

Biasing and Decoupling Op Amps in Single Supply Applications

by Charles Kitchen

SINGLE OR DUAL SUPPLY?

Battery-powered op amp applications such as those found in automotive and marine equipment have only a single available power source. Other applications, such as computers, may operate from the ac power lines but still have only a single polarity power source, such as 5 V or 12 V dc. Therefore, it is often a practical necessity to power op amp circuits from a single polarity supply. But single supply operation does have its drawbacks: it requires additional passive components in each stage and, if not properly executed, can lead to serious instability problems.

COMMON PROBLEMS WITH RESISTOR BIASING

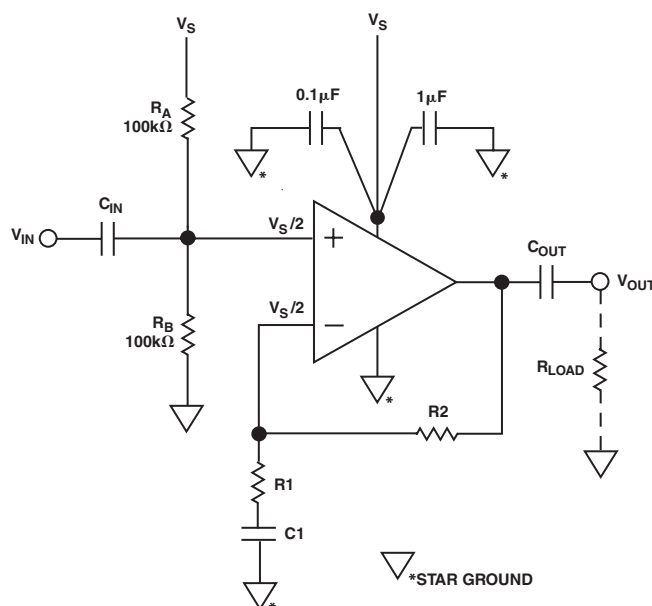
Single supply applications have inherent problems that are not usually found in dual supply op amp circuits. The fundamental problem is that an op amp is a dual supply device and so some type of biasing, using external components, must be used to center the op amp's output voltage at midsupply. This allows the maximum input and output voltage swing for a given supply voltage.

In some low gain applications, where input signals are very small, the op amp's output can be lifted above ground by only 2 V or 3 V. But in most cases, all clipping needs to be avoided and so the output needs to be centered around midsupply.

The circuit of Figure 1 shows a simple single supply biasing method. This noninverting, ac-coupled, amplifier circuit uses a resistor divider with two biasing resistors, R_A and R_B , to set the voltage on the noninverting input equal to $V_S/2$. As shown, the input signal, V_{IN} , is capacitively coupled to the noninverting input terminal.

This simple circuit has some serious limitations. One is that the op amp's power supply rejection is almost entirely gone, as any change in supply voltage will directly change the $V_S/2$ biasing voltage set by the resistor divider. Power Supply Rejection (PSR) is a very important (and frequently overlooked) op amp characteristic.

Since a one volt change on the supply line causes a one-half volt change at the output of the divider, the circuit's PSR is only 6 dB. So, the normally high power supply rejection provided by any modern op amp, which greatly reduces any ac signals (and power supply hum) from feeding into the op amp via its supply line, is now gone.



$$BW1 = \frac{1}{2\pi (1/2R_A) C_{IN}}$$

$$BW2 = \frac{1}{2\pi R_1 C_1}$$

$$BW3 = \frac{1}{2\pi R_{LOAD} C_{OUT}}$$

FOR $R_A = R_B$

FOR AC SIGNALS, $V_{OUT} = V_{IN} (1 + (R_2/R_1))$
WHERE $X_{C1} \ll R_1$

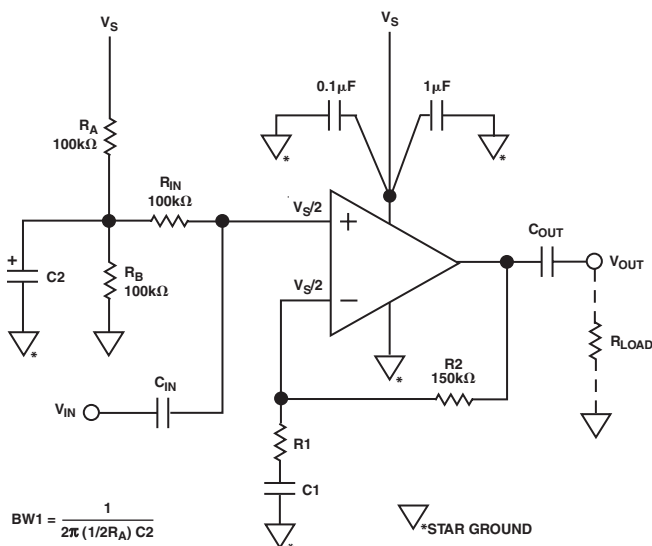
Figure 1. A Potentially Unstable Single Supply Op Amp Circuit

Even worse, instability often occurs in circuits where the op amp must supply large output currents into a load. Unless the power supply is well regulated (and well bypassed), large signal voltages will appear on the supply line. With the op amp's noninverting input referenced directly off the supply line, these signals will be fed directly back into the op amp often initiating "motor boating" or other forms of instability.

While the use of extremely careful layout, multicapacitor power supply bypassing, star grounds, and a printed circuit board "power plane," may provide circuit stability, it is far easier to reintroduce some reasonable amount of power supply rejection into the design.

DECOUPLING THE BIASING NETWORK FROM THE SUPPLY

The solution is to modify the circuit, as shown in Figure 2. The tap point on the voltage divider is now bypassed for ac signals by capacitor C2, restoring some ac PSR. Resistor R_{IN} provides a dc return path for the V_S/2 reference voltage and also sets the circuit's (ac) input impedance.



$$BW1 = \frac{1}{2\pi (1/2R_A) C2}$$

$$BW2 = \frac{1}{2\pi R_{IN} C_{IN}}$$

$$BW3 = \frac{1}{2\pi R1 C1}$$

$$BW4 = \frac{1}{2\pi R_{LOAD} C_{OUT}}$$

FOR $R_A = R_B$ AND $BW1 = 1/10TH$ $BW2$,
 $BW3$, AND $BW4$

FOR AC SIGNALS, $V_{OUT} = V_{IN} (1 + (R2/R1))$
WHERE $X_{C1} \ll R1$

TO MINIMIZE INPUT BIAS CURRENT ERRORS,
 $R2$ SHOULD EQUAL $R_{IN} + (1/2 R_A)$

Figure 2. A Decoupled Single Supply Op Amp Biasing Circuit

Many published applications circuits show a 100 kΩ/100 kΩ voltage divider for R_A and R_B with a 0.1 μF or similar capacitance value for C2. However, the -3 dB bandwidth of this network is set by the parallel combination of R_A and R_B and Capacitor C2 and is equal to:

$$-3 \text{ dB BW} = \frac{1}{2\pi (50,000)(0.1 \times 10^{-6} \text{ Farads})} = 30 \text{ Hz}$$

Motor boating or other forms of instability can still occur, as the circuit has essentially no power supply rejection for frequencies below 30 Hz. So any signals below 30 Hz that are present on the supply line, can very easily find their way back to the + input of the op amp.

A practical solution to this problem is to increase the value of capacitor C2. It needs to be large enough to effectively bypass the voltage divider at all frequencies within the circuit's passband. A good rule of thumb is to set this pole at one-tenth the -3 dB input bandwidth, set by R_{IN}/C_{IN} and R1/C1.

Note that the dc circuit gain is unity. Even so, the op amp's input bias currents need to be considered. The R_A/R_B voltage divider adds considerable resistance in series with the op amp's positive input terminal, equal to the parallel combination of the two resistors. Maintaining the op amp's output close to midsupply requires "balancing" this resistance by increasing the resistance in the minus input terminal by an equal amount. Current feedback op amps often have unequal input bias currents, which further complicates the design.

Therefore, designing a single supply op amp circuit design that considers input bias current errors as well as power supply rejection, gain, input and output circuit bandwidth, etc., can become quite involved. However, the design can be greatly simplified by using a "cookbook" approach. For a common voltage feedback op amp operating from a 15 V or 12 V single supply, a resistor divider using two 100 kΩ resistors is a reasonable compromise between supply current consumption and input bias current errors. For a 5 V supply, the resistors can be reduced to a lower value such as 42 kΩ. Finally, some applications need to operate from the new 3.3 V standard. For 3.3 V applications, it is essential that the op amp be a "rail-to-rail" device and be biased very close to midsupply; the biasing resistors can be further reduced to a value of around 27 kΩ.

Note that current feedback op amps are typically designed for high frequency use and a low-pass filter is formed by R2 and stray circuit capacitance, which can severely reduce the circuit's 3 dB bandwidth. Therefore, current feedback op amps normally need to use a fairly low resistance value for R2. An op amp such as the AD811, which was designed for video speed applications, typically will have optimum performance using a 1 kΩ resistor for R2. Therefore, these types of applications need to use much smaller resistor values in the R_A/R_B voltage divider to minimize input bias current errors.

Instead of a bipolar device, the use of a modern FET input op amp will greatly reduce any input bias current errors unless the circuit is required to operate over a very wide temperature range. In that case, balancing the resistance in the op amp's input terminals is still a wise precaution.

Table I provides typical component values for the circuit of Figure 2 for several different gains and 3 dB bandwidths.

Table I. Typical Component Values for the Circuit of Figure 2
Where R_A = R_B = 100 kΩ, R_{IN} = 100 kΩ, and R2 = 150 kΩ

Gain	Input BW (Hz)	Output BW (Hz)	C _{IN} * (μF)	R1 (kΩ)	C1* (μF)	C2 (μF)	C _{OUT} (μF)	R _{LOAD} (kΩ)
10	10	10	0.3	16.5	1.5	3	0.2	100
20	10	10	0.3	7.87	3	3	0.2	100
10	50	50	0.1	16.5	0.3	0.6	0.05	100
101	20	20	0.2	1.5	6.8	2	0.1	100

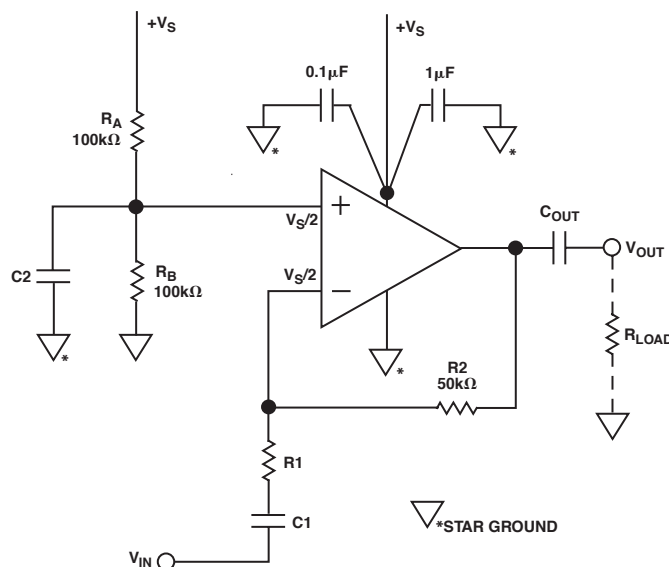
*Capacitance values rounded off to next highest common value. Since the C_{IN}/R_{IN} pole and C1/R1 poles are at the same frequency, and both affect the input BW, each capacitor is $\sqrt{2}$ larger than it would otherwise be for a single pole RC-coupled input. C2 is selected to provide a corner frequency of 1/10th that of the input BW.

Table II provides typical component values for several different gains and 3 dB bandwidths.

Table II. Typical Component Values for the Circuit of Figure 3
Where R2 = 50 kΩ and R_A = R_B = 100 kΩ

Gain	Input BW (Hz)	Output BW (Hz)	R1 (kΩ)	C1* (μF)	C2* (μF)	C _{OUT} (μF)	R _{LOAD} (kΩ)
10	10	10	2	8.2	0.5	0.2	100
20	10	10	1	20	0.5	0.2	100
10	50	50	2	2	0.1	0.05	100
100	20	20	1	8.2	0.3	0.1	100

*Capacitance values rounded off to next highest common value. Since the C1/R1 pole and C2/R_A/R_B poles are at the same frequency, and both affect the input BW, each capacitor is $\sqrt{2}$ larger than it would otherwise be for a single pole RC-coupled input.



$$BW1 = \frac{1}{2\pi (1/2 R_A) C2}$$

$$BW2 = \frac{1}{2\pi R1 C1}$$

$$BW3 = \frac{1}{2\pi R_{LOAD} C_{OUT}}$$

FOR R_A = R_B AND X_{C2} << X_{C1}

FOR AC SIGNALS, V_{OUT} = V_{IN} (R2/R1)
WHERE X_{C1} << R1

TO MINIMIZE INPUT BIAS CURRENT ERRORS,
R2 SHOULD EQUAL 1/2 R_A.

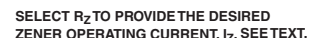
Figure 3. A Decoupled Single Supply Inverting Amplifier Circuit

Figure 3 shows a circuit similar to Figure 2, but for an inverting amplifier.

Although the resistor divider biasing technique is low cost, and always keeps the op amp's output voltage at $V_S/2$, the op amp's common-mode rejection is entirely dependent upon the R_C time constant formed by R_A/R_B and capacitor C2. Using a C2 value that provides at least 10 times the R_C time constant of the input R_C coupling network ($R1/C1$ and R_{IN}/C_{IN}) will help ensure a reasonable common-mode rejection ratio. With 100 k Ω resistors for R_A and R_B , practical values of C2 can be kept fairly small as long as the circuit bandwidth is not too low. However, another way to provide the necessary $V_S/2$ biasing for single supply operation is to use a Zener diode regulator. Just such a scheme is shown in Figure 4. Here, current flows through resistor R_Z to the Zener. Capacitor C_N helps prevent any Zener-generated noise from feeding into the op amp. Low noise circuits may need to use a larger value for C_N than the 10 μ F specified.

Within the operating limits of the Zener, the circuit of Figure 4 basically restores the op amp's power supply rejection. But this does not come without a price: the op amp's output is now at the Zener voltage rather than at $V_S/2$. If the power supply voltage drops, nonsymmetrical clipping can occur on large signals. Furthermore, the circuit now consumes more power. Finally, input bias currents still need to be considered. Resistors R_{IN} and R_2 should be close to the same value to prevent input bias currents from creating a large offset voltage error.

Figure 5 is an inverting amplifier circuit using the same Zener biasing method.



$$R_Z = \frac{+V_S - V_{ZENER}}{I_Z}$$

$$BW1 = \frac{1}{2\pi R_{IN} C_{IN}}$$

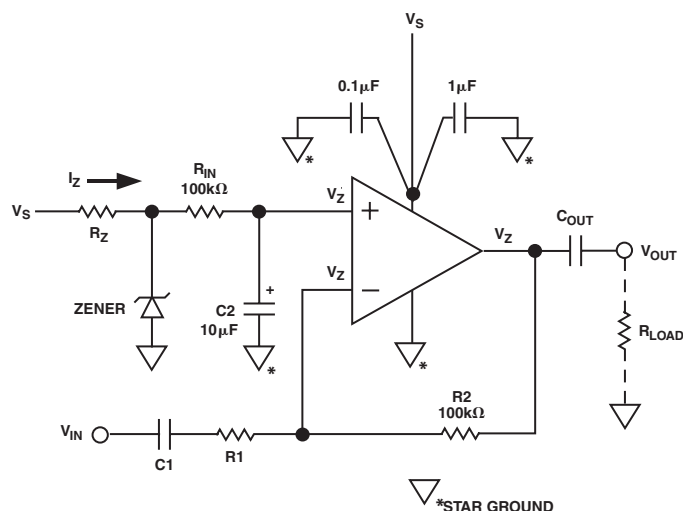
$$BW2 = \frac{1}{2\pi R1 C1}$$

$$BW3 = \frac{1}{2\pi R_{LOAD} C_{OUT}}$$

FOR AC SIGNALS, $V_{OUT} = V_{IN} (1 + (R2/R1))$
WHERE $X_{C1} \ll R1$

TO MINIMIZE INPUT BIAS CURRENT ERRORS,
R2 SHOULD EQUAL R_{IN} .

Figure 4. A Noninverting Single Supply Amplifier Using Zener Diode Biasing



SELECT R_Z TO PROVIDE THE DESIRED ZENER OPERATING CURRENT, I_Z . SEE TEXT.

$$R_Z = \frac{+V_S - V_{ZENER}}{I_Z}$$

$$BW1 = \frac{1}{2\pi R1 C1}$$

$$BW2 = \frac{1}{2\pi R_{IN} C2}$$

$$BW3 = \frac{1}{2\pi R_{LOAD} C_{OUT}}$$

FOR AC SIGNALS, $V_{OUT} = V_{IN} (R2/R1)$
WHERE $X_{C1} \ll R1$

TO MINIMIZE INPUT BIAS CURRENT ERRORS,
 $R2$ SHOULD EQUAL R_{IN} .

Figure 5. An Inverting Single Supply Amplifier Using Zener Diode Biasing

Table III can be used with circuits 4 and 5 to provide practical R_Z resistor values for use with some common Zener diodes. Note that for the lowest possible circuit noise, the optimum Zener current should be selected by referring to the Zener product data sheet.

Table III. Recommended R_Z Values and Motorola Zener Diode Part Numbers for Use with Figures 4 and 5

Supply Voltage (V)	Zener Voltage (V)	Zener Type	Zener Current (I_Z)	R_Z Value (Ω)
+15	7.5	1N4100	500 μ A	15 k
+15	7.5	1N4693	5 mA	1.5 k
+12	6.2	1N4627	500 μ A	11.5 k
+12	6.2	1N4691	5 mA	1.15 k
+9	4.3	1N4623	500 μ A	9.31 k
+9	4.3	1N4687	5 mA	931
+5	2.4	1N4617	500 μ A	5.23 k
+5	2.7	1N4682	5 mA	464

Tables IV and V provide practical component values for Figures 4 and 5 for several different circuit gains and bandwidths.

Table IV. Typical Component Values for the Circuit of Figure 4 Where $R_{IN} = R2 = 100$ k Ω and $C_N = 0.1$ μ F. Select R_Z from Table III

Gain	Input BW (Hz)	Output BW (Hz)	C_{IN}^* (μ F)	$R1$ (k Ω)	$C1^*$ (μ F)	C_{OUT} (μ F)	R_{LOAD} (k Ω)
10	10	10	0.3	11.0	2	0.2	100
20	10	10	0.3	5.23	4.7	0.2	100
10	50	50	0.1	11.0	0.47	0.05	100
101	20	20	0.2	1.0	15	0.1	100

*Capacitance values rounded off to next highest common value. Since the C_{IN}/R_{IN} pole and $C1/R1$ poles are at the same frequency, and both affect the input BW, each capacitor is $\sqrt{2}$ larger than it would otherwise be for a single pole R_C -coupled input.

Table V. Typical Component Values for the Circuit of Figure 5 Where $R_{IN} = R2 = 100$ k Ω . Select R_Z from Table III

Gain	Input BW (Hz)	Output BW (Hz)	$R1$ (k Ω)	$C1^*$ (μ F)	$C2^*$ (μ F)	C_{OUT} (μ F)	R_{LOAD} (k Ω)
10	10	10	10	2.7	0.2	0.2	100
20	10	10	5	4.7	0.2	0.2	100
10	50	50	10	0.5	0.05	0.05	100
100	20	20	1	12	0.1	0.1	100

*Capacitance values rounded off to next highest common value. Since the $C1/R1$ pole and $C2/R_{IN}$ poles are at the same frequency, and both affect the input BW, each capacitor is $\sqrt{2}$ larger than it would otherwise be for a single pole R_C -coupled input.

OP AMP BIASING USING A LINEAR VOLTAGE REGULATOR

For op amp circuits operating from the new 3.3 V standard, a 1.65 V biasing voltage is needed. Zener diodes are commonly available only down to 2.4 V. The easiest way to provide this biasing voltage is to use a linear voltage regulator, such as the ADM663A or ADM666A devices. This is shown in Figure 6.

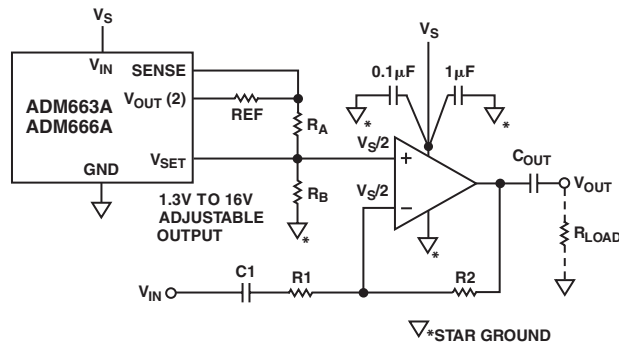


Figure 6. An Op Amp Single Supply Biasing Circuit Using A Linear Voltage Regulator

Although a Zener diode is usually the cheapest voltage regulator available, a linear voltage regulator has lower drift over temperature than a Zener and far less noise.

Resistors R_A and R_B are selected to provide the desired $V_S/2$ voltage reference; consult AD663A datasheet.

DC-COUPLED BATTERY-POWERED CIRCUITS

So far, only ac-coupled op amp circuits have been discussed. Although with the use of suitably large input and output coupling capacitors, an ac-coupled circuit can operate at frequencies well below 1 Hz, some applications require a true dc response.

Battery-powered applications permit the use of a “phantom ground” circuit as shown in Figure 7. This provides dual supply voltages, both positive and negative with respect to ground, from a single battery. An op amp is used to buffer the output of a $V_S/2$ voltage divider. If a low voltage battery such as 3.3 V is used, the op amp should be a “rail-to-rail” device and able to operate effectively from this supply voltage. The op amp also needs to be able to supply an output current large enough to power the load circuit. Capacitor C2 bypasses the voltage divider output enough to prevent any resistor noise from feeding into the op amp. This capacitor does not need to provide power supply rejection because the load current flows directly to ground and so any signal currents flow equally from both sides of the battery.

Resistors R_A and R_B are selected to provide the desired $V_S/2$ voltage reference; consult AD663A datasheet.

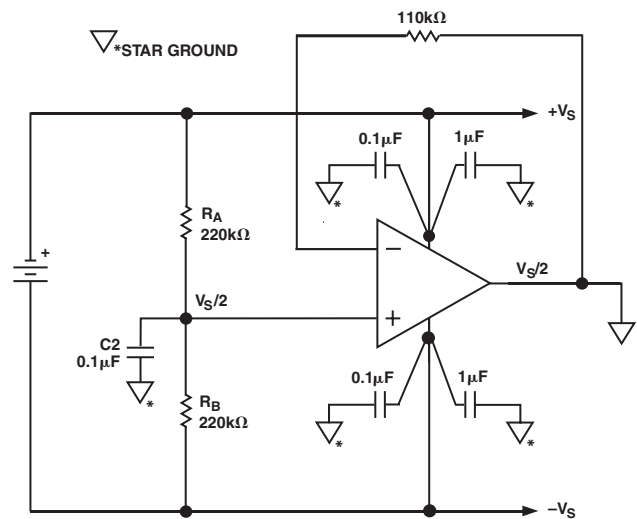


Figure 7. Using an Op Amp to Provide a “Phantom Ground” for Battery-Powered DC-Coupled Applications

NOISE ISSUES

Some op amp applications need a low noise amplifier and low noise amplifier circuits require low resistance values in the signal path. Johnson (resistor) noise equals 4 nV times the square root of the resistance value in kΩ. While the Johnson noise of a 1 kΩ resistor is only 4 nV/√Hz, this increases to 18 nV/√Hz for a 20 kΩ resistor and 40 nV/√Hz for a 100 kΩ resistor. Even though the R_A/R_B resistor divider is bypassed to ground with a capacitor (C2), these resistors set a limit on the minimum value that can be used for the op amp’s feedback resistor and, the larger this is, the greater the Johnson noise. So low noise applications need to use much smaller op amp biasing resistor values than the 100 kΩ specified here. However, lower value resistors in the divider mean higher power supply current and reduced battery life.

Fortunately, the Zener diode biasing method supplies $V_S/2$ without the need for large resistors. As long as the Zener is bypassed to keep its noise out of the circuit, both noise and supply current can be kept low. The use of a linear voltage regulator is even better, as its noise and output impedance are both very low.

CIRCUIT TURN-ON TIME ISSUES

One final issue that needs to be considered is circuit turn-on time. The approximate turn-on time will equal the R_C time constant of the lowest BW filter being used.

The circuits shown here all call for the R_A/R_B , C2 voltage divider network to have a 10 times longer time constant than that of the input or output circuit. This is to simplify the circuit design (since up to three different R_C poles set the input BW). This long time constant also helps keep the biasing network from “turning on” before the op amp’s input and output networks and, therefore, the op amp’s output gradually climbs from zero volts to $V_S/2$ without “railing” to the positive supply line. The value supplied by this table is for a 3 dB corner frequency that is 1/10th that of $R1/C1$ and R_{LOAD}/C_{OUT} . For example: in Figure 2, for a circuit BW of 10 Hz and a gain of 10, Table I recommends a C2 value of 3 μ F, which provides a 3 dB bandwidth of 1 Hz.

Fifty thousand ohms (the parallel combination of R_A and R_B) times 3 microFarads equals an R_C time constant of 0.15 seconds. So the op amp’s output will take 0.15 seconds (approximately) to settle to $V_S/2$. The input and output R_C networks will charge up ten times faster.

In some applications, where the circuit’s –3 dB low frequency bandwidth is very low, the circuit turn-on time may become excessively long. In that case, a Zener biasing method may be a better choice.

INPUT “HEADROOM” CONSIDERATIONS

Some specialty op amps are designed for low voltage operation. When these are operated from a low voltage, single supply, such as 5 V or 3.3 V, input headroom limitations may be introduced. This can happen if the amplifier’s input stage does not limit symmetrically.

For example: the AD8061 op amp is designed to have an input common-mode voltage range that extends all the way down to “ground” (or the negative supply line). However, its inputs can only swing to within 1.8 V of the positive supply voltage without introducing dc errors or limiting device bandwidth. So, if this amplifier is operated from a single 5V supply and the amplifier’s positive input is biased at $V_S/2$ (2.5 V), the input voltage can swing in the negative direction a full 2.5 V (down to zero volts). But, in the positive direction, it can only swing 1 V before clipping.

Note that this is not a problem if the amplifier is being operated at a gain of 2.5 or higher, as the maximum output swing (± 2.5 V) will be reached before the input stage limits. However, if the amplifier is being operated at a lower gain, the positive input needs to be biased below $V_S/2$, to allow symmetrical input stage limiting. In the case of the AD8061, biasing the positive input at 1.5 V will allow a 3 V p-p input swing without clipping. Refer to the individual product data sheet to determine the optimum single supply biasing voltage.

Table VI. Rail-to-Rail Op Amps Recommended for New Designs

Type	Single	Dual	Quad
High Speed	AD8031 AD8061 AD8051 AD8063	AD8032 AD8062 AD8052 AD823	AD8054
High Output	AD8591 AD8531	AD8592 AD8532	AD8594 AD8534
JFET Input	AD820	AD822	AD824
Auto Zero	AD8551	AD8552	AD8554
Digital Trim	AD8601	AD8602	AD8604
Low Noise	OP184 OP162 AD8605 AD8628	OP284 OP262 AD8606	OP484 OP462 AD8608
Low Power	OP196 AD8541	OP296 AD8542	OP496 AD8544
Precision	OP777	OP727	OP747

