIGURE 5. Highpass Filter**

Writing the KCL for this circuit:

\[
\frac{v_1 - v}{1/j\omega C} = \frac{v_1 - v}{R_1}
\]

\[
\frac{v + v_1}{R_1} = \frac{v + v_o}{R_2}
\]

(12)

(13)

Solving these two equations to find the transfer function and using:

\[
f_o = \frac{1}{2\pi R_1 C}
\]

(high frequency gain)

\[
H_o = \frac{-R_2}{R_1} \quad \text{and} \quad H = \frac{V_o}{V_1}
\]

Which results:

\[
H = H_o \frac{j (f/f_o)}{1 + j (f/f_o)}
\]

(14)

Looking at the transfer function, it is clear that when \(f/f_o\) is small, the capacitor is open and hence no signal is getting into the amplifier. As the frequency increases the amplifier starts operating. At \(f = f_o\), the capacitor behaves like a short circuit and the amplifier will have a constant, high frequency, gain of \(H_o\). **Figure 6** shows the transfer function of this high pass filter:

![Highpass Filter Transfer Function](image)

**FIGURE 6. Highpass Filter Transfer Function**

BAND PASS FILTER

Combining a low pass filter and a high pass filter will generate a band pass filter. In this network the input impedance forms the high pass filter while the feedback impedance forms the low pass filter. Choosing the corner frequencies so that \(f_1 < f_o < f_2\), then all the frequencies in between, \(f_1 \leq f \leq f_2\), will pass through the filter while frequencies below \(f_1\) and above \(f_2\) will be cut off.

The transfer function can be easily calculated using the same methodology as before:

\[
H = H_o \frac{j (f_1)}{[1 + j (f_1/f_o)] [1 + j (f_2/f_o)]}
\]

(15)

Where

\[
f_1 = \frac{1}{2\pi R_1 C_1}
\]

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

\[
H_o = \frac{-R_2}{R_1}
\]

The transfer function is presented in the following figure.

![Bandpass Filter Circuit](image)

**FIGURE 7. Bandpass Filter**
STATE VARIABLE ACTIVE FILTER

State variable active filters are circuits that can simultaneously represent high pass, band pass, and low pass filters. The state variable active filter uses three separate amplifiers to achieve this task. A typical state variable active filter is shown in Figure 9. The first amplifier in the circuit is connected as a gain stage. The second and third amplifiers are connected as integrators, which means they behave as low pass filters. The feedback path from the output of the third amplifier to the first amplifier enables this low frequency signal to be fed back with a finite and fairly low closed loop gain. This is while the high frequency signal on the input is still gained up by the open loop gain of the 1st amplifier. This makes the first amplifier a high pass filter. The high pass signal is then fed into a low pass filter. The outcome is a band pass signal, meaning the second amplifier is a band pass filter. This signal is then fed into the third amplifiers input and so, the third amplifier behaves as a simple low pass filter.

The transfer function of each filter needs to be calculated. The derivations will be more trivial if each stage of the filter is shown on its own.

The three components are:

For \( A_1 \) the relationship between input and output is:

\[
V_{O1} = \frac{-R_4}{R_1} V_0 + \left[ \frac{R_6}{R_5 + R_6} \right] V_{IN} + \left[ \frac{R_5}{R_5 + R_6} \right] \frac{R_1 + R_4}{R_1} V_{O2}
\]

This relationship depends on the output of all the filters. The input-output relationship for \( A_2 \) can be expressed as:

\[
V_{O2} = \frac{-1}{sC_2R_2} V_{O1}
\]

And finally this relationship for \( A_3 \) is as follows:

\[
V_O = \frac{-1}{sC_3R_3} V_{O2}
\]

Re-arranging these equations, one can find the relationship between \( V_O \) and \( V_{IN} \) (transfer function of the lowpass filter), \( V_{O1} \) and \( V_{IN} \) (transfer function of the highpass filter), and \( V_{O2} \) and \( V_{IN} \) (transfer function of the bandpass filter) These relationships are as follows:

**Lowpass Filter**

\[
V_{O} = \frac{R_1 + R_4}{R_1} \frac{R_6}{R_5 + R_6} \frac{1}{C_3C_2R_2R_3}
\]

**Highpass Filter**

\[
V_{O1} = \frac{R_1 + R_4}{R_1} \frac{R_6}{R_5 + R_6} \frac{1}{C_3C_2R_2R_3}
\]

FIGURE 8. Bandpass filter Transfer Function

FIGURE 9. State Variable Active Filter
Bandpass Filter

\[ \frac{V_{O2}}{V_{IN}} = \frac{s \left[ \frac{1}{C_2R_2^2} \right] \left[ \frac{R_1 + R_4}{R_1} \right] \left[ \frac{R_6}{R_5 + R_6} \right]}{s^2 + s \left[ \frac{1}{C_2R_2^2} \right] \left[ \frac{R_5 + R_4}{R_1} \right] + \frac{1}{C_2C_3R_2R_3}} \]

The center frequency and Quality Factor for all of these filters is the same. The values can be calculated in the following manner:

\[ \omega_c = \sqrt{\frac{1}{C_2C_3R_2R_3}} \]

and

\[ Q = \sqrt{\frac{C_2R_2}{C_3R_3} \left[ \frac{R_5 + R_6}{R_6} \right] \left[ \frac{R_1}{R_1 + R_4} \right]} \]

A design example is shown here:

Designing a bandpass filter with center frequency of 10kHz and Quality Factor of 5.5

To do this, first consider the Quality Factor. It is best to pick convenient values for the capacitors. \( C_2 = C_3 = 1000\, \text{pF} \). Also, choose \( R_1 = R_4 = 30k\, \Omega \). Now values of \( R_5 \) and \( R_6 \) need to be calculated. With the chosen values for the capacitors and resistors, \( Q \) reduces to:

\[ Q = \frac{11}{2} = \frac{1}{2} \left[ \frac{R_5 + R_6}{R_6} \right] \]

\[ \text{or} \]

\[ R_5 = 10R_6 \]

\[ R_6 = 1.5k\, \Omega \]

\[ R_5 = 15k\, \Omega \]

Also, for \( f = 10kHz \), the center frequency is \( \omega_c = 2\pi f = 62.8kHz \).

Using the expressions above, the appropriate resistor values will be \( R_2 = R_3 = 16k\, \Omega \).

The following graphs show the transfer function of each of the filters. The DC gain of this circuit is:

\[ \text{DC GAIN} = \left[ \frac{R_1 + R_4}{R_1} \right] \left[ \frac{R_6}{R_5 + R_6} \right] = -14.8 \, \text{dB} \]

30155590
Physical Dimensions inches (millimeters) unless otherwise noted

SC70-5
NS Package Number MAA05A
SM73308 Low Offset, Low Noise, RRO Operational Amplifier

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