

## Low Offset, Low Noise, RRO Operational Amplifiers

The HT2771/HT2772/HT2774 are Single, Dual, and Quad low noise precision operational amplifiers intended for use in a wide range of applications. Other important characteristics of the family include extended operating temperature range,  $-40^{\circ}\text{C}$  to  $125^{\circ}\text{C}$ , tiny SC70-5 package for HT2771, and low input bias current. The extended temperature range of  $-40^{\circ}\text{C}$  to  $125^{\circ}\text{C}$  allows the HT2771/HT2772/HT2774 to accommodate a broad range of applications. HT2771 expands National Semiconductor's Silicon Dust™ amplifier portfolio offering enhancements in size, speed, and power savings. The HT2771/HT2772/HT2774 are guaranteed to operate over the voltage range of 2.7V to 5.0V and all have rail-to-rail output. The HT2771/HT2772/HT2774 family is designed for precision, low noise, low voltage, and miniature systems. These amplifiers provide rail-to-rail output swing into heavy loads. The maximum input offset voltage for HT2771 is  $850\mu\text{V}$  at room temperature and the input common mode voltage range includes ground.

### Features

(Typical 2.7V Supply Values; Unless Otherwise Noted)

n Guaranteed 2.7V and 5V specifications	
n Maximum $V_{OS}$ (HT2771)	850 $\mu\text{V}$ (limit)
n Voltage Noise	
— $f = 100\text{Hz}$	12.5nV/
— $f = 10\text{kHz}$	7.5nV/ $\sqrt{\text{Hz}}$
n Rail-to-Rail output swing	
— w/600 $\Omega$ load	100mV from rail
— w/2k $\Omega$ load	50mV from rail
n Open loop gain w/2k $\Omega$ load	100dB
n $V_{CM}$	0 to $V^+ - 0.9\text{V}$
n Supply current (per amplifier)	550 $\mu\text{A}$
n Gain bandwidth product	3.5MHz
n Temperature range	$-40^{\circ}\text{C}$ to $125^{\circ}\text{C}$

### Applications

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

### ORDERING INFORMATION



SOT23-5 T SUFFIX  
HT2771ARTZ



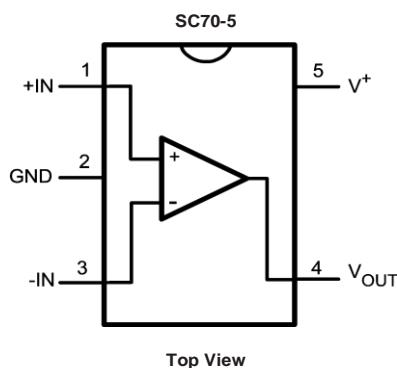
MSOP8 M SUFFIX  
HT2772ARMZ



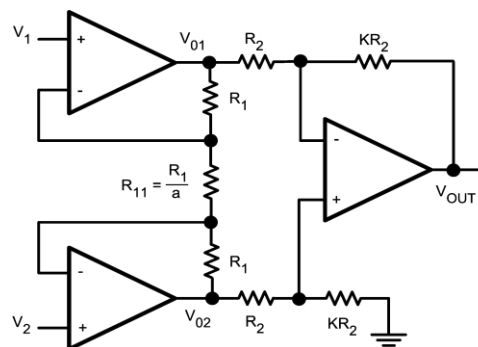
SOP-8 R SUFFIX  
HT2772ARZ

$T_A = -40^{\circ}$  to  $125^{\circ}\text{C}$  for all packages.

### 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	± Supply Voltage
Supply Voltage ( $V^+ - V^-$ )	5.5V
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
Junction Temperature (Note 5)	150°C

**Operating Ratings** (Note 1)

Supply Voltage	2.7V to 5.5V
Temperature Range	-40°C to 125°C
Thermal Resistance ( $\theta_{JA}$ )	
SC70-5 Package	440 °C/W
8-Pin MSOP	235°C/W
8-Pin SOIC	190°C/W
14-Pin TSSOP	155°C/W

**2.7V DC Electrical Characteristics** (Note 13)

Unless otherwise specified, all limits guaranteed for  $T_J = 25^\circ\text{C}$ .  $V^+ = 2.7\text{V}$ ,  $V^- = 0\text{V}$ ,  $V_{CM} = V^+/2$ ,  $V_O = V^+/2$  and  $R_L > 1\text{M}\Omega$ . **Boldface** limits apply at the temperature extremes.

Symbol	Parameter	Condition	Min (Note 7)	Typ (Note 6)	Max (Note 7)	Units
$V_{OS}$	Input Offset Voltage	HT2771		0.3	0.85 <b>1.0</b>	mV
		HT2772/HT2774		0.3	1.0 <b>1.2</b>	
$TCV_{OS}$	Input Offset Voltage Average Drift			-0.45		$\mu\text{V}/^\circ\text{C}$
$I_B$	Input Bias Current (Note 8)			-0.1	100	pA
$I_{OS}$	Input Offset Current (Note 8)			0.004	100	pA
$I_S$	Supply Current (Per Amplifier)			550	900 <b>910</b>	$\mu\text{A}$
CMRR	Common Mode Rejection Ratio	$0.5 \leq V_{CM} \leq 1.2\text{V}$	74 <b>72</b>	80		dB
PSSR	Power Supply Rejection Ratio	$2.7\text{V} \leq V^+ \leq 5\text{V}$	82 <b>76</b>	90		dB
$V_{CM}$	Input Common-Mode Voltage Range	For CMRR $\geq 50\text{dB}$	0		1.8	V
$A_V$	Large Signal Voltage Gain (Note 9)	$R_L = 600\Omega$ to 1.35V, $V_O = 0.2\text{V}$ to 2.5V, (Note 10)	92 <b>80</b>	100		dB
		$R_L = 2\text{k}\Omega$ to 1.35V, $V_O = 0.2\text{V}$ to 2.5V, (Note 11)	98 <b>86</b>	100		
$V_O$	Output Swing	$R_L = 600\Omega$ to 1.35V $V_{IN} = \pm 100\text{mV}$ , (Note 10)	0.11 <b>0.14</b>	0.084 to 2.62	2.59 <b>2.56</b>	V
		$R_L = 2\text{k}\Omega$ to 1.35V $V_{IN} = \pm 100\text{mV}$ , (Note 11)	0.05 <b>0.06</b>	0.026 to 2.68	2.65 <b>2.64</b>	
$I_O$	Output Short Circuit Current	Sourcing, $V_O = 0\text{V}$ $V_{IN} = 100\text{mV}$	18 <b>11</b>	24		mA
		Sinking, $V_O = 2.7\text{V}$ $V_{IN} = -100\text{mV}$	18 <b>11</b>	22		

**2.7V AC Electrical Characteristics** (Note 13)

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

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

Symbol	Parameter	Conditions	Min (Note 7)	Typ (Note 6)	Max (Note 7)	Units
SR	Slew Rate	(Note 12)		1.4		V/ $\mu\text{s}$
GBW	Gain-Bandwidth Product			3.5		MHz
$\Phi_m$	Phase Margin			79		Deg
$G_m$	Gain Margin			-15		dB
$e_n$	Input-Referred Voltage Noise (Flatband)	$f = 10\text{kHz}$		7.5		nV/ $\sqrt{\text{Hz}}$
$e_n$	Input-Referred Voltage Noise (1/f)	$f = 100\text{Hz}$		12.5		nV/ $\sqrt{\text{Hz}}$
$i_n$	Input-Referred Current Noise	$f = 1\text{kHz}$		0.001		pA/ $\sqrt{\text{Hz}}$
THD	Total Harmonic Distortion	$f = 1\text{kHz}$ , $A_V = +1$ $R_L = 600\Omega$ , $V_{IN} = 1 V_{PP}$		0.007		%

**5.0V DC Electrical Characteristics** (Note 13)

 Unless otherwise specified, all limits guaranteed for  $T_J = 25^\circ\text{C}$ .  $V^+ = 5.0\text{V}$ ,  $V^- = 0\text{V}$ ,  $V_{CM} = V^+/2$ ,  $V_O = V^+/2$  and

 $R_L > 1\text{M}\Omega$ . **Boldface** limits apply at the temperature extremes.

Symbol	Parameter	Condition	Min (Note 7)	Typ (Note 6)	Max (Note 7)	Units
$V_{OS}$	Input Offset Voltage	HT2771		0.25	0.85 <b>1.0</b>	mV
		HT2772/HT2774		0.25	1.0 <b>1.2</b>	
$TCV_{OS}$	Input Offset Voltage Average Drift			-0.35		$\mu\text{V}/^\circ\text{C}$
$I_B$	Input Bias Current (Note 8)			-0.23	100	pA
$I_{OS}$	Input Offset Current (Note 8)			0.017	100	pA
$I_S$	Supply Current (Per Amplifier)			600	950 <b>960</b>	$\mu\text{A}$
CMRR	Common Mode Rejection Ratio	$0.5 \leq V_{CM} \leq 3.5\text{V}$	80 <b>79</b>	90		dB
PSRR	Power Supply Rejection Ratio	$2.7\text{V} \leq V^+ \leq 5\text{V}$	82 <b>76</b>	90		dB
$V_{CM}$	Input Common-Mode Voltage Range	For CMRR $\geq 50\text{dB}$	0		4.1	V
$A_V$	Large Signal Voltage Gain (Note 9)	$R_L = 600\Omega$ to 2.5V, $V_O = 0.2\text{V}$ to 4.8V, (Note 10)	92 <b>89</b>	100		dB
		$R_L = 2\text{k}\Omega$ to 2.5V, $V_O = 0.2\text{V}$ to 4.8V, (Note 11)	98 <b>95</b>	100		
$V_O$	Output Swing	$R_L = 600\Omega$ to 2.5V $V_{IN} = \pm 100\text{mV}$ , (Note 10)	0.15 <b>0.23</b>	0.112 to 4.9	4.85 <b>4.77</b>	V
		$R_L = 2\text{k}\Omega$ to 2.5V $V_{IN} = \pm 100\text{mV}$ , (Note 11)	0.06 <b>0.07</b>	0.035 to 4.97	4.94 <b>4.93</b>	
$I_O$	Output Short Circuit Current (Note 8), (Note 14)	Sourcing, $V_O = 0\text{V}$ $V_{IN} = 100\text{mV}$	35 <b>35</b>	75		mA
		Sinking, $V_O = 2.7\text{V}$ $V_{IN} = -100\text{mV}$	35 <b>35</b>	66		

### 5.0V AC Electrical Characteristics (Note 13)

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

Symbol	Parameter	Conditions	Min (Note 7)	Typ (Note 6)	Max (Note 7)	Units
SR	Slew Rate	(Note 12)		1.4		V/ $\mu\text{s}$
GBW	Gain-Bandwidth Product			3.5		MHz
$\Phi_m$	Phase Margin			79		Deg
$G_m$	Gain Margin			-15		dB
$e_n$	Input-Referred Voltage Noise (Flatband)	$f = 10\text{kHz}$		6.5		$\text{nV}/\sqrt{\text{Hz}}$
$e_n$	Input-Referred Voltage Noise (1/f)	$f = 100\text{Hz}$		12		$\text{nV}/\sqrt{\text{Hz}}$
$i_n$	Input-Referred Current Noise	$f = 1\text{kHz}$		0.001		$\text{pA}/\sqrt{\text{Hz}}$
THD	Total Harmonic Distortion	$f = 1\text{kHz}$ , $A_V = +1$ $R_L = 600\Omega$ , $V_{IN} = 1 V_{PP}$		0.007		%

**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,  $1.5\text{k}\Omega$  in series with  $100\text{pF}$ . Machine model,  $0\Omega$  in series with  $20\text{pF}$ .

**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  $T_{J(\text{MAX})}$ ,  $\theta_{JA}$ , and  $T_A$ . The maximum allowable power dissipation at any ambient temperature is  $P_D = (T_{J(\text{MAX})} - T_A) / \theta_{JA}$ . 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  $200\text{mV}$  from the rails.  $V_O = \text{GND} + 0.2\text{V}$  and  $V_O = V^+ - 0.2\text{V}$

**Note 10:** For HT2772/HT2774, temperature limits apply to  $-40^\circ\text{C}$  to  $85^\circ\text{C}$ .

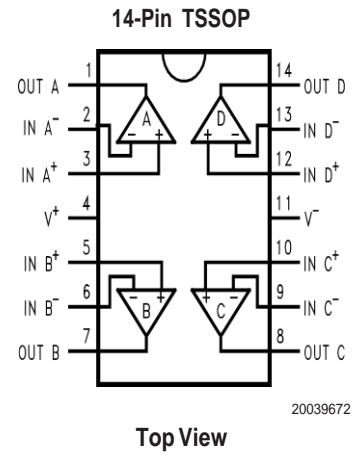
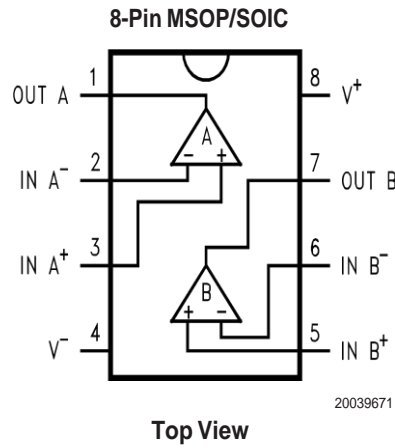
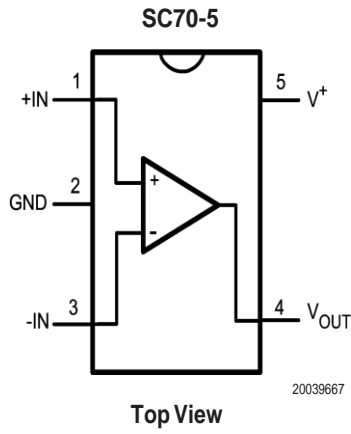
**Note 11:** For HT2772/HT2774, temperature limits apply to  $-40^\circ\text{C}$  to  $85^\circ\text{C}$ . If  $R_L$  is relaxed to  $10\text{k}\Omega$ , then for HT2772/HT2774 temperature limits apply to  $-40^\circ\text{C}$  to  $125^\circ\text{C}$ .

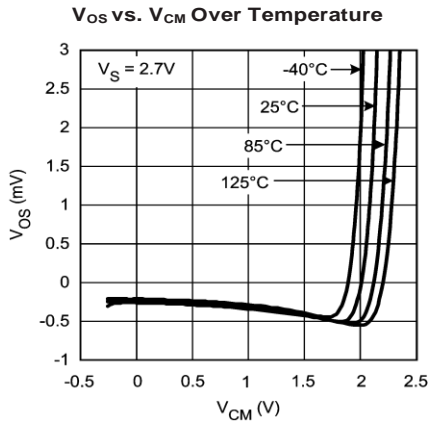
**Note 12:** Connected as voltage follower with  $2V_{PP}$  step input. Number specified is the slower of positive and negative slew rates.

**Note 13:** 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  $T_J = T_A$ . No guarantee of parametric performance is indicated in the electrical tables under the conditions of internal self-heating where  $T_J > T_A$ . Absolute Maximum Rating indicated junction temperature limits beyond which the device may be permanently degraded, either mechanically or electrically.

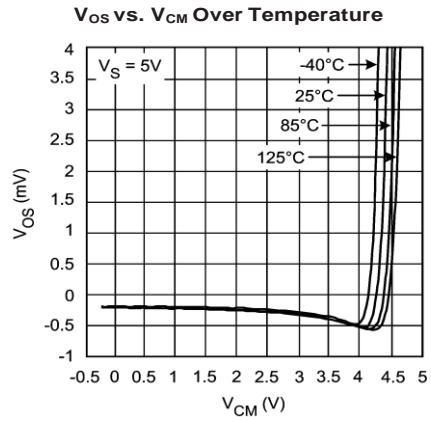
**Note 14:** Continuous operation of the device with an output short circuit current larger than  $35\text{mA}$  may cause permanent damage to the device.

**Connection Diagrams**

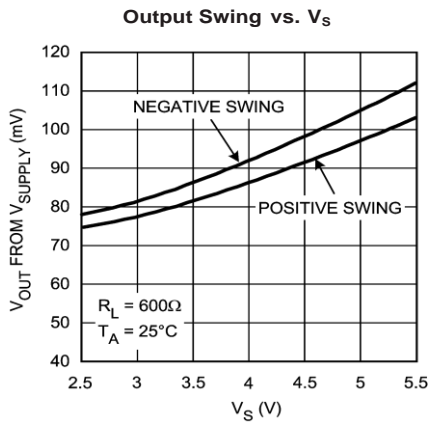


**Typical Performance Characteristics**


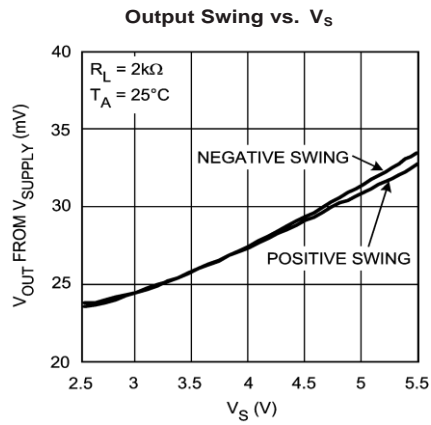
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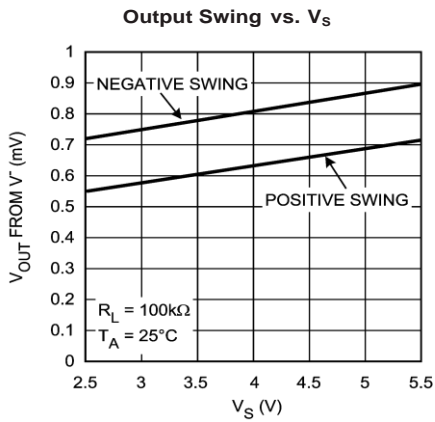
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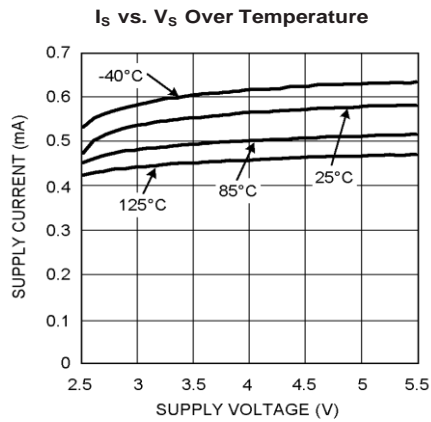
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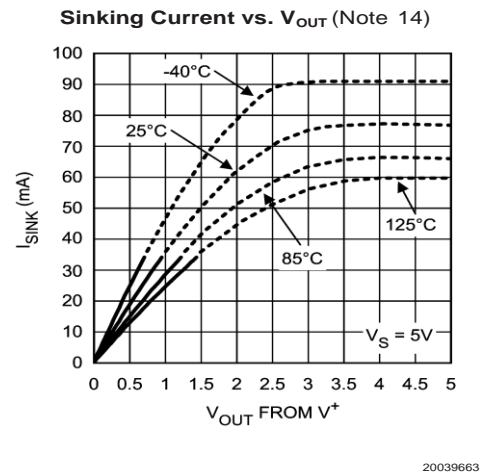
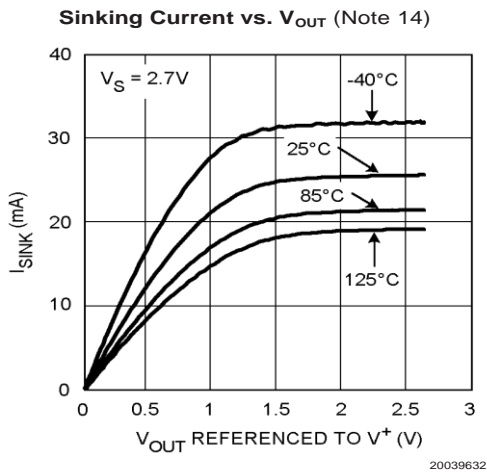
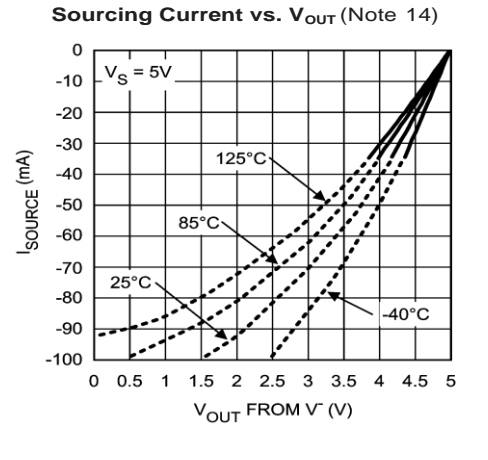
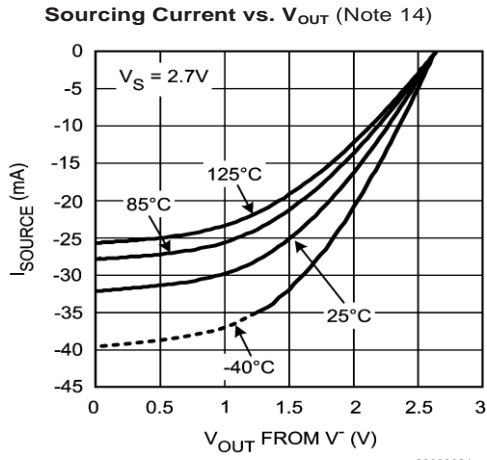
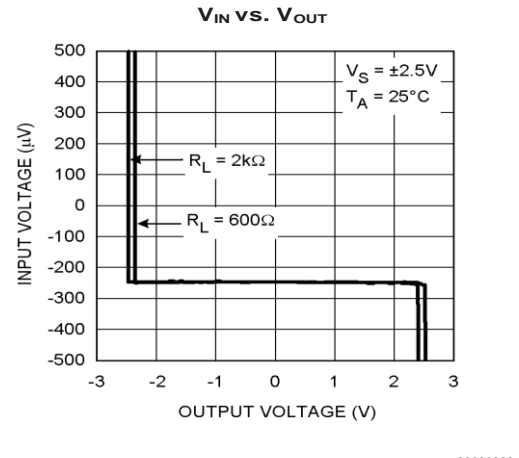
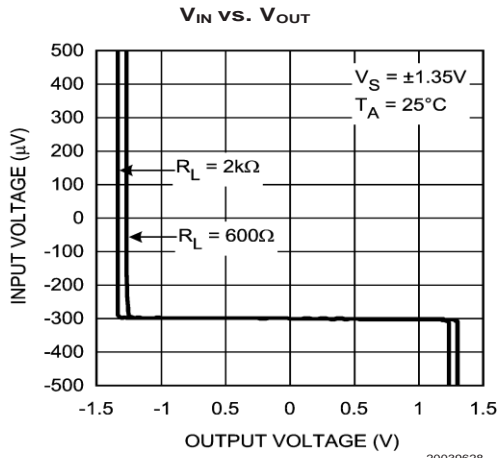
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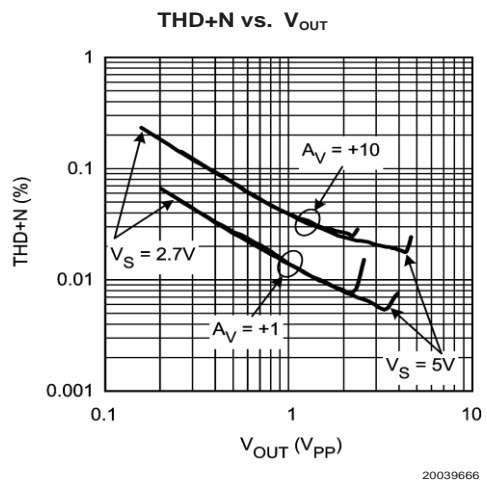
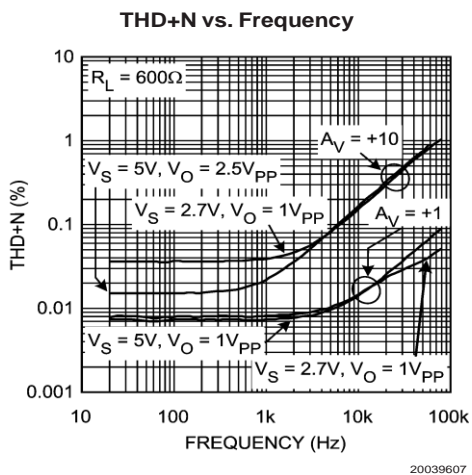
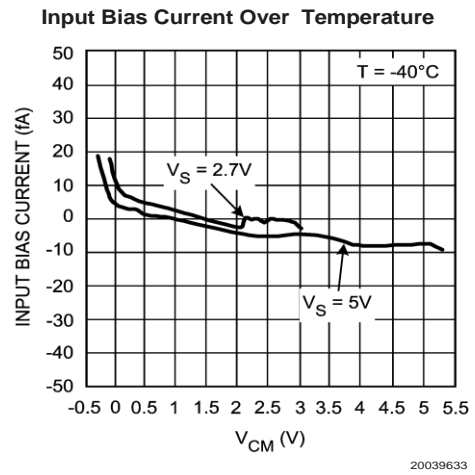
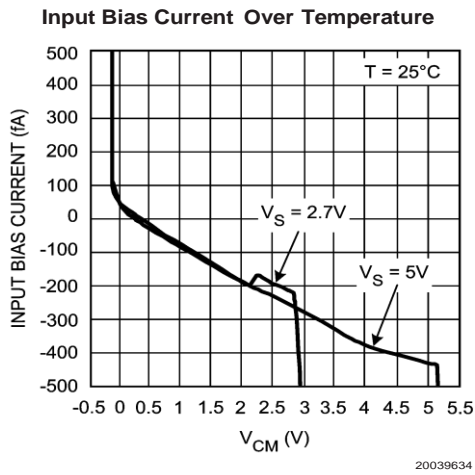
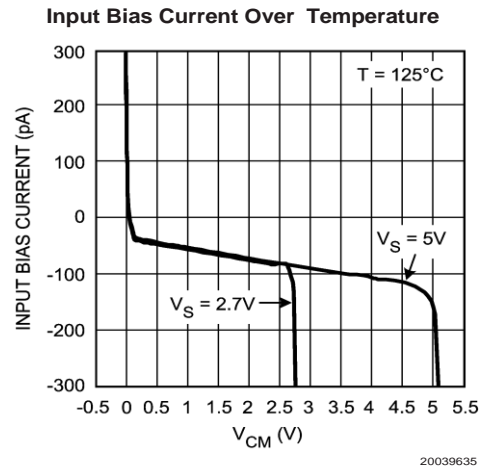
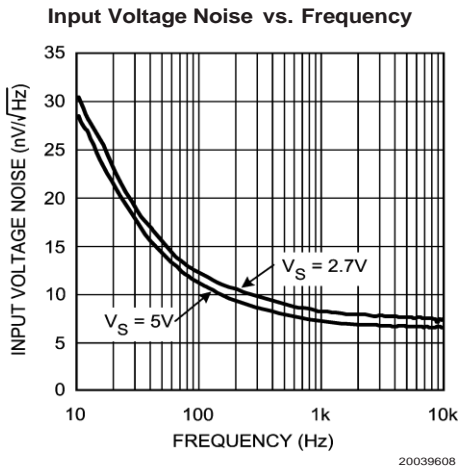


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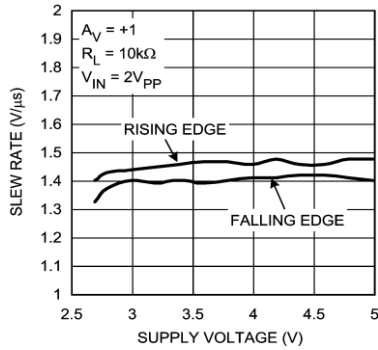


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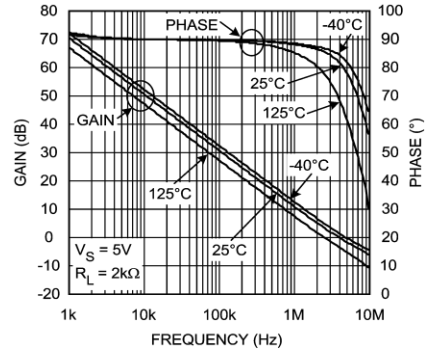
**Typical Performance Characteristics (Continued)**


**Typical Performance Characteristics (Continued)**


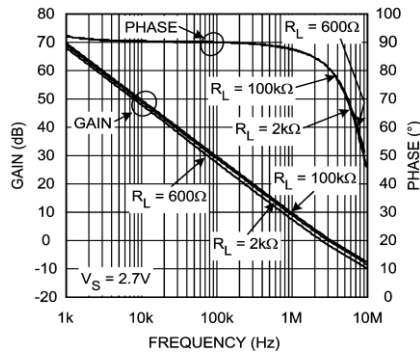


**Typical Performance Characteristics (Continued)**
**Slew Rate vs. Supply Voltage**


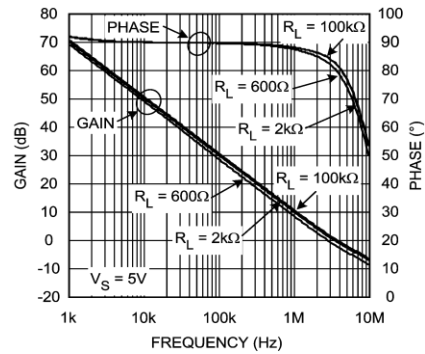
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**Open Loop Frequency Response Over Temperature**


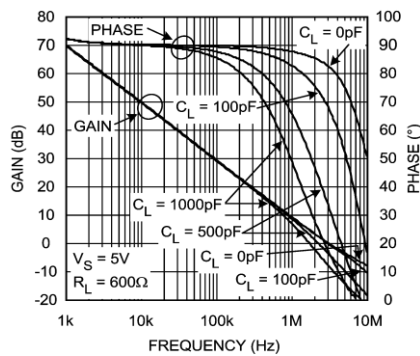
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**Open Loop Frequency Response**


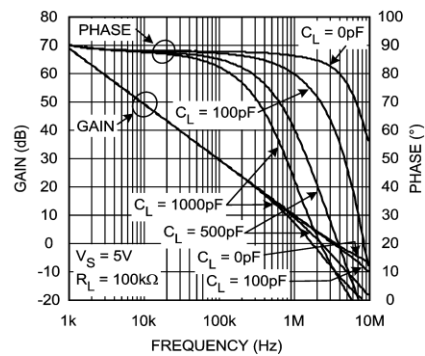
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**Open Loop Frequency Response**


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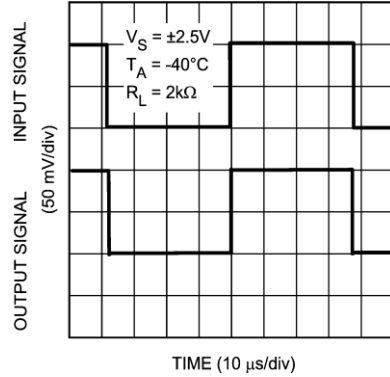
**Open Loop Gain & Phase with Cap. Loading**


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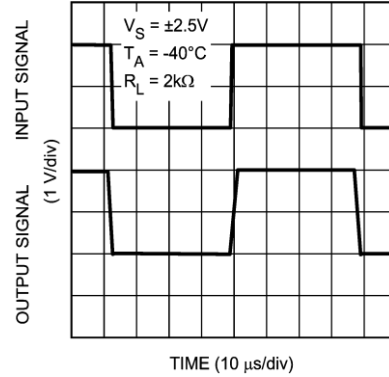
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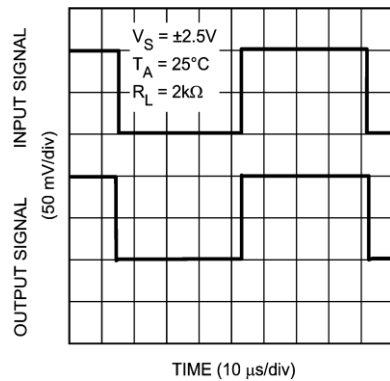
**Typical Performance Characteristics** (Continued)

**Non-Inverting Small Signal Pulse Response**


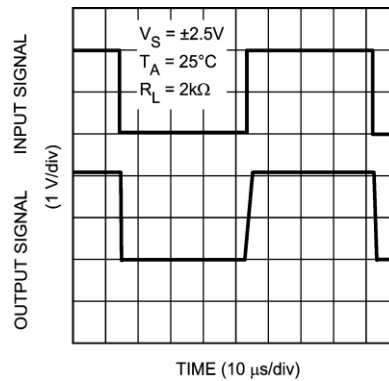
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**Non-Inverting Large Signal Pulse Response**


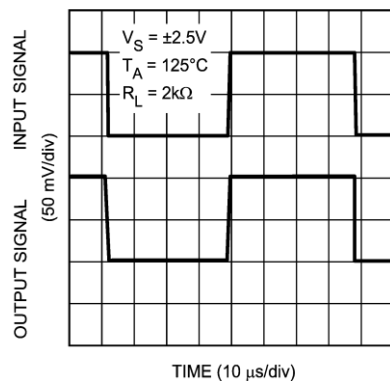
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**Non-Inverting Small Signal Pulse Response**


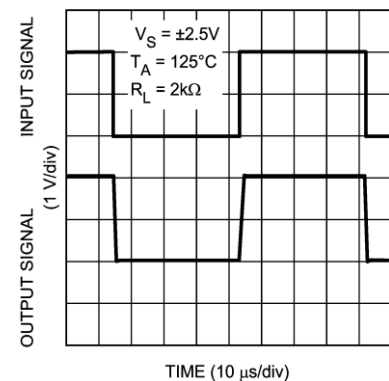
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**Non-Inverting Large Signal Pulse Response**


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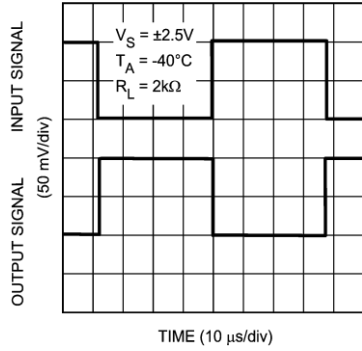
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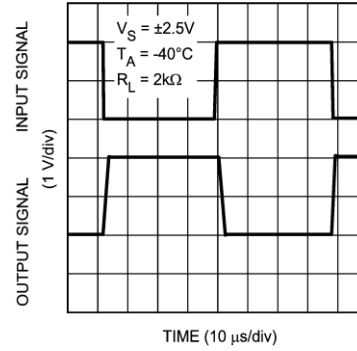
**Non-Inverting Large Signal Pulse Response**


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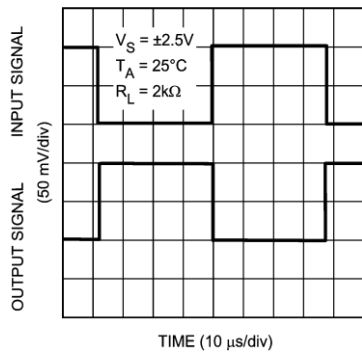
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**Inverting Small Signal Pulse Response**


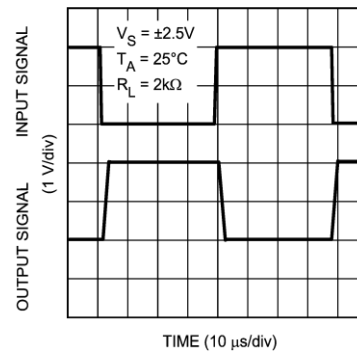
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**Inverting Large Signal Pulse Response**


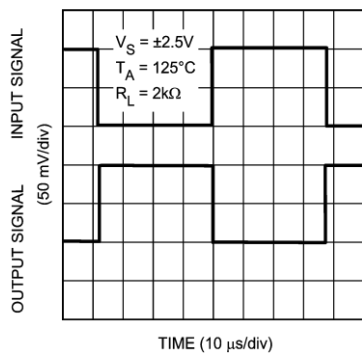
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**Inverting Small Signal Pulse Response**


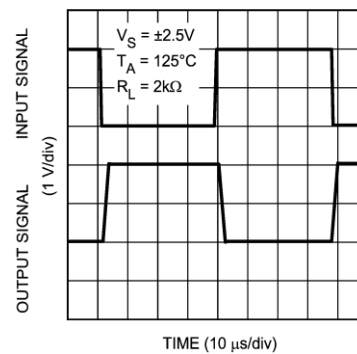
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**Inverting Large Signal Pulse Response**


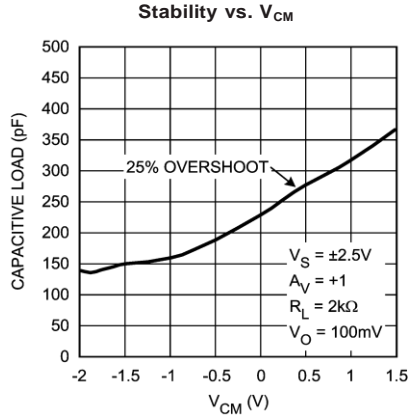
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**Inverting Small Signal Pulse Response**


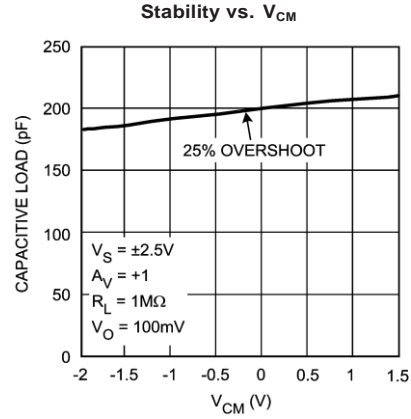
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**Inverting Large Signal Pulse Response**


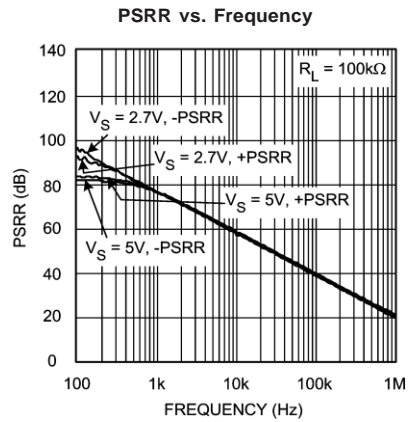
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**Typical Performance Characteristics** (Continued)


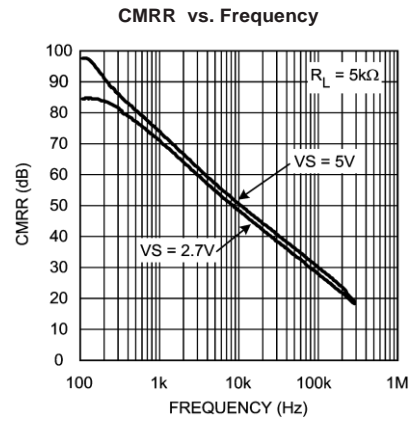
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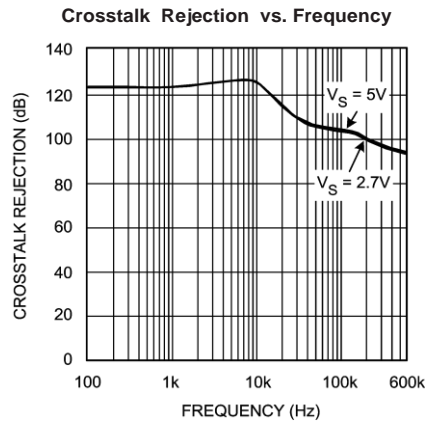
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## Application Note

### HT2771/HT2772/HT2774

The HT2771/HT2772/HT2774 is a family of precision amplifiers with very low noise and ultra low offset voltage. HT2771/HT2772/HT2774's extended temperature range of  $-40^{\circ}\text{C}$  to  $125^{\circ}\text{C}$  enables the user to design this family of products in a variety of applications including automotive.

HT2771 has a maximum offset voltage of 1mV over the extended temperature range. This makes HT2771 ideal for applications where precision is of importance.

HT2772/HT2774 have a maximum offset voltage of 1mV at room temperature and 1.2mV over the extended temperature range of  $-40^{\circ}\text{C}$  to  $125^{\circ}\text{C}$ . Care must be given when HT2772/HT2774 are designed in applications with heavy loads under extreme temperature conditions. As indicated in the DC tables, the HT2772/HT2774's gain and output swing may be reduced at temperatures between  $85^{\circ}\text{C}$  and  $125^{\circ}\text{C}$  with loads heavier than  $2\text{k}\Omega$ .

### 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*.

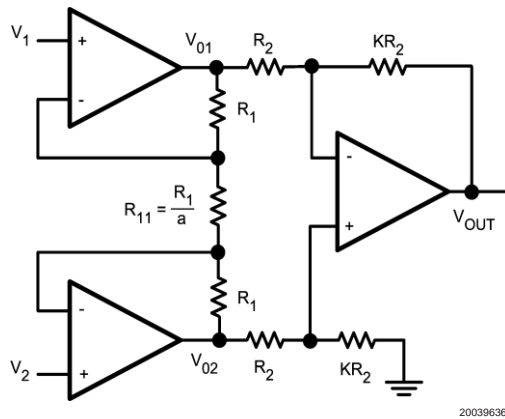


FIGURE 1.

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 amplifiers mismatch. That is why there is a balancing resistor between the two. The product of the two stages of the gain will give the gain of the instrumentation amplifier. Ideally, the CMRR should be infinity. 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 HT2771. With the node equations we have:

$$\text{GIVEN: } I_{R_1} = I_{R_{11}} \quad (1)$$

By Ohm's Law:

$$\begin{aligned} V_{O1} - V_{O2} &= (2R_1 + R_{11}) I_{R_{11}} \\ &= (2a + 1) R_{11} \cdot I_{R_{11}} \\ &= (2a + 1) V_{R_{11}} \end{aligned} \quad (2)$$

However:

$$V_{R_{11}} = V_1 - V_2 \quad (3)$$

So we have:

$$V_{O1} - V_{O2} = (2a + 1) (V_1 - V_2) \quad (4)$$

Now looking at the output of the instrumentation amplifier:

$$\begin{aligned} V_O &= \frac{KR_2}{R_2} (V_{O2} - V_{O1}) \\ &= -K (V_{O1} - V_{O2}) \end{aligned} \quad (5)$$

Substituting from equation 4:

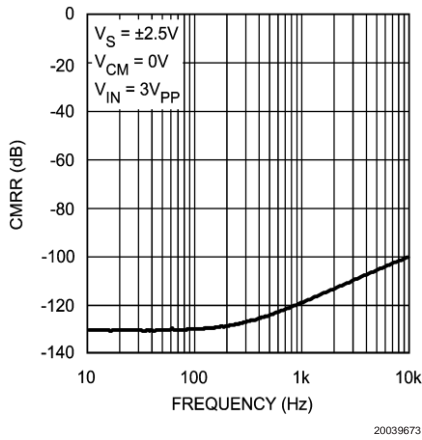
$$V_O = -K (2a + 1) (V_1 - V_2) \quad (6)$$

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 HT2771 amplifiers are used along with 1% resistors to minimize resistor mismatch. Resistors used to build the circuit are:  $R_1 = 21.6\text{k}\Omega$ ,  $R_{11} = 1.8\text{k}\Omega$ ,  $R_2 = 2.5\text{k}\Omega$  with  $K = 40$  and  $a = 12$ . This results in an overall gain of  $-1000$ ,  $-K(2a+1) = -1000$ .

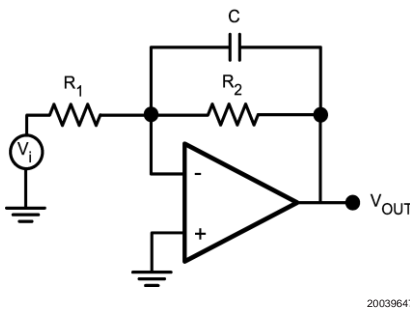
**Application Note** (Continued)

**FIGURE 2. CMRR vs. Frequency**
**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.


**FIGURE 3.**

The transfer function can be expressed as follows:

By KCL:

$$\frac{-V_i}{R_1} - \frac{V_o}{\left[ \frac{1}{j\omega C} \right]} - \frac{V_o}{R_2} = 0$$

(7)

Simplifying this further results in:

$$V_o = \frac{-R_2}{R_1} \left[ \frac{1}{j\omega C R_2 + 1} \right] V_i \quad (8)$$

or

$$\frac{V_o}{V_i} = \frac{-R_2}{R_1} \left[ \frac{1}{j\omega C R_2 + 1} \right] \quad (9)$$

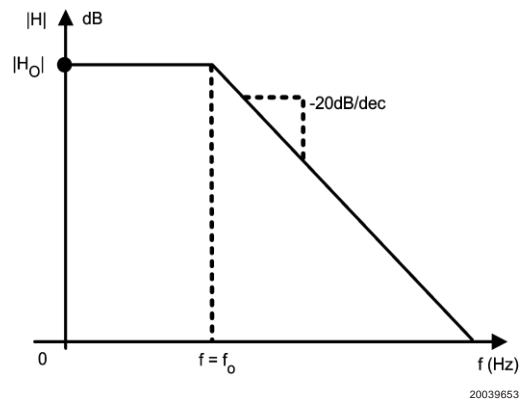
Now, substituting  $\omega = 2\pi f$ , so that the calculations are in  $f$ (Hz) and not  $\omega$ (rad/s), and setting the DC gain  $\left[ \frac{-R_2}{R_1} = H_o \right]$  and  $H = \frac{V_o}{V_i}$

$$H = H_o \left[ \frac{1}{j2\pi f C R_2 + 1} \right] \quad (10)$$

$$\text{Set: } f_o = \frac{1}{2\pi R_2 C}$$

$$H = H_o \left[ \frac{1}{1 + j(f/f_o)} \right] \quad (11)$$

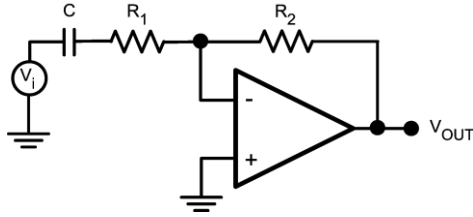
Low pass filters are known as lossy integrators because they only behave as an integrator at higher frequencies. Just by looking at the transfer function one can predict the general form of the bode plot. When the  $f/f_o$  ratio is small, the capacitor is in effect an open circuit and the amplifier behaves at a set DC gain. Starting at  $f_o$ , -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:


**FIGURE 4.**

**Application Note** (Continued)

**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:


**FIGURE 5.**

Writing the KCL for this circuit :

( $V_1$  denotes the voltage between C and  $R_1$ )

$$\frac{V_1 - V_i}{\frac{1}{j\omega C}} = \frac{V_1 - V^-}{R_1} \quad (12)$$

$$\frac{V^- + V_1}{R_1} = \frac{V^- + V_O}{R_2} \quad (13)$$

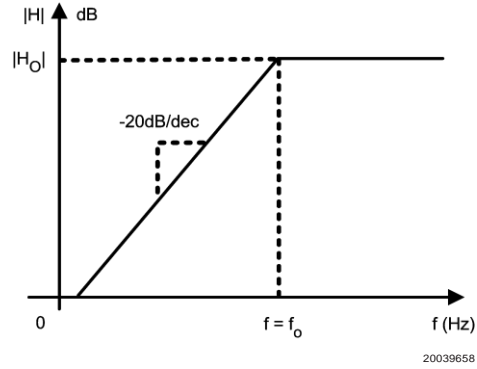
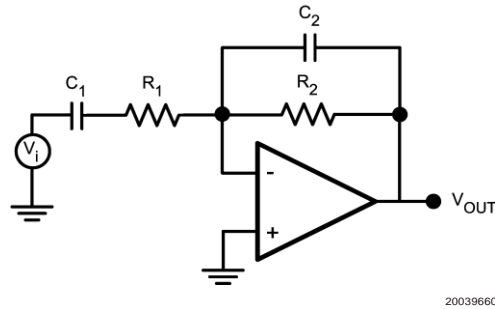
Solving these two equations to find the transfer function and using:

$$f_o = \frac{1}{2\pi R_2 C}$$

(high frequency gain)  $H_o = \frac{-R_2}{R_1}$  and  $H = \frac{V_O}{V_i}$   
 Which results:

$$H = H_o \frac{j(f/f_o)}{1 + j(f/f_o)} \quad (14)$$

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 in to 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  $H_o$ . The bode plot of the transfer function follows:


**FIGURE 6.**
**BAND PASS FILTER**

**FIGURE 7.**

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  $f_1 < f_2$ , 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.

$$H = H_o \frac{j(f/f_1)}{[1 + j(f/f_1)] [1 + j(f/f_2)]} \quad (15)$$

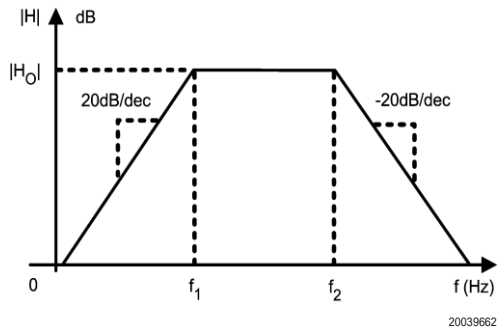
Where

$$f_1 = \frac{1}{2\pi R_1 C_1}$$

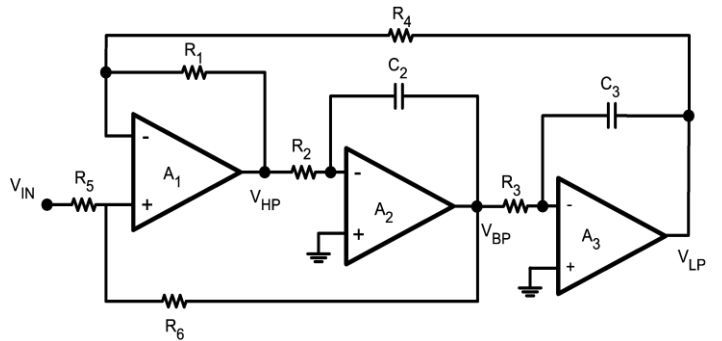
$$f_2 = \frac{1}{2\pi R_2 C_2}$$

$$H_o = \frac{-R_2}{R_1}$$

The transfer function is presented in the following figure.

**Application Note** (Continued)

**FIGURE 8.**
**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 in to a low pass filter. The outcome is a band pass signal, meaning the second amplifier 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.

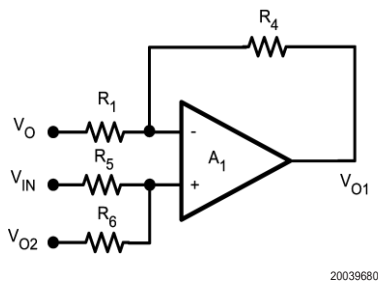


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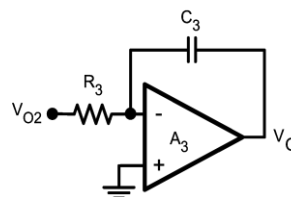
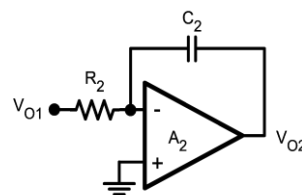
**FIGURE 9.**

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:



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For A<sub>1</sub> the relationship between input and output is:

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



### Application Note (Continued)

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

$$V_{O2} = \frac{-1}{s C_2 R_2} V_{O1}$$

And finally this relationship for  $A_3$  is as follows:

$$V_O = \frac{-1}{s C_3 R_3} V_{O2}$$

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

$$\frac{V_O}{V_{IN}} = \frac{\left[ \frac{R_1 + R_4}{R_1} \right] \left[ \frac{R_6}{R_5 + R_6} \right] \left[ \frac{1}{C_2 C_3 R_2 R_3} \right]}{s^2 + s \left[ \frac{1}{C_2 R_2} \right] \left[ \frac{R_5}{R_5 + R_6} \right] \left[ \frac{R_1 + R_4}{R_1} \right] + \left[ \frac{1}{C_2 C_3 R_2 R_3} \right]}$$

#### Highpass filter

$$\frac{V_{O1}}{V_{IN}} = \frac{s^2 \left[ \frac{R_1 + R_4}{R_1} \right] \left[ \frac{R_6}{R_5 + R_6} \right]}{s^2 + s \left[ \frac{1}{C_2 R_2} \right] \left[ \frac{R_5}{R_5 + R_6} \right] \left[ \frac{R_1 + R_4}{R_1} \right] + \left[ \frac{1}{C_2 C_3 R_2 R_3} \right]}$$

#### Bandpass Filter

$$\frac{V_{O2}}{V_{IN}} = \frac{s \left[ \frac{1}{C_2 R_2} \right] \left[ \frac{R_1 + R_4}{R_1} \right] \left[ \frac{R_6}{R_5 + R_6} \right]}{s^2 + s \left[ \frac{1}{C_2 R_2} \right] \left[ \frac{R_5}{R_5 + R_6} \right] \left[ \frac{R_1 + R_4}{R_1} \right] + \left[ \frac{1}{C_2 C_3 R_2 R_3} \right]}$$

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

$$\omega_c = \sqrt{\frac{1}{C_2 C_3 R_2 R_3}}$$

and

$$Q = \sqrt{\frac{C_2 R_2}{C_3 R_3} \left[ \frac{R_5 + R_6}{R_6} \right] \left[ \frac{R_1}{R_1 + R_4} \right]}$$

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.  $C_2 = C_3 = 1000\mu\text{F}$ . Also, choose  $R_1 = R_4 = 30\text{k}\Omega$ . Now Values of  $R_5$  and  $R_6$  need to be calculated. With the chosen values for the capacitors and resistors, Q reduces to:

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

or

$$\begin{aligned} R_5 &= 10R_6 \\ R_6 &= 1.5\text{k}\Omega \\ R_5 &= 15\text{k}\Omega \end{aligned}$$

Also, for  $f = 10\text{kHz}$ , value of center frequency is  $\omega_c = 2\pi f = 62.8\text{kHz}$ .

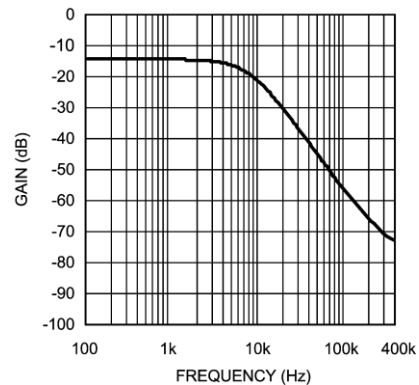
Using the expressions above, the appropriate resistor values will be  $R_2 = R_3 = 16\text{k}\Omega$ .

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

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

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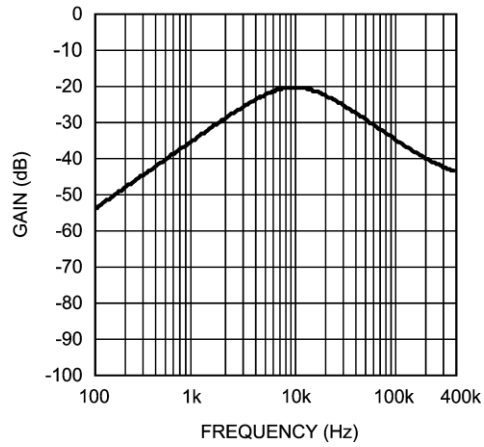
The following graphics show the frequency response of each of the stages when using HT2774 as the amplifier:



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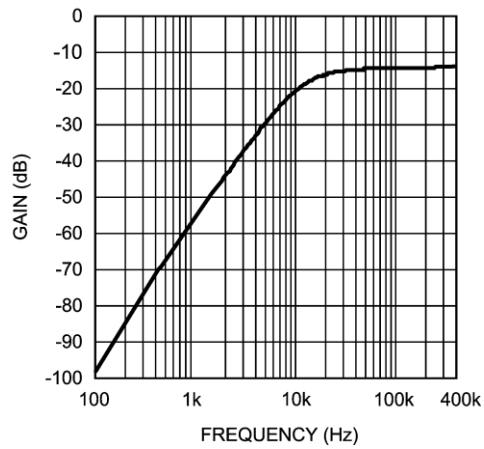
FIGURE 10. Lowpass Filter Frequency Response

**Application Note** (Continued)



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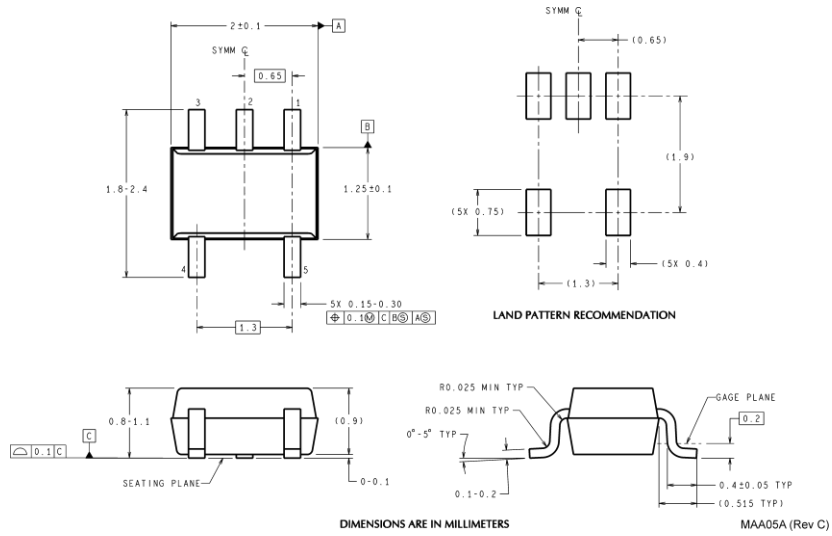
**FIGURE 11. Bandpass Filter Frequency Response**



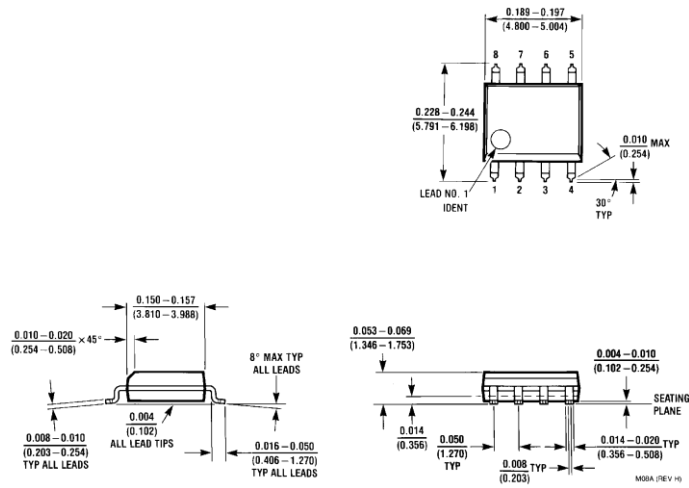
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**FIGURE 12. Highpass Filter Frequency Response**

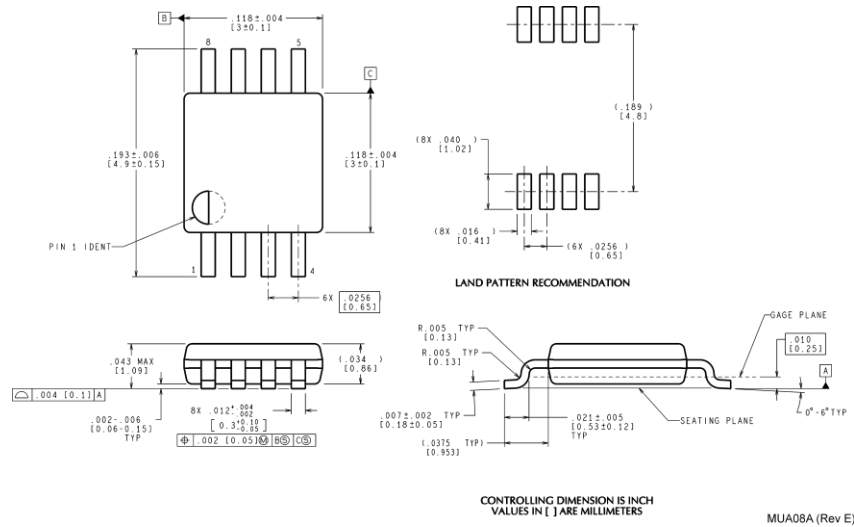
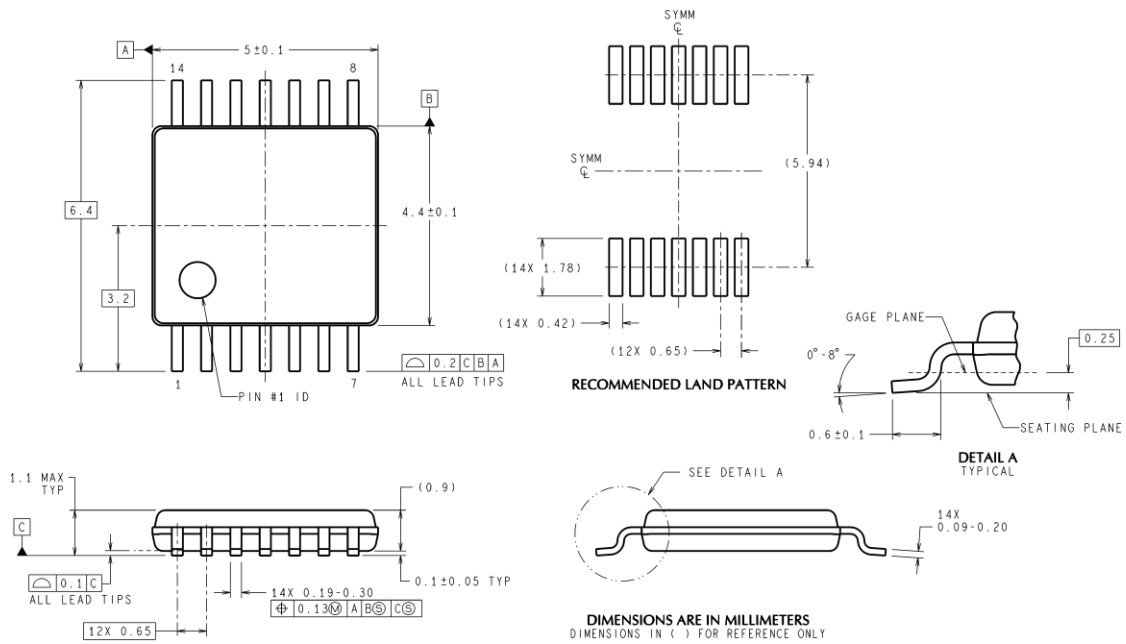
**Physical Dimensions** inches (millimeters)  
unless otherwise noted



**SC70-5**



**8-Pin SOIC**

**Physical Dimensions** inches (millimeters) unless otherwise noted (Continued)

**8-Pin MSOP**

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