

# CHOPPER-STABILIZED OPERATIONAL AMPLIFIER

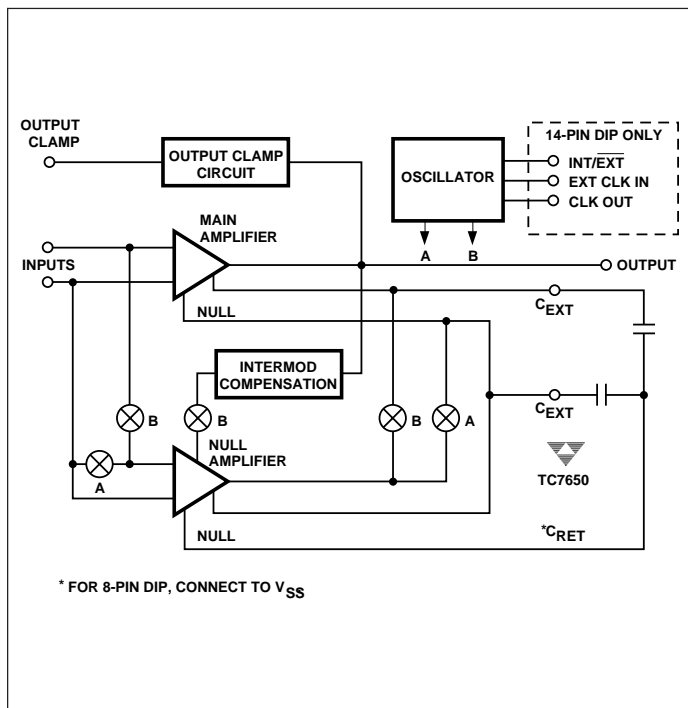
## FEATURES

- Low Input Offset Voltage ..... 0.7 $\mu$ V Typ
- Low Input Offset Voltage Drift ..... 0.05 $\mu$ V/ $^{\circ}$ C Max
- Low Input Bias Current ..... 10pA Max
- High Impedance Differential CMOS Inputs .... 10<sup>12</sup> $\Omega$
- High Open-Loop Voltage Gain ..... 120dB Min
- Low Input Noise Voltage ..... 2.0 $\mu$ Vp-p
- High Slew Rate ..... 2.5V/ $\mu$ sec
- Low-Power Operation ..... 20mW
- Output Clamp Speeds Recovery Time
- Compensated Internally for Stable Unity Gain Operation
- Direct Replacement for ICL7650
- Available in 8-Pin Dip and 14-Pin Dip

## ORDERING INFORMATION

Part No.	Package	Temperature Range	Max Vos
TC7650CPA	8-Pin Plastic DIP	0 $^{\circ}$ C to +70 $^{\circ}$ C	5 $\mu$ V
TC7650CPD	14-Pin Plastic DIP	0 $^{\circ}$ C to +70 $^{\circ}$ C	5 $\mu$ V

## FUNCTIONAL BLOCK DIAGRAM



## GENERAL DESCRIPTION

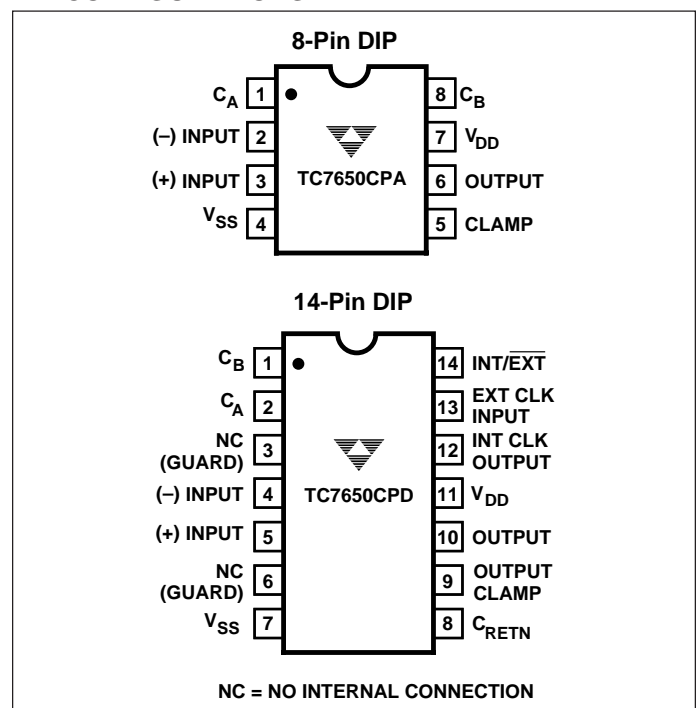
The TC7650 CMOS chopper-stabilized operational amplifier practically removes offset voltage error terms from system error calculations. The 5 $\mu$ V maximum  $V_{OS}$  specification, for example, represents a 15 times improvement over the industry-standard OP07E. The 50nV/ $^{\circ}$ C offset drift specification is over 25 times lower than the OP07E. The increased performance eliminates  $V_{OS}$  trim procedures, periodic potentiometer adjustment and the reliability problems caused by damaged trimmers.

The TC7650 performance advantages are achieved without the additional manufacturing complexity and cost incurred with laser or "zener zap"  $V_{OS}$  trim techniques.

The TC7650 nulling scheme corrects both DC  $V_{OS}$  errors and  $V_{OS}$  drift errors with temperature. A nulling amplifier alternately corrects its own  $V_{OS}$  errors and the main amplifier  $V_{OS}$  error. Offset nulling voltages are stored on two user-supplied external capacitors. The capacitors connect to the internal amplifier  $V_{OS}$  null points. The main amplifier input signal is never switched. Switching spikes are not present at the TC7650 output.

The 14-pin dual-in-line package (DIP) has an external oscillator input to drive the nulling circuitry for optimum noise performance. Both the 8 and 14-pin DIPs have an output voltage clamp circuit to minimize overload recovery time.

## PIN CONFIGURATIONS



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## TC7650

### ABSOLUTE MAXIMUM RATINGS\*

Total Supply Voltage ( $V_{DD}$ to $V_{SS}$ )	18V
Input Voltage ( $V_{DD} + 0.3V$ ) to ( $V_{SS} - 0.3V$ )	
Storage Temperature Range	-65°C to +150°C
Lead Temperature (Soldering, 10 sec)	300°C
Voltage on Oscillator Control Pins	$V_{DD}$ to $V_{SS}$
Output Short Circuit Duration	Indefinite
Current Into Any Pin	10mA
While Operating (Note 3)	100 $\mu$ A
Operating Temperature Range	
C Device	0°C to +70°C

### Package Power Dissipation ( $T_A \leq 70^\circ\text{C}$ )

8-Pin Plastic DIP	730mW
14-Pin Plastic DIP	800mW

\*Static-sensitive device. Unused devices must be stored in conductive material. Protect devices from static discharge and static fields. Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. These are stress ratings only and functional operation of the device at these or any other conditions above those indicated in the operational sections of the specifications is not implied. Exposure to Absolute Maximum Rating Conditions for extended periods may affect device reliability.

### ELECTRICAL CHARACTERISTICS: $V_{DD} = +5V$ , $V_{SS} = -5V$ , $C_A = C_B = 0.1\mu\text{F}$ , $T_A = 25^\circ\text{C}$ , unless otherwise indicated.

Symbol	Parameter	Test Conditions	Min	Typ	Max	Units
<b>Input</b>						
$V_{OS}$	Input Offset Voltage	$T_A = +25^\circ\text{C}$ Over Operating Temp Range	—	$\pm 0.7$ $\pm 1.0$	$\pm 5$ —	$\mu\text{V}$
$\Delta V_{OS}/\Delta T$	Input Offset Voltage Average Temperature Coefficient	Operating Temperature Range	—	0.01	0.05	$\mu\text{V}/^\circ\text{C}$
	Offset Voltage vs. Time		—	100	—	nV/ month
$I_{BIAS}$	Input Bias Current	$T_A = +25^\circ\text{C}$ $0^\circ\text{C} \leq T_A \leq +70^\circ\text{C}$ $-25^\circ\text{C} \leq T_A \leq +85^\circ\text{C}$	—	1.5 35 100	10 150 400	pA pA pA
$I_{OS}$	Input Offset Current		—	0.5	—	pA
$e_{NP-P}$	Input Noise Voltage	$R_S = 100\Omega$ , 0 to 10Hz	—	2	—	$\mu\text{V}_{P-P}$
$I_N$	Input Noise Current	$f = 10\text{ Hz}$	—	0.01	—	$\text{pA}/\sqrt{\text{Hz}}$
$R_{IN}$	Input Resistance		—	$10^{12}$		$\Omega$
CMVR	Common-Mode Voltage Range		-5	-5.2 to +2	+1.6	V
CMRR	Common-Mode Rejection Ratio	CMVR = -5V to +1.5V	120	130	—	dB
<b>Output</b>						
A	Large Signal Voltage Gain	$R_L = 10\text{k}\Omega$	120	130	—	dB
$V_{OUT}$	Output Voltage Swing (Note 2)	$R_L = 10\text{k}\Omega$ $R_L = 100\text{k}\Omega$	$\pm 4.7$ —	$\pm 4.85$ $\pm 4.95$	— —	V V
	Clamp ON Current	$R_L = 100\text{k}\Omega$ (Note 1)	25	70	200	$\mu\text{A}$
	Clamp OFF Current	$-4\text{V} < V_{OUT} < +4\text{V}$ (Note 1)	—	1	—	pA
<b>Dynamic</b>						
$B_W$	Unity-Gain Bandwidth	Unity Gain (+1)	—	2.0	—	MHz
$S_R$	Slew Rate	$C_L = 50\text{ pF}$ , $R_L = 10\text{k}\Omega$	—	2.5	—	V/ $\mu\text{sec}$
$t_R$	Rise Time		—	0.2	—	$\mu\text{sec}$
	Overshoot		—	20	—	%
$f_{CH}$	Internal Chopping Frequency	Pins 12–14 Open (DIP)	120	200	375	Hz

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**ELECTRICAL CHARACTERISTICS:**  $V_{DD} = +5V$ ,  $V_{SS} = -5V$ ,  $C_A = C_B = 0.1\mu F$ ,  $T_A = 25^\circ C$ , unless otherwise specified.

Symbol	Parameter	Test Conditions	Min	Typ	Max	Units
<b>Supply</b>						
$V_{DD}, V_{SS}$	Operating Supply Range		4.5	—	16	V
$I_S$	Supply Current	No Load	—	2	3.5	mA
PSRR	Power Supply Rejection Ratio	$V_S = \pm 3V$ to $\pm 8V$	120	130		dB

- NOTES:**
1. See "Output Clamp" discussion.
  2. Output clamp not connected. See typical characteristics curves for output swing versus clamp current characteristics.
  3. Limiting input current to 100 $\mu A$  is recommended to avoid latch-up problems.

## Theory of Operation

Figure 1 shows the major elements of the TC7650. There are two amplifiers (the main amplifier and the nulling amplifier), and both have offset-null capability. The main amplifier is connected full-time from the input to the output. The nulling amplifier, under the control of the chopping frequency oscillator and clock circuit, alternately nulls itself and the main amplifier. Two external capacitors provide the required storage of the nulling potentials and the necessary nulling-loop time constants. The nulling arrangement operates over the full common-mode and power-supply ranges, and is also independent of the output level, thus giving exceptionally high CMRR, PSRR, and  $A_{VOL}$ .

Careful balancing of the input switches minimizes chopper frequency charge injection at the input terminals, and the feed-forward-type injection into the compensation capacitor that can cause output spikes in this type of circuit.

The circuit's offset voltage compensation is easily shown. With the nulling inputs shorted, a voltage almost identical to the nulling amplifier offset voltage is stored on  $C_A$ . The effective offset voltage at the null amplifier input is:

$$V_{OSE} = \frac{1}{A_N + 1} V_{OSN} \quad (1)$$

After the nulling amplifier is zeroed, the main amplifier is zeroed; the A switches open and B switches close.

The output voltage equation is:

$$V_{OUT} = A_M [V_{OSM} + (V^+ - V^-) + A_N(V^+ - V^-) + A_N V_{OSE}] \quad (2)$$

Substituting (1)  $\rightarrow$  (2) and assuming  $A_N \gg 1$ :

$$V_{OUT} = A_M A_N \left[ (V^+ - V^-) + \frac{V_{OSM} + V_{OSN}}{A_N} \right] \quad (3)$$

As desired, the device offset voltages are reduced by the high open-loop gain of the nulling amplifier.

## Output Stage/Loading

The output circuit is a high-impedance stage (approximately 18k $\Omega$ ). With loads less than this, the chopper amplifier behaves in some ways like a transconductance amplifier whose open-loop gain is proportional to load resistance. For example, the open-loop gain will be 17dB lower with a 1k $\Omega$  load than with a 10k $\Omega$  load. If the amplifier is used strictly for DC, the lower gain is of little consequence, since the DC gain is typically greater than 120dB, even with a 1k $\Omega$  load. In wideband applications, the best frequency response will be achieved with a load resistor of 10k $\Omega$  or higher. This results in a smooth 6 dB/octave response from 0.1Hz to 2 MHz, with phase shifts of less than 10 $^\circ$  in the transition region, where the main amplifier takes over from the null amplifier. The clock frequency sets the transition region.

## Intermodulation

Previous chopper-stabilized amplifiers have suffered from intermodulation effects between the chopper frequency and input signals. These arise because the finite AC gain of the amplifier results in a small AC signal at the input. This is seen by the zeroing circuit as an error signal, which is chopped and fed back, thus injecting sum and difference frequencies, and causing disturbances to the gain and phase versus frequency characteristics near the chopping frequency. These effects are substantially reduced in the TC7650 by feeding the nulling circuit with a dynamic current corresponding to the compensation capacitor current in such a way as to cancel that portion of the input signal due to a finite AC gain. The intermodulation and gain/phase disturbances are held to very low values, and can generally be ignored.

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## TC7650

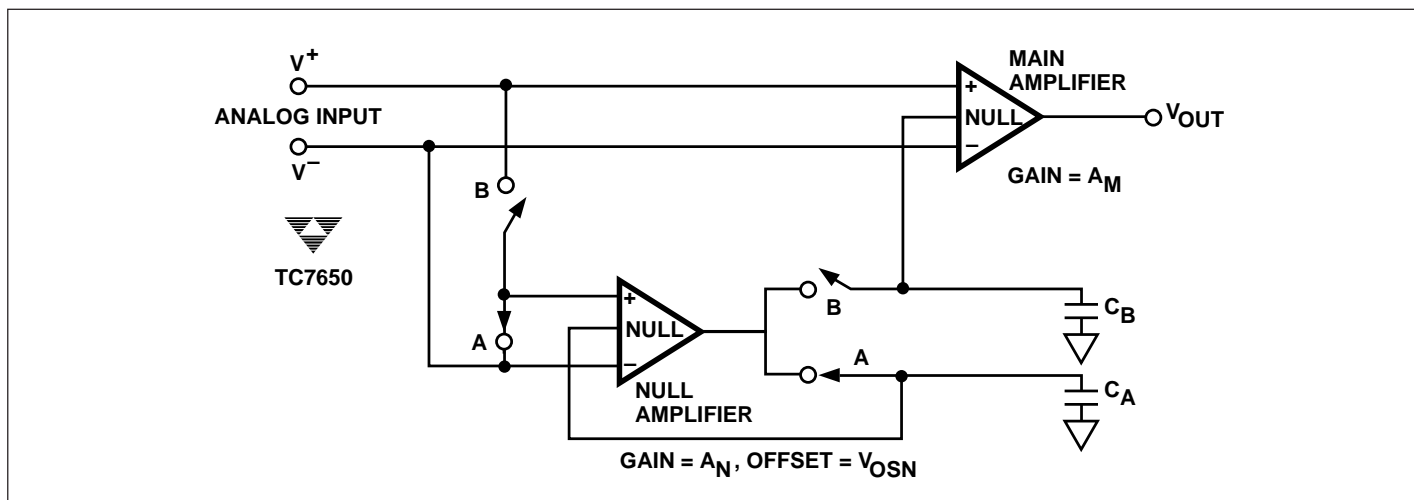


Figure 1. TC7650 Contains a Nulling and Main Amplifier. Offset Correction Voltages Are Stored on Two External Capacitors.

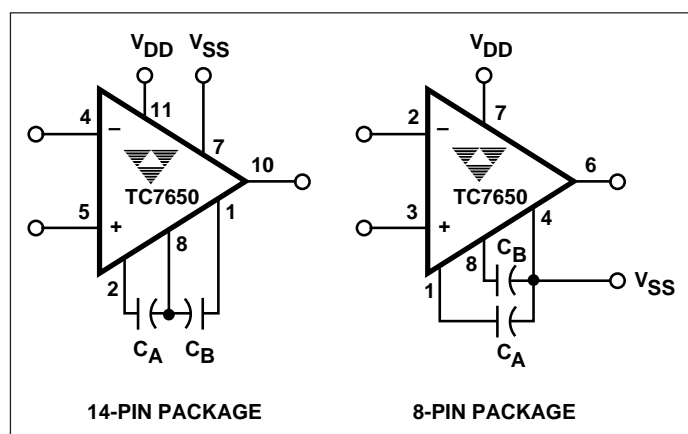


Figure 2. Nulling Capacitor Connection

### Nulling Capacitor Connection

The offset voltage correction capacitors are connected to  $C_A$  and  $C_B$ . The common capacitor connection is made to  $V_{SS}$  (pin 4) on the 8-pin packages and to capacitor return ( $C_R$ , pin 8) on the 14-pin packages. The common connection should be made through a separate PC trace or wire to avoid voltage drops. The capacitors outside foil, if possible, should be connected to  $C_R$  or  $V_{SS}$ .

### Clock Operation

The internal oscillator is set for a 200Hz nominal chopping frequency on both the 8- and 14-pin DIPs. With the 14-pin DIP TC7650, the 200Hz internal chopping frequency is available at the internal clock output (pin 12). A 400Hz nominal signal will be present at the external clock input pin (pin 13) with  $\text{INT}/\overline{\text{EXT}}$  high or open. This is the internal clock signal before a divide-by-two operation.

The 14-pin DIP device can be driven by an external clock. The  $\text{INT}/\overline{\text{EXT}}$  input (pin 14) has an internal pull-up and may be left open for internal clock operation. If an external clock is used,  $\text{INT}/\overline{\text{EXT}}$  must be tied to  $V_{SS}$  (pin 7) to disable the internal clock. The external clock signal is applied to the external clock input (pin 13).

The external clock amplitude should swing between  $V_{DD}$  and ground for power supplies up to  $\pm 6V$  and between  $V^+$  and  $V^+ - 6V$  for higher supply voltages.

At low frequencies the external clock duty cycle is not critical, since an internal divide-by-two gives the desired 50% switching duty cycle. The offset storage correction capacitors are charged only when the external clock input is high. A 50% to 80% external clock positive duty cycle is desired for frequencies above 500Hz to guarantee transients settle before the internal switches open.

The external clock input can also be used as a strobe input. If a strobe signal is connected at the external clock input so that it is LOW during the time an overload signal is applied, neither capacitor will be charged. The leakage currents at the capacitors pins are very low. At 25°C a typical TC7650 will drift less than 10 $\mu$ V/sec.

### Output Clamp

Chopper-stabilized systems can show long recovery times from overloads. If the output is driven to either supply rail, output saturation occurs. The inputs are no longer held at a "virtual ground." The  $V_{OS}$  null circuit treats the differential signal as an offset and tries to correct it by charging the external capacitors. The nulling circuit also saturates. Once the input signal returns to normal, the response time is lengthened by the long recovery time of the nulling amplifier and external capacitors.

Through an external clamp connection, the TC7650

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eliminates the overload recovery problem by reducing the feedback network gain before the output voltage reaches either supply rail.

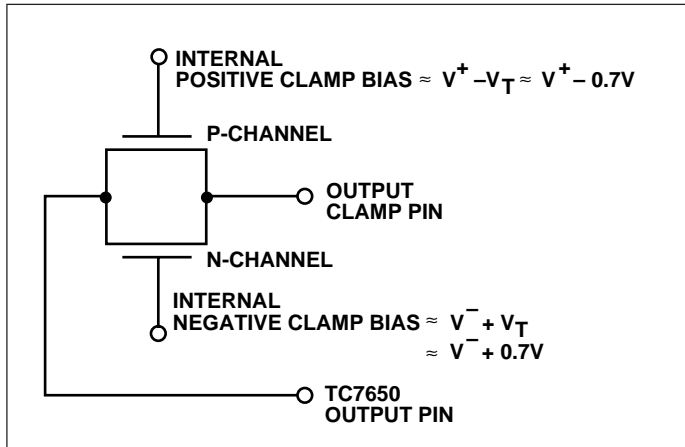


Figure 3. Internal Clamp Circuit

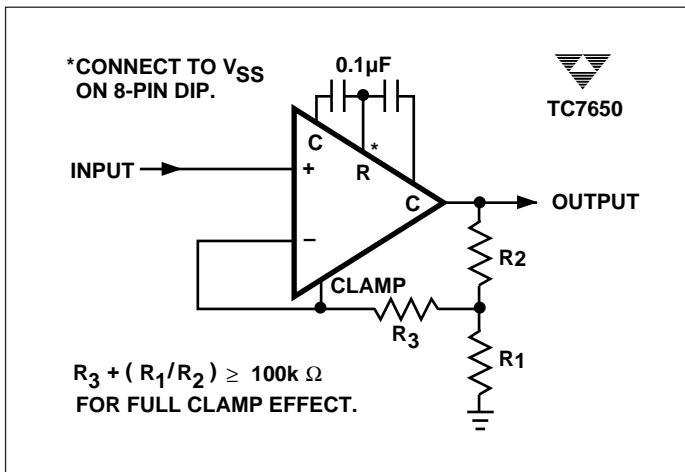


Figure 4. Noninverting Amplifier With Optional Clamp

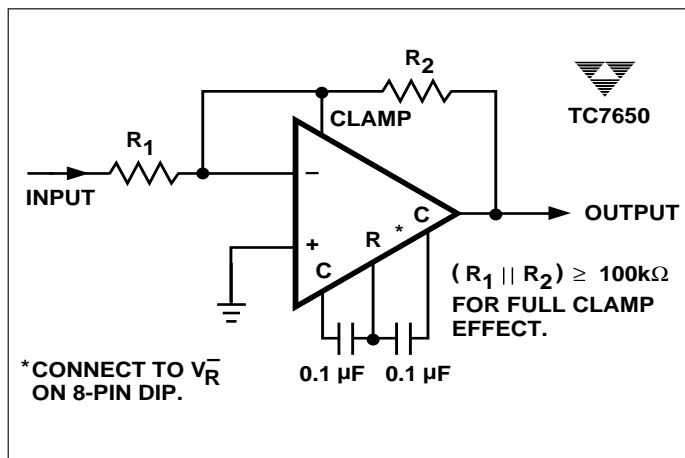


Figure 5. Inverting Amplifier with Optional Clamp

The output clamp circuit is shown in Figure 3, with typical inverting and noninverting circuit connections shown in Figures 4 and 5. Output voltage versus clamp circuit current characteristics are shown in the typical operating curves. For the clamp to be fully effective, the impedance across the clamp output should be greater than 100kΩ.

## Latch-Up Avoidance

Junction-isolated CMOS circuits inherently include a parasitic 4-layer (p-n-p-n) structure which has characteristics similar to an SCR. Under certain circumstances this junction may be triggered into a low-impedance state, resulting in excessive supply current. To avoid this condition, no voltage greater than 0.3V beyond the supply rails should be applied to any pin. In general, the amplifier supplies must be established either at the same time or before any input signals are applied. If this is not possible, the drive circuits must limit input current flow to under 0.1mA to avoid latch-up.

## Thermoelectric Potentials

Precision DC measurements are ultimately limited by thermoelectric potentials developed in thermocouple junctions of dissimilar metals, alloys, silicon, etc. Unless all junctions are at the same temperature, thermoelectric voltages, typically around 0.1µV/°C, but up to tens of µV/°C for some materials, will be generated. In order to realize the benefits extremely-low offset voltages provide, it is essential to take special precautions to avoid temperature gradients. All components should be enclosed to eliminate air movement, especially those caused by power-dissipating elements in the system. Low thermoelectric-coefficient connections should be used where possible and power supply voltages and power dissipation should be kept to a minimum. High-impedance loads are preferable, and separation from surrounding heat-dissipating elements is advised.

## Pin Compatibility

On the 8-pin mini-DIP TC7650, the external null storage capacitors are connected to pins 1 and 8. On most other operational amplifiers these are left open or are used for offset potentiometer or compensation capacitor connections.

For OP05 and OP07 operational amplifiers, the replacement of the offset null potentiometer between pins 1 and 8 by two capacitors from the pins to V<sub>SS</sub> will convert the OP05/07 pin configurations for TC7650 operation. For LM108 devices, the compensation capacitor is replaced by the external nulling capacitors. The LM101/748/709 pinouts are modified similarly by removing any circuit connections to pin 5. On the TC7650, pin 5 is the output clamp connection.

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Other operational amplifiers may use this pin as an offset or compensation point.

The minor modifications needed to retrofit a TC7650 into existing sockets operating at reduced power supply voltages make prototyping and circuit verification straightforward.

### Input Guarding

High impedance, low leakage CMOS inputs allow the TC7650 to make measurements of high-impedance sources. Stray leakage paths can increase input currents and decrease input resistance unless inputs are guarded. A guard is a conductive PC trace surrounding the input terminals. The ring connects to a low-impedance point at the same potential as the inputs. Stray leakages are absorbed by the low-impedance ring. The equal potential between ring and inputs prevents input leakage currents. Typical guard connections are shown in Figure 6.

The 14-pin DIP configuration has been specifically designed to ease input guarding. The pins adjacent to the inputs are unused.

In applications requiring low leakage currents, boards should be cleaned thoroughly and blown dry after soldering. Protective coatings will prevent future board contamination.

### Component Selection

The two required capacitors,  $C_A$  and  $C_B$ , have optimum values, depending on the clock or chopping frequency. For the preset internal clock, the correct value is  $0.1\mu\text{F}$ . To maintain the same relationship between the chopping frequency and the nulling time constant, the capacitor values should be scaled in proportion to the external clock, if used. High-quality film-type capacitors (such as Mylar) are preferred; ceramic or other lower-grade capacitors may be suitable in some applications. For fast settling on initial turn-on, low dielectric absorption capacitors (such as polypropylene) should be used. With ceramic capacitors, several seconds may be required to settle to  $1\mu\text{V}$ .

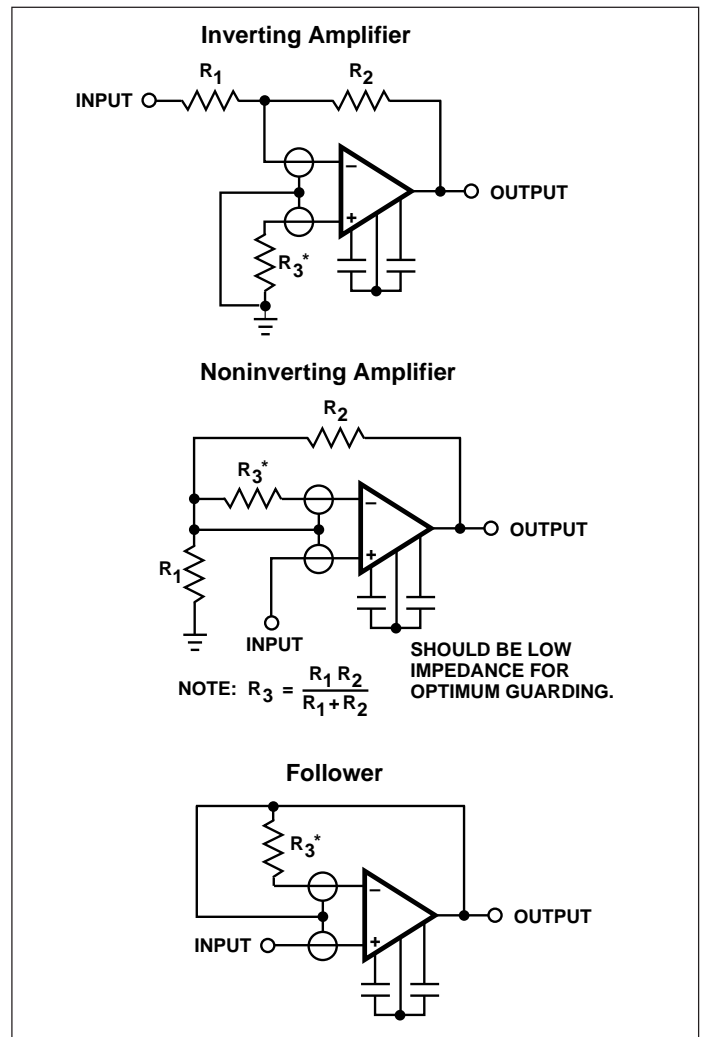
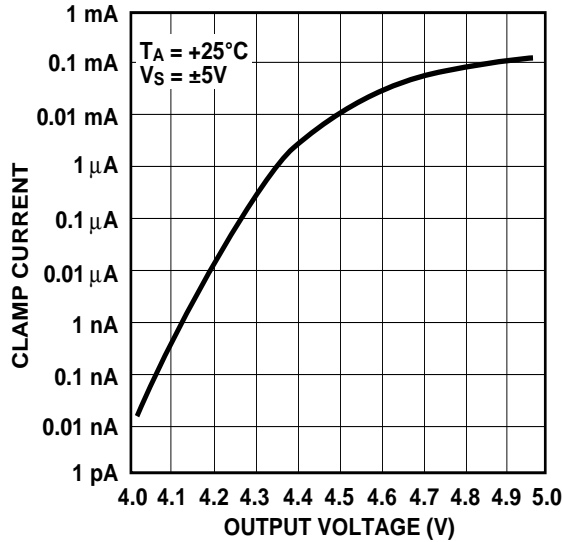


Figure 6. Input Guard Connection

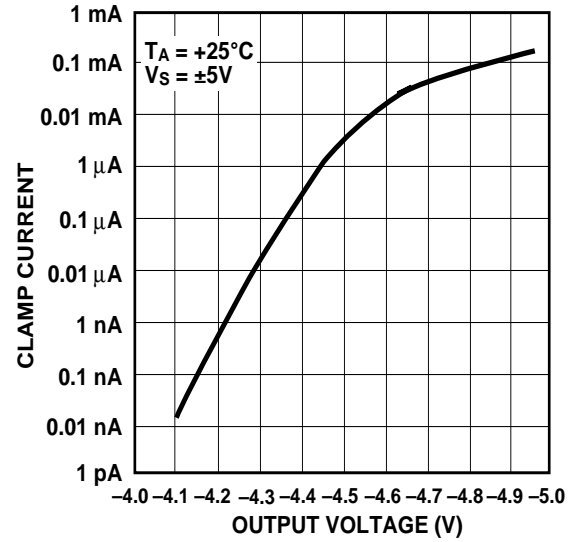


## TYPICAL CHARACTERISTICS

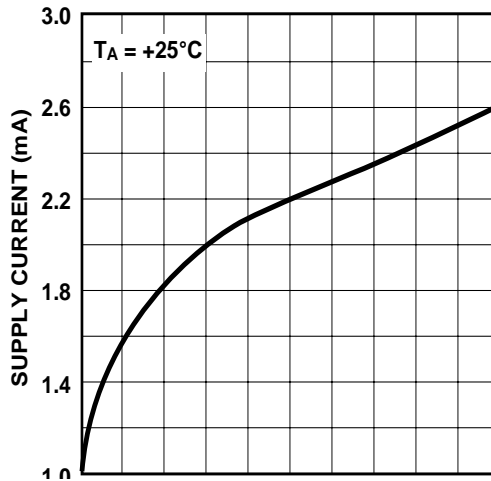
**Positive Clamp Current vs. Output Voltage**



**Negative Clamp Current vs. Output Voltage**



**Supply Current vs. Supply Voltage**



**Gain/Phase vs. Frequency**

