"Design Considerations when migrating from split to single supply amplifiers"

Written by: Scott Gustafson
Systems Engineer
Texas Instruments
(972) 480-3473

1. Introduction

As companies are continuously striving to develop more portable and cost effective products, the number of analog engineers being asked to migrate their split supply amplifiers to a single supply voltage is increasing. The use of amplifiers with a single supply voltage introduces some issues that didn't necessarily need to be considered with split supply designs. Violation of the common-mode input range is one of the most common mistakes. Therefore, proper input signal biasing using a dc bias voltage is a major key to success in single supply systems. This dc bias voltage (sometimes called a virtual ground) can be generated using several methods; each with its own advantages and disadvantages.

2. Split supply and single supply amplifiers…is there a difference?

Many questions arise when the discussion of whether or not amplifiers specified for split supply can be operated with a single supply and vice versa. Actually, the overwhelming majority of operational amplifiers on the market today can be used with either. The amplifier can be powered by any combination of split or single supply voltages as long as the total voltage across the amplifier doesn't exceed the absolute maximum ratings. The only real differences between split supply amplifiers and those designed for single supply operation are their common-mode input voltage range and output voltage swing. The common-mode input voltage range of an amplifier is defined as the range of input voltages common to both terminals that if exceeded may cause the op amp to cease functioning properly. It is usually symbolized in the datasheet as V_{ICR} or V_{CM}. The output voltage range (V_O) can be broken up into a high level (V_{OH}) and low level value (V_{OL}) and defines the maximum voltage range the output of the amplifier can swing.

A split supply amplifier typically has a common-mode input voltage range and output voltage swing that extends to within a few volts of the supply rails. Figure 1a shows a TLE2027 configured as a voltage follower. Operating from +/-5 V supplies, the amplifier is able to swing +/ 3 V on the input and output; therefore providing 6 volts of dynamic range. If a small signal biased just above ground is fed into the input, the amplifier will operate on it without issue. Now powering the amplifier with a +10 V single supply, the user will also get 6 volts of usable signal range, since the total voltage applied to the amplifier is the same. However, the common-mode input voltage range and output voltage now swings from +2 V to +8 V. The same signal is now outside of the linear operating range of the amplifier and therefore will not be operated on properly.

A single supply amplifier is designed so the common-mode input voltage range and output voltage swing includes the negative rail (or ground in a single supply system) and extends to within one or two volts of the positive rail. There are also rail-to-rail amplifiers available that have a V_{ICR} and V_O that includes both supply rails. Figure 1b shows the TLC2272 rail-to-rail output amplifier in the same voltage follower configuration. The common-mode input voltage range is 0V to 9V and the output swings from 0 V to +10V with a +10 V single supply (or V_{ICR}= –5 V to 4V and V_O=-5V to 5V with +/-5 V supplies). Therefore, any signals near ground are still within the operating region of the amplifier and will be passed.

3. Biasing of the input signal in single supply applications

One of the most frequent calls we receive at the factory is from split supply amplifier users having problems using an amplifier with a single supply voltage. The root of the problem usually comes from the violation of the common-mode input voltage specifications of the amplifier. Proper biasing of the input signal, especially in single supply applications is extremely important.

Figure 2 shows the TLC2272 in an inverting configuration with a gain of -1. The positive input pin and load are tied to ground. The input waveform is a 4 V peak-to-peak, 100kHz-sine wave referenced to ground. Since the amplifier is using +/-5 V supplies, the signal is well within the linear region and the output is therefore an inverted version of the input.

Figures 3a and 3b show this same amplifier with a gain of –1 now operating from a single +10 V supply. The same ground referenced signal is applied to the amplifier and in the case of figure 3a, both the positive input and load are tied to ground. The resulting output waveform is now a half-wave rectified version of the input. This is obviously not what we are looking for. The amplifier is unable to operate on the positive portions of the waveform since the resulting output is at a voltage potential more negative than the lower supply rail. This causes the output to saturate just above the negative supply rail (ground in this case). All negative input voltages will drive the output into its normal positive output swing.

As shown in figure 3b, the amplifier now has a dc bias voltage (virtual ground) equal to half of the supply voltage (in this case +5 V) applied to the positive input pin in an attempt to bias up the input signal to mid rail. Using Kirchhoff's junction rule at the negative input of the op amp, the following equation can be derived for the output voltage of this amplifier.

$$V_O = V_B\left(\frac{Rf}{Ri}+1\right) - Vi\left(\frac{Rf}{Ri}\right)$$

The second portion of the equation represents the gain of the amplifier at the inverting input terminal. It can be easily identified as the gain equation usually used for inverting amplifier configurations. The first term represents the gain at the non-inverting input terminal. In a split supply application, the positive input is usually connected to ground and therefore the dc bias voltage (V_B) is zero, leaving the typical inverting amplifier gain equation. However, since we are biased at a point other than ground this term must be taken into consideration. In our example, this dc voltage is gained up and causes the output to saturate just below the positive supply rail. The output remains saturated for all negative portions of the input signal. All positive inputs on the inverting terminal will subtract from the dc output voltage. Again, this is clearly not what we had hoped for. The resulting waveform can be seen in figure 3b.

The previous figure illustrates two very common mistakes made when attempting to bias the input signal in a single supply application. Now we will analyze a few simple methods of proper biasing.

Figure 4a shows the same inverting gain stage we have been discussing in the previous examples. The input waveform, positive input pin and load are now connected to a virtual ground equal to $V_{CC}/2$. With the virtual ground being set at $V_{CC}/2$, the circuit is now equal distant from both supply rails, allowing for maximum dynamic range. The signal is able to swing freely about the virtual ground without clipping.

Another example of proper input signal biasing is shown in figure 4b. The configuration is almost identical to the one analyzed in figure 3b, but a capacitor has been added to the input. The capacitor blocks the flow of dc current and prevents the amplifier from gaining up the dc bias voltage on the non-inverting input pin. All ac current passes through the capacitor, so the output waveform is an inverted version of the input biased at V_B (in this case + 5V). This can also be explained using the output voltage equation derived earlier. Adding the impedance of the capacitor, the equation is as follows.

$$V_O = V_B\left(\frac{Rf}{\frac{1}{sCi}+Ri}+1\right) - Vi\left(\frac{Rf}{\frac{1}{sCi}+Ri}\right)$$

Again, the first term represents the gain of the non-inverting input terminal. Assuming our virtual ground is a pure dc voltage (i.e. no ac noise, etc), the impedance of the capacitor is essentially infinite, which makes the gain factor in this equation go to zero, leaving only V_B. Therefore the dc output of this amplifier will be equal to the bias voltage. The gain at the inverting terminal of the op amp remains the same with one exception. With the inclusion of the capacitor, the gain of this circuit is now frequency dependent. There is an RC high-pass filter created on the input by Ri and Ci. The values of these components determine the low frequency cutoff for the system. The frequency at which the gain has been attenuated by –3dB can be calculated using the following equation.

$$f(-3dB) = 1/2\pi RiCi$$

For our circuit Ci = 0.1µF and Ri = 10kΩ, making a low frequency cutoff point of 159Hz. Any signals lower than this frequency will be attenuated at 20dB/decade.

In figure 4c, a capacitor has also been added at the output of the amplifier. This output capacitor blocks all dc current across the load. This changes the dc bias point across the load from V_B to ground. The capacitor forms an RC network with the load resistor and will also cause signal frequencies near its low frequency limit to attenuate. In this example, the capacitor and resistor values are the same as in figure 4b so the low frequency cutoff point is again 159 Hz. With the inclusion of the second RC network, signals at the cutoff frequency will now be attenuated by –6dB instead of –3dB.

The three previous examples demonstrate the proper way to bias the input signal in a single supply application. The first example is probably the most desirable as no external components are required (other than the virtual ground). However, if the application doesn't allow the input waveform, load, and positive input pin of the amplifier to be referenced to a virtual ground, then examples two and three would be more suitable. The designer must always keep in mind the addition of capacitors make the circuit frequency dependent.

4. Methods for generating a virtual ground

We have spent some time discussing both proper and improper methods for biasing single supply amplifiers using a dc bias voltage. However, little time has been dedicated to how this virtual ground is generated. In the examples presented earlier we were assuming this dc bias voltage was ideal. We all know this is never the case though. We will now look at several examples of virtual grounds and their inherent advantages and disadvantages.

Some parameters that should be evaluated when selecting a virtual ground are power dissipation, load and input regulation, and output impedance. Ultimately, the decision on which virtual ground to use will come down to what key care-abouts the engineer has for his/her particular application and how much they are willing to pay for them.

Probably the most widely used technique for generating a virtual ground is a resistor divider plus a bypass capacitor. It is also probably the most cost effective solution available, as the price of resistors and capacitors are usually much less than integrated circuits. However, among its disadvantages are poor load regulation and low supply rejection. If the load is tied to the virtual ground, any high source or sink current requirements will cause errors in the dc bias voltage. Also, any type of noise ripple generated from the power supply will feed through the divider and introduce errors into the system. The level of power dissipation of the divider can be calculated using the total series resistance of the divider and the supply voltage. For a 1-kΩ divider with a +5 V power supply, the power dissipation is 12.5 mW. This is shown in figure 5a.

Using an amplifier to buffer this resistor divider will solve the load regulation problem. The amplifier is able to handle load current demands much more effectively than the divider network. Unfortunately, an additional component is needed which will increase the cost of your system. A large increase in board space used to be a major concern of designers when considering this method. However, with the recent introduction of amplifiers in extremely small packages, like SOT23, the extra real estate needed is minimized. The supply current of the additional amplifier also takes away from battery life in portable applications. This configuration is shown in figure 5b.

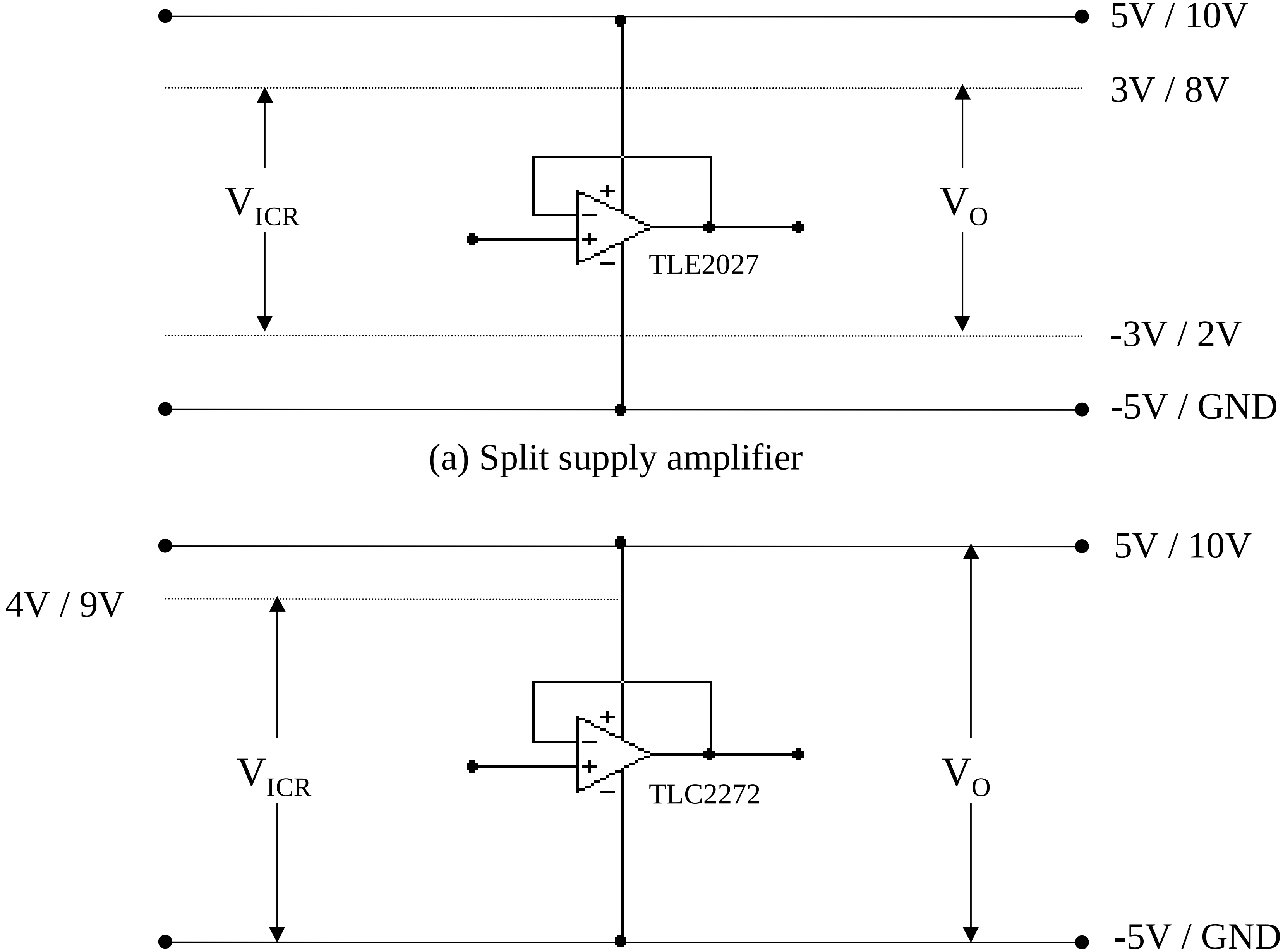
Another method for generating a virtual ground is by using a voltage reference. This can be seen in figure 5c. The active device significantly increases input regulation over the previous two methods. However, a drawback of the voltage reference is its high power consumption. For the reference to offer a very stable dc voltage, enough bias current must be available at all times. This equates into constant levels of dc current, which increases your total power consumption. For this reason, this is not the most ideal case especially in portable applications.

This reference can also be buffered with an amplifier. The input and load regulation from the reference and amplifier respectively is by far the best among the four solutions. Added components, power dissipation and cost are the penalties. Figure 5d shows this configuration.

The selection of a virtual ground is really dependent on the needs of the particular application. If the system will demand high source and sink current capabilities from the virtual ground then one may need to select an option with a buffer. If input regulation is a critical parameter then use of a voltage reference might be the best option. Less demanding applications may only need a simple, low cost divider network.

5. Conclusion

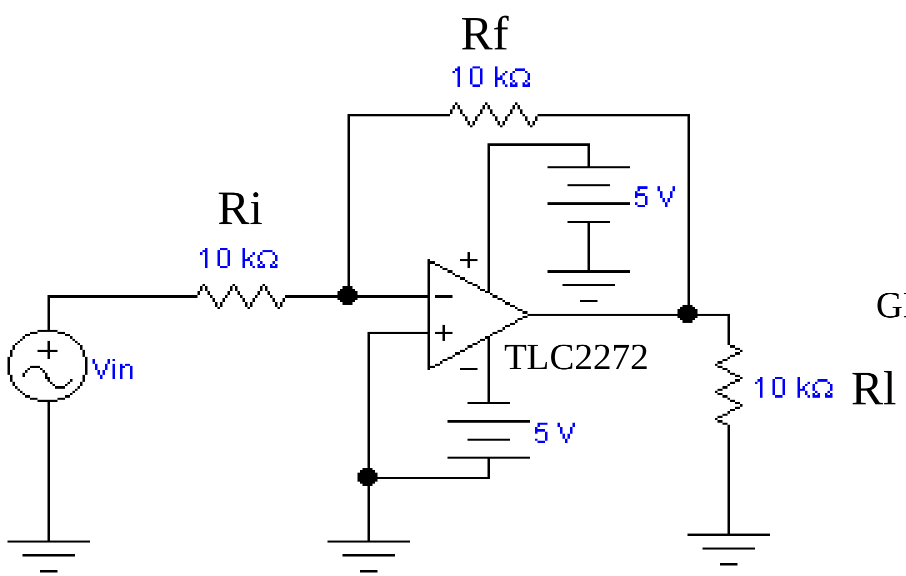
The number of designers migrating from split supply to single supply amplifiers is at an all time high. When using a single supply voltage, the engineer will be introduced to new design issues. In order to be successful designing with these single supply products, a good understanding of V_{ICR} limitations and input signal biasing is critical. Proper selection of a virtual ground is also important. Several examples were presented that cover a majority of single supply applications.



(a) Split supply amplifier

(b) Single supply amplifier

Figure 1: Input/output characteristics of split and single supply amplifiers



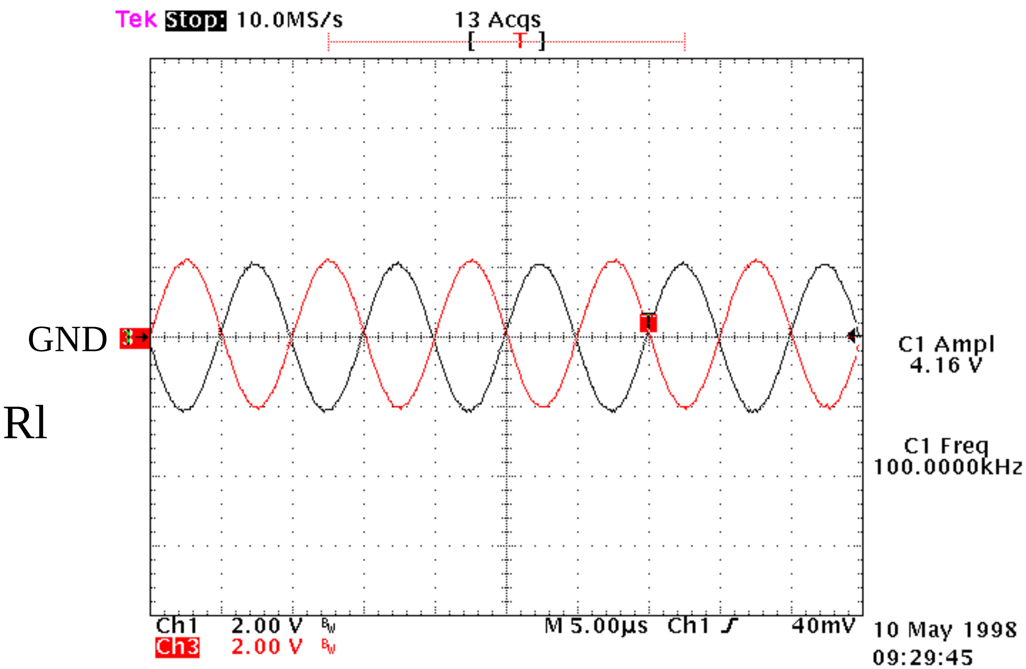


Figure 2: Op amp configured with an inverting gain of 1 powered by dual +/-5V supplies

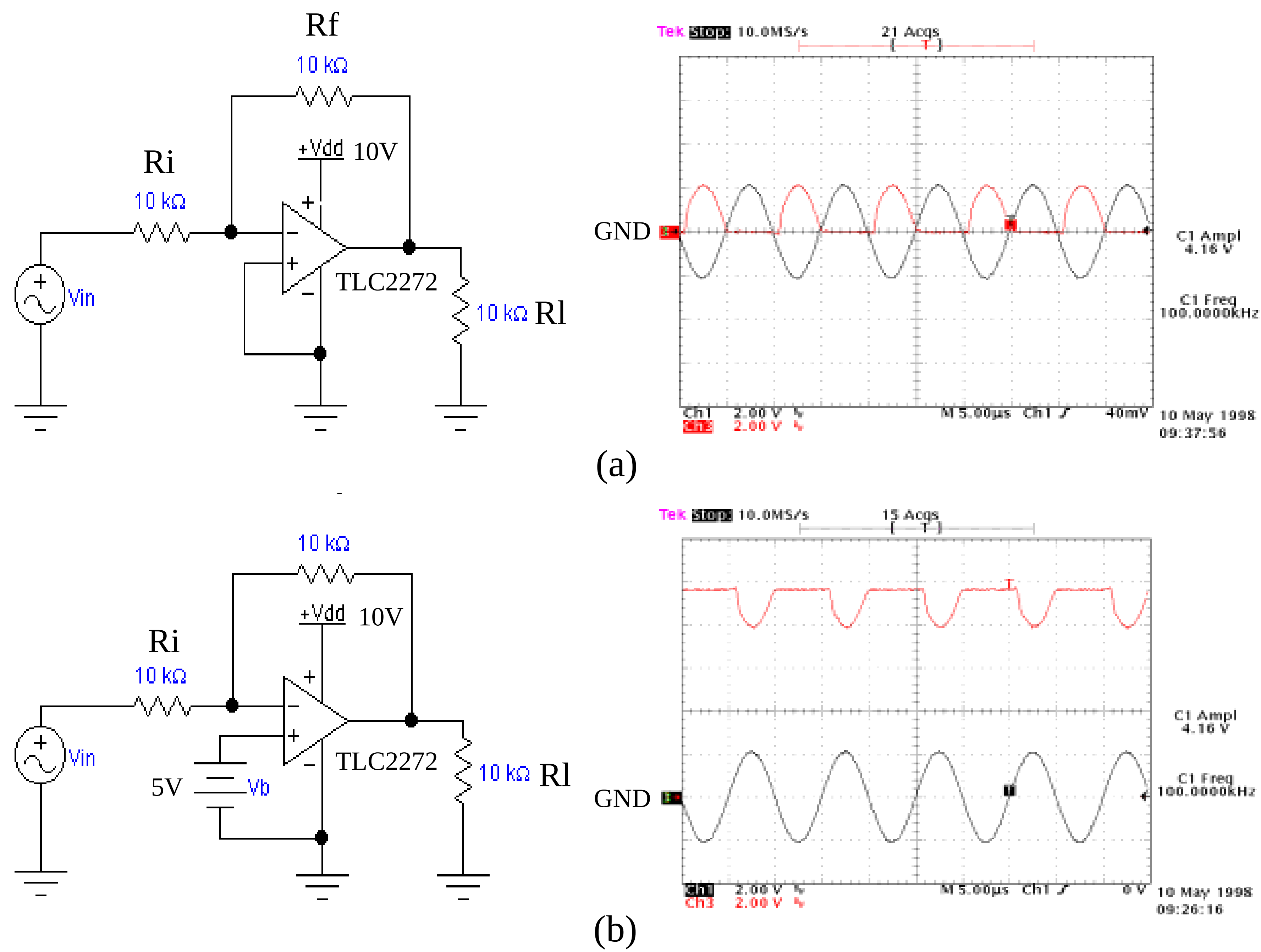


Figure 3: Improper input signal biasing for a single supply application

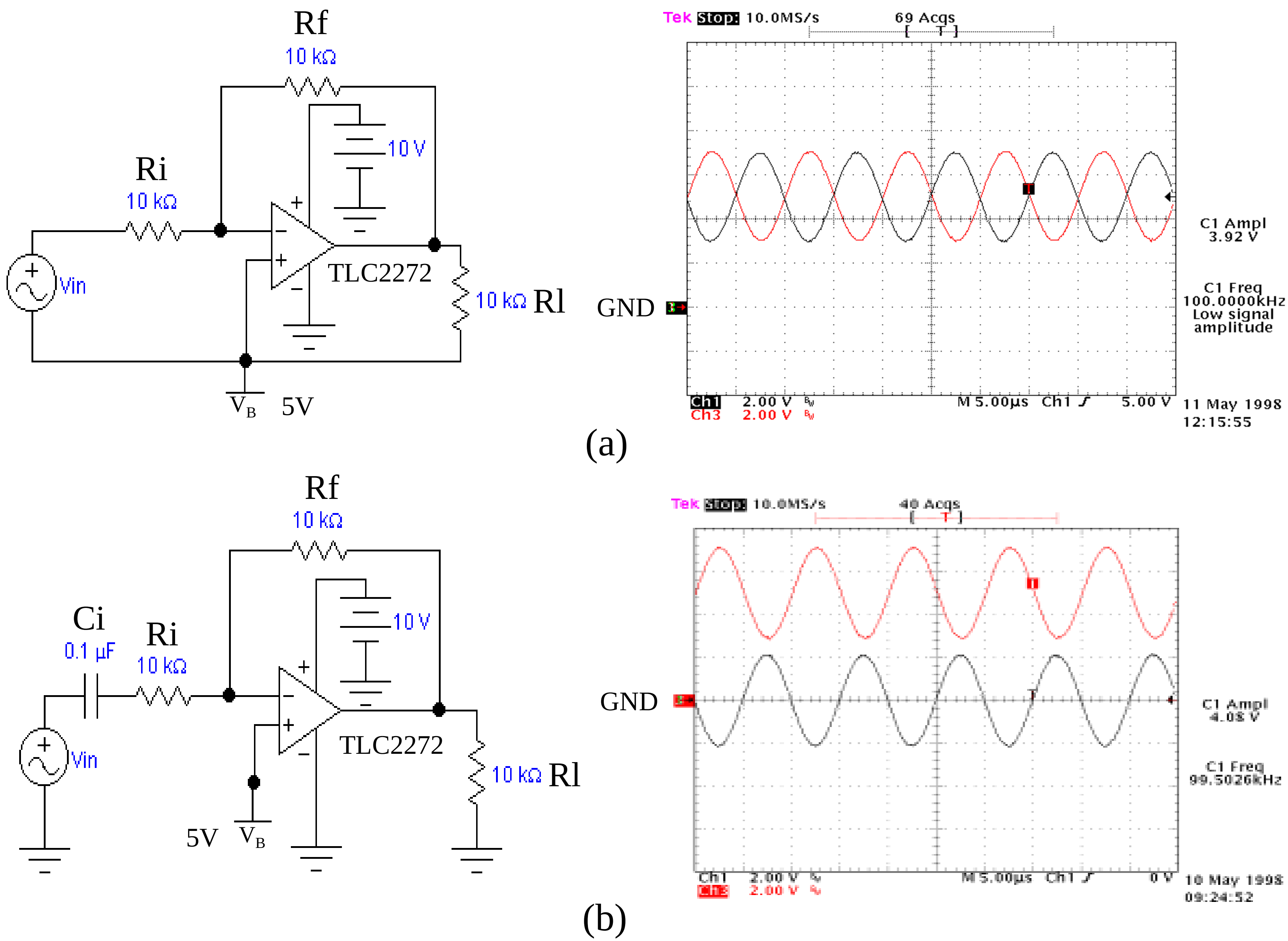
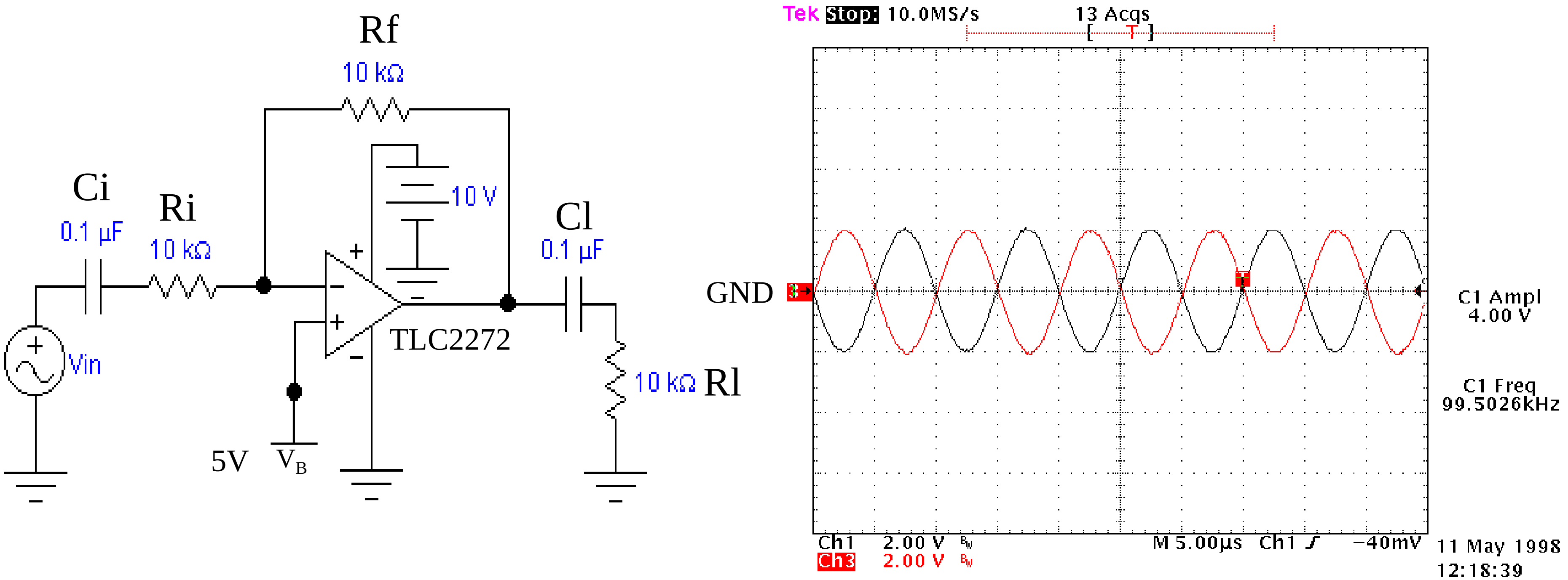


Figure 4: Proper signal biasing methods for single supply applications



(c)

Figure 4: Proper signal biasing methods for single supply applications

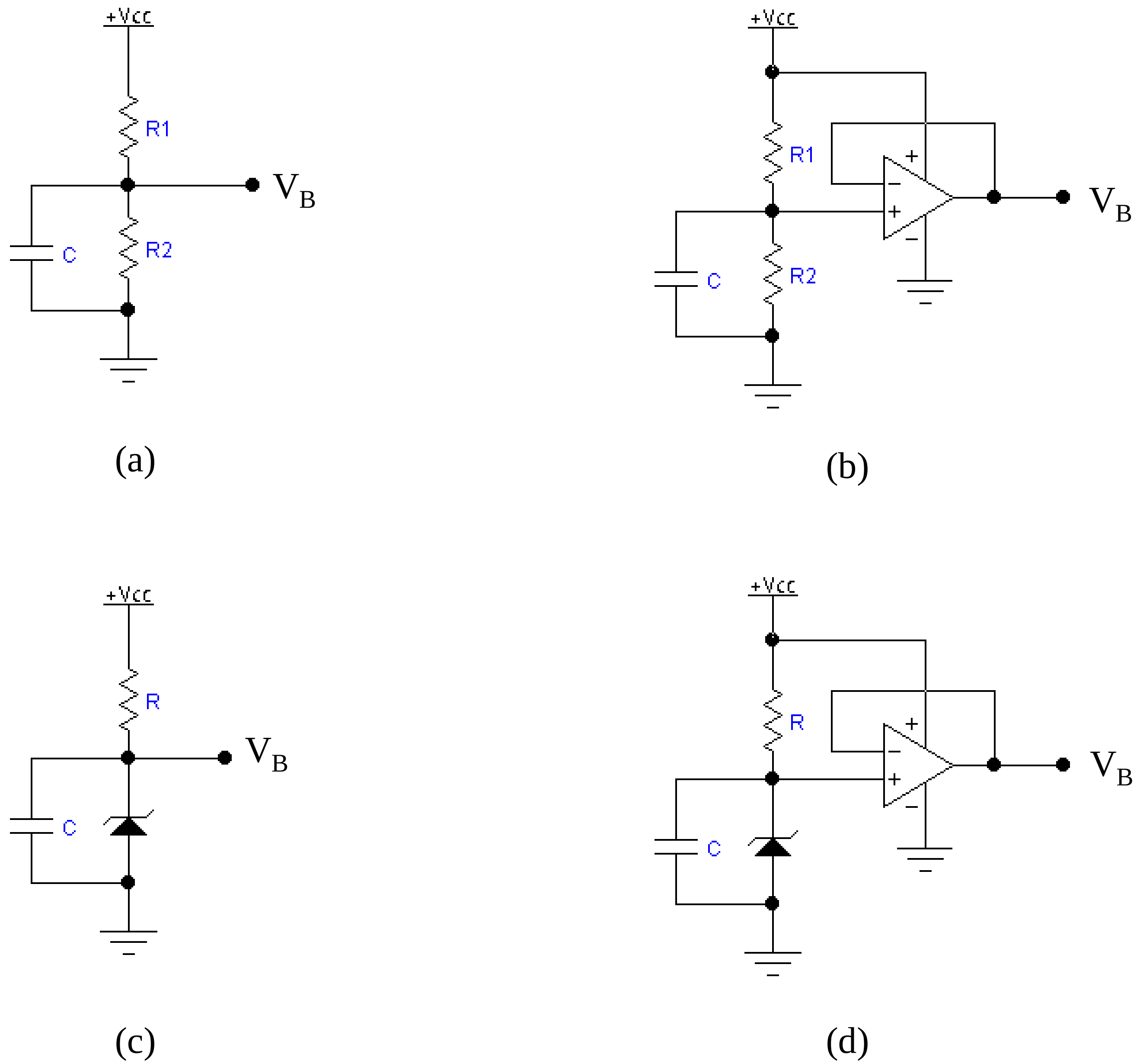


Figure 5: Different methods for generating a virtual ground

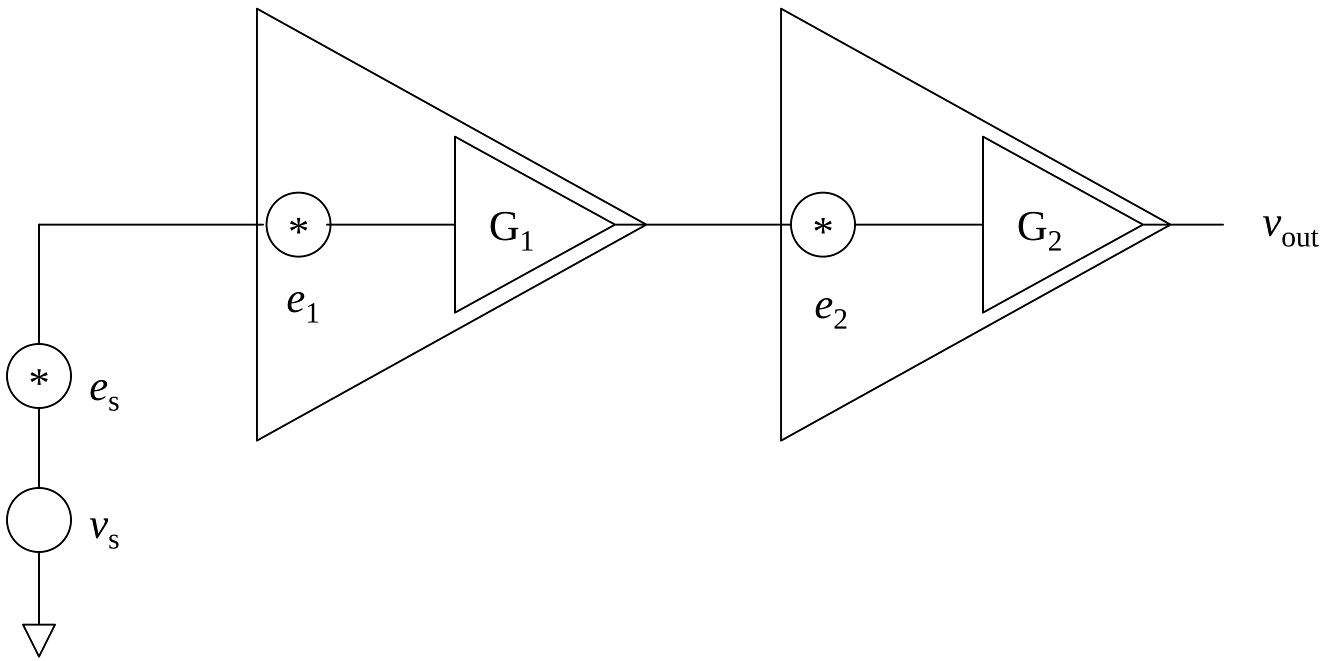


Figure 1
Analog Processing Channel

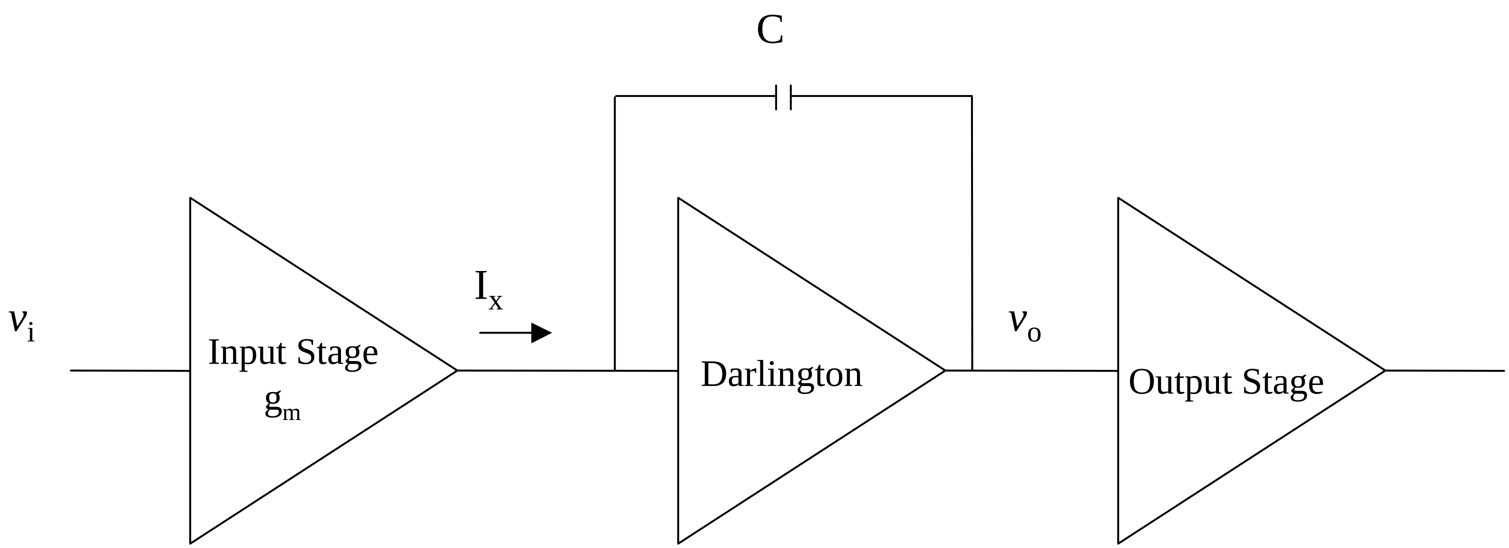


Figure 2
Simplified High-Speed Bipolar Op Amp
Block Diagram

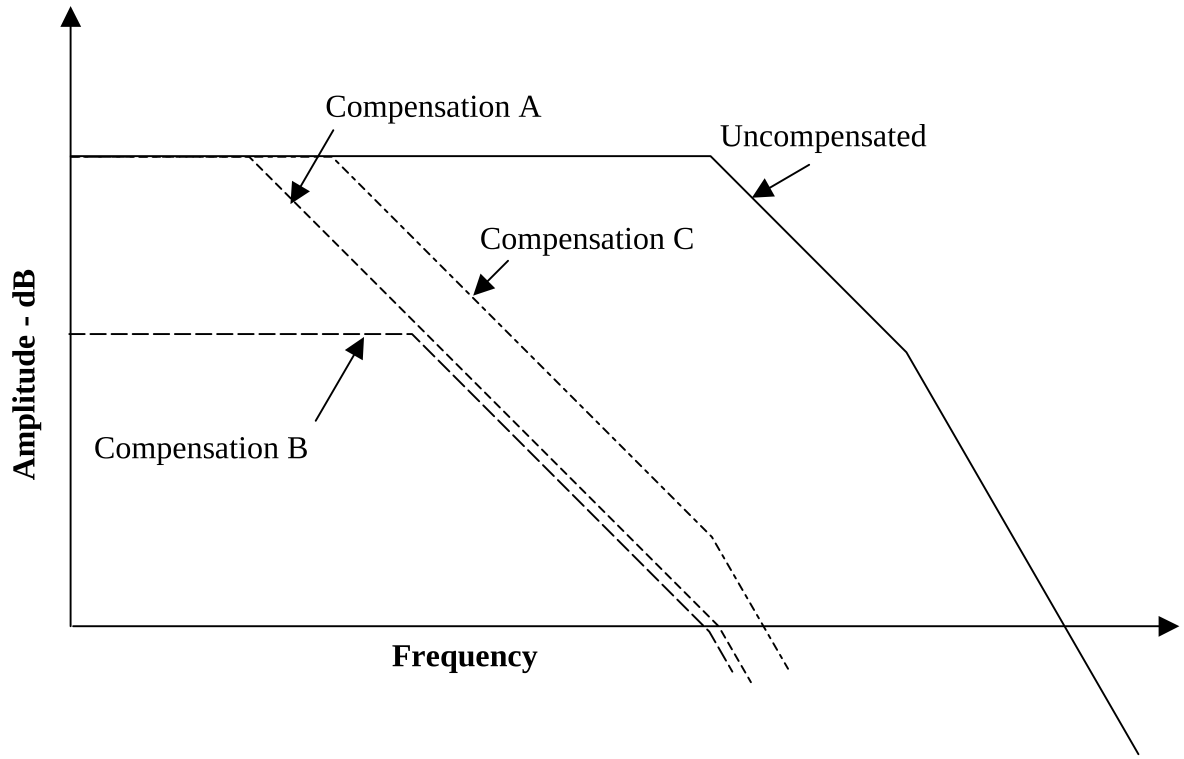


Figure 3
Frequency Response and
Compensation Options