Single-supply op-amps

There are no free lunches in op-amp design. Phil Darrington helps you make the right choice by explaining the trade-offs involved in producing op-amps designed to work from a single supply rail.

In Maxim's application note on the design of operational amplifiers for single-supply working,[1] the clearly heartfelt observation is made that, in engineering, you usually have to sacrifice one aspect of performance to improve another

How true, and designing an op-amp for use in a piece of equipment that has to be small, inexpensive, miserly in its use of current and yet produce the required performance from a single, low-voltage supply rail is a typical example of a collection of Murphy's Laws Common-mode input range, output swing, common-mode rejection, noise and all the other little annoyances become bigger ones and the result is that trade-offs have to be made

Input

Common-mode input voltage range in a single-supply op-amp is of first concern for a circuit designer and the obvious thing to do is to specify a rail-to-rail type – the phrase is claimed as a trademark by Nippon Motorola, so it ought to have capital initials, but not here – sorry. But there are things to watch A pause here for definitions

Operational amplifiers allowing inputs only down to the negative rail are referred to as ground-sensing types; those allowing signals to go to either rail are rail-to-rail devices.

And there are others that let the inputs go within a volt or two of positive and down to ground. If the amplifier has a voltage gain of two or more from a signal referred to ground, a ground sensor is probably a good choice and may well work better than a rail-to-rail op-amp, for reasons to do with the use of two differential input pairs in the rail-to-rail type, as shown in **Fig. 1**.

As the input voltage shifts from one rail to the other, one or the other amplifier pair handles it but, at the crossover, input bias current and input offset voltage can be changed in magnitude and polarity; the change in offset has a tendency to increase distortion in comparison with ground sensors unless the offset is trimmed at both ends of the common-mode range

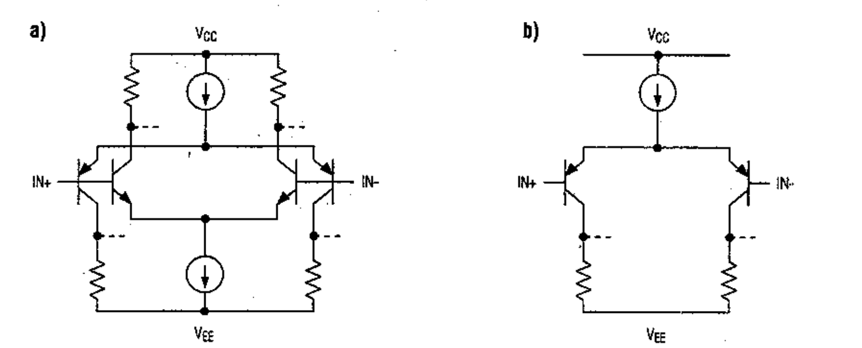

Fig. 1. Two types of rail-to-rail input. That at a) has two differential pairs, which can cause trouble when the input moves from one rail to the other and the amplifier uses one pair or the other. The crossover can change input bias current and offset voltage, which requires careful trimming during manufacture.

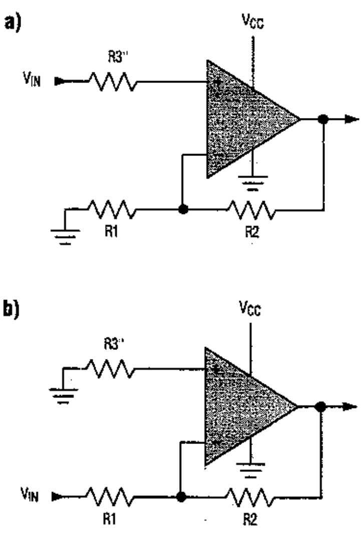

Fig. 2. Normal method of reducing offset-voltage errors by matching impedances 'seen' by each input of the op-amp.

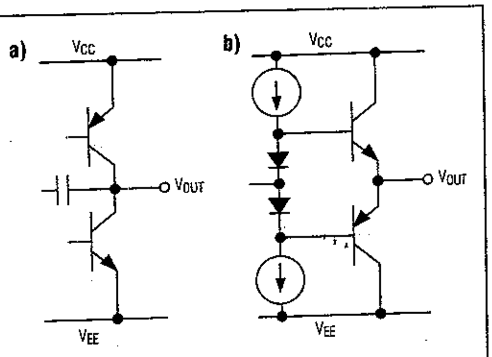

Fig. 3. Rail-to-rail output a) contrasted with a standard emitter-follower output, which interposes two junction voltages between output and rail.

Rail-to-rail op-amps are inherently more difficult to provide with high slewing rates than the ground-sensing variety, simply because the input stage is rather more exotic and is unable to take advantage of the available techniques. It is usual in any op-amp circuit to match the impedances seen at both inputs of the amplifier to match input bias currents and therefore reduce offsets caused by them.

Maxim quotes a change in bias current of 85nA for a 0-5V input voltage swing, while the offset current changes by only ±1nA when the above precautions are taken. in a rail-to-rail op-amp.

Figure 2 shows another way to eliminate input bias current changes, in this case by making the common-mode voltage constant at V_{ref}. Output is now,

$$V_{out}=(-V_{in}R_2/R_1)+V_{ref}(1+R_2/R_1).$$

If $R_2=R_1$, output is $V_{out}=-V_{in}+2V_{ref}$, which is 1-4V for inputs of 0-3V. Common-mode voltage is fixed and common-mode rejection errors eliminated.

Output

Since op-amps are – more often than not – required to produce voltage gain, it follows that a rail-to-rail output is needed more than rail-to-rail input. In a single-supply op-amp, the output stage is of somewhat different design to that found in a dual-supply type.

In rail-to-rail output stages, it is common to use a common-emitter stage, while the output of a standard op-amp is usually an emitter-follower pair, **Fig. 3**. At (a), the common-emitter form has only one junction between rail and output and the output voltage can approach the rail to within $V_{CE(sat)}$. In the emitter-follower at (b), however, the output gets no closer to the rail than a $V_{CE(sat)}$ and a V_{BE}.

Since saturation voltage depends on collector current, output swing varies and, infect, never really gets to the rail; it will approach to within tens or hundreds of millivolts.

Cmos output stages have the same problem: drain-source voltage caused by channel current flowing through the finite on-resistance

Load-dependent gain

A further problem with rail-to-rail op-amps is the matter of gain dependence on load current. Common-emitter stages provide gain at fairly high impedance, the output node therefore being included in the compensation network, while the emitter followers used in standard types have less than unity gain and are compensated before the output. In rail-to-rail op-amps, therefore, gain depends on load current and instability with capacitive loads is a possibility.

Once again, trade-offs are needed and in this case the circuitry needed to make the op-amp stable requires more supply current than is the case with standard designs. Nevertheless, some of Maxim's op-amps with rail-to-rail input and output will drive a 500pF load, the extra circuitry also conferring good large-signal voltage gain into heavy resistive loads.

Charge-pumps

A novel use for the up-and-coming charge-pump circuit[2] is the provision of bias voltage for an emitter-follower output stage and power to the other stages.

This use of the internal charge pump enables a ground-sensing amplifier inputs to swing from ground to the supply rail; in other words, input and output are of standard form and it is found that such devices perform rather better than rail-to-rail amplifiers, with good cmrr, high gain and stability into capacitive loads. A typical amplifier of this type takes 35mA, has a 200kHz bandwidth and drives a load of 20kΩ and 500pF.

Sometimes, you just have to give in and bow to the inevitable; for the absolute maximum performance it might be necessary to use two supply rails. But, of course, this does not mean that you have to redesign the system power supply for one op-amp; there are ways of making a dual supply from one rail.

An attractive method of obtaining the complementary rail is, again, to use a charge pump. **Figure 4** shows the Maxim *861* charge-pump voltage converter accepting a +1.5 to 5.5V input and providing an inverted output equal in magnitude to the input. The device can be made to operate at 13, 100 or 250kHz for more trade-offs: quiescent current, capacitor size and output voltage ripple.

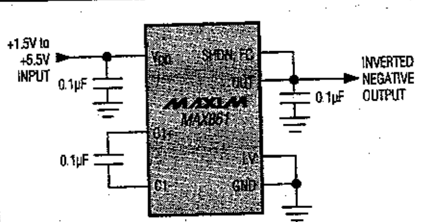

Fig. 4. In extreme cases, where a dual-rail circuit is the only option, this charge-pump provides the second rail by inverting the existing one.

Noise

This is an area where you simply cannot win. There seems not to be a way in which you can have low-voltage, single-supply rails, low noise and low power.

Using low-voltage rails demands lower-noise circuitry just to maintain a reasonable s:n ratio, but low voltage usually means a requirement for low power and lower currents mean more noise. There is no way round the unpalatable fact that, for low noise, an amplifier must dissipate higher power.

Noise sources are shown in **Fig. 5**, the cir-

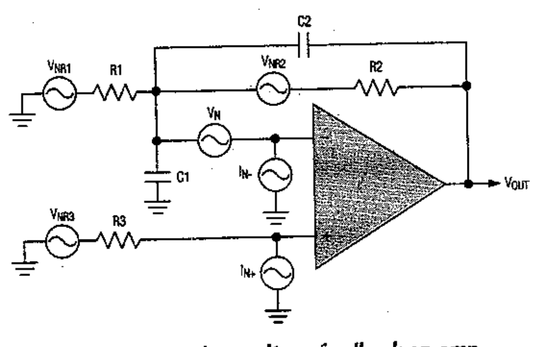

Fig. 5. Noise sources in a voltage-feedback op-amp.

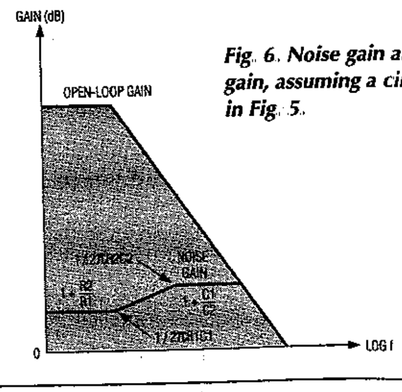

Fig. 6. Noise gain and open-loop gain, assuming a circuit such as that in Fig. 5.

cuit being a voltage-feedback op-amp. Sources in evidence are input voltage and current noise and the thermal noise from R_1 and R_2, the gain-setting resistors. Capacitor C_1 is the inverting input stray, C_2 limits noise gain and signal bandwidth and R_3 is the impedance-balancing resistor referred to earlier.

As you will see in **Fig. 6**, noise gain at lower frequencies is $1+R_2/R_1$, which applies up to the first zero at the frequency $1/2\pi R_1C_1$, from which point it increases at 6dB/octave as far as the pole $1/2\pi R_2C_2$. From here, the noise gain is equal to $1+C_1/C_2$ until the frequency hits the point at which the open-loop gain of the amplifier is equal to the noise gain, from where the two gains roll off together at 6dB/octave.

Noise due to input voltage, current noise at the non-inverting input and that from R_3 are integrated over the whole closed-loop bandwidth and multiplied by the noise gain. Circuit noise is smallest when an op-amp having a low unity-gain crossover frequency is used.

At the inverting input, current noise and thermal noise from R_1 and R_2 are only integrated over the signal bandwidth. Capacitor C_2 is not used in current-feedback amplifiers and noise for this type is integrated over the whole closed-loop bandwidth.

Distortion

Since an amplifier's gain falls off at high frequencies, non-linearity of input/output transfer function becomes relatively more important and harmonic distortion increases. At a given frequency, therefore, you get less harmonic distortion if the amplifier is in its more linear region at maximum loop gain, which can be obtained by biasing output away from the supply rails in a circuit such as that in **Fig. 7a)**.

This configuration provides the offset and also inversion or in **7b)** which just provides the offset. That of Fig. 7a) keeps the common-mode input voltage constant and so eliminates common-mode non-linearity, useful in rail-to-rail op-amps where the non-linearity is caused by common-mode input changes as one or the other input pair comes into use. ■

References

1. Maxim Engineering Journal. Vol 26
2. Charge pumps get new life, *EW*, August 1997

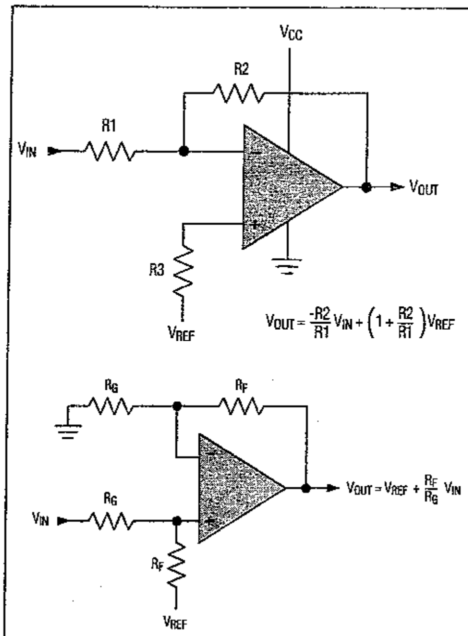

Fig. 7. At a), an inverting op-amp providing gain and offset to the input and biasing the output away from the supply. The circuit at b) does the same, but without inversion.