Amplifiers: Op Amps

feedback amplifiers better for the design?

The RF designer considering op amps is presented with a
dilemma. Are voltage-feedback amplifiers or current-
feedback amplifiers more suitable for the design?

This article will be presented in two parts. Part 1 focuses
on the actual topology of RF stages formed with op amps
and the scattering parameters. Part 2 will focus on some fine
points of RF design and more specifications unique to RF.

Advantages

The major advantage of using high-speed op amps is a
high degree of flexibility over discrete transistor imple-
mentations. When discrete transistors are used, the bias
and operating point of the transistor interact with the gain
and tuning of the stage. In contrast, when op amps are
used, the bias of the stage is accomplished simply by
applying the appropriate power supplies to the op amp
power pins. Gain of the stage is completely independent
of the bias. Gain does not affect the tuning of the stage,
which is accomplished through passive components.

Op amps also reduce transistor parameter drift over the
system operating temperature range.

Disadvantages

As attractive as op amps are for RF design, there are some
barriers hindering their use. The first is, of course, cost.
The RF designer must learn how to set the op amp’s
operating point, but the process is considerably easier
than biasing a transistor stage.

The RF designer is used to describing RF performance
in certain ways. Op amp ac performance is described in
terms of ac performance. The RF designer must learn how
to translate op amp ac performance parameters into an RF
context. That is one of the main purposes of this article.

Voltage feedback or current feedback?
The RF designer considering op amps is presented with a
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feedback amplifiers better for the design?

The bandwidth specification given in op amp data sheets
refers only to the point where the unity gain bandwidth of
the device has been reduced by 3 dB by internal compen-
sation and/or parasitics—not very useful for determining
the actual operating frequency range of the device.

Internally compensated, voltage-feedback amplifier
bandwidth is dominated by an internal “dominant pole”
compensation capacitor, resulting in a constant gain/band-
width limitation. Current-feedback amplifiers, in contrast,
have no dominant pole capacitor and therefore can operate
much more closely to their maximum frequency at higher
gain. Stated another way, the gain/bandwidth dependence
has been broken.

Comparing a voltage-feedback and current-feedback op
amp illustrates this:

- THS4001, a voltage-feedback amplifier with a 270-MHz
  (–3-dB) open-loop bandwidth, is usable to only about
  10 MHz at a gain of 100 (20 dB).
- THS3001, a current-feedback amplifier with a 420-MHz
  (–3-dB) open-loop bandwidth, is usable to about 150 MHz
  at a gain of 100 (20 dB).

The choice is still up to the designer. At unity and low
 gains there may not be much advantage to using a current-
feedback amplifier, but at higher gains the choice is clearly
a current-feedback amplifier. Many RF designers would be
extremely happy if they could obtain a gain of 10 (20 dB)
in a single stage with a transistor—difficult to do. With an
op amp, it is almost trivial.

The RF designer must be aware of some issues with
current-feedback amplifiers:

- Conventional circuit topologies are unchanged for
current-feedback amplifiers.
- Current-feedback amplifier data sheets recommend
  values for RF, the feedback resistor. These recommenda-
  tions should be taken seriously. Gain adjustment
  should be made with RF.
- Keep capacitors out of the feedback loop.

Other than these restrictions, no additional care is needed
with the current-feedback amplifier except the normal
care in layout and meeting bypass requirements of high-
speed RF circuitry.

For both voltage- and current-feedback amplifiers,
capacitance on the inverting op amp input should be limited,
as this is a major cause of instability. It is very easy to
accumulate stray capacitance on a sloppy PCB layout. To
reduce this stray capacitance, Texas Instruments recom-
mends a hole in the ground and power planes under the
inverting input of an op amp on a multilayer board.
A review of traditional RF amplifiers

A traditional RF amplifier (Figure 1) uses a transistor (or, in the early days, a tube) as the gain element. The dc bias (+V_{BB}) is injected into the gain element at the load through a bias resistor, R_B. RF is blocked from being shorted to the supply by an inductor, L_C, and dc is blocked from the load by a coupling capacitor.

Both the input impedance and the load are 50 Ω, which ensures matching between stages.

When an op amp is substituted as the active circuit element, several changes are made to accommodate it.

By themselves, op amps are differential-input, open-loop devices. They are intended for a closed-loop operation (different from a receiver's AGC loop). The feedback loop for each op amp must be closed locally, within the individual RF stage.

There are two ways of accomplishing this—“inverting” and “non-inverting.” These terms refer to whether or not the output of the op amp circuit is inverted from the input. From the standpoint of RF design, this is seldom of any concern. For all practical purposes, either configuration will work and give equivalent results. The non-inverting configuration is probably the easiest to use.

Figure 2 shows a non-inverting RF amplifier. The input impedance of the non-inverting input is high, so the input is terminated with a 50-Ω resistor. Gain is set by the ratio of R_F and R_G. For log gain,

$$ G = 20 \log \left( \frac{1 + \frac{R_F}{R_G}}{2} \right) \text{ dB}. $$

For a desired gain,

$$ 1 + \frac{R_F}{R_G} = 2 \times 10^{\left( \frac{G}{20} \right)}. $$

The output of the stage is converted to 50 Ω by placing a 50-Ω resistor in series with the output. This, combined with a 50-Ω load, means that the gain is divided by 2 (–6 dB) in a voltage divider; so a unity-gain (0-dB) gain stage would become a gain of 0.5, or –6 dB.

The RF designer may notice that the power-supply requirements have been complicated by the addition of a second negative supply. The stage can be modified easily for single-supply operation.

Amplifier gain, revisited

Op amp designers think of the gain of an op amp stage in terms of voltage gain. RF designers, however, are used to thinking of RF stage gain in terms of power:

$$ \text{Absolute power (W)} = \frac{V_{rms}^2}{50 \, \Omega}. $$

$$ P_{0} \text{(dBm)} = 10 \log \left( \frac{\text{Absolute power}}{0.001 \, \text{W}} \right). $$

$$ \text{dBm} = \text{dBV} + 13 \text{ in a 50-Ω system.} $$
Scattering parameters

RF stage performance is often characterized by four “scattering” parameters, which are defined in Table 1. (VSWR, or voltage standing-wave ratio, is just another term for input or output reflection.)

The term “scattering” has a certain implication of loss, and that is indeed true in three cases. Reflections, as in the VSWR scattering parameters $S_{11}$ and $S_{22}$, can cancel useful signals. Reverse transmission, $S_{12}$, steals output power from the load. The only desirable scattering parameter is $S_{21}$, the forward transmission. Design of an RF stage involves maximizing $S_{21}$ and minimizing $S_{11}$, $S_{22}$, and $S_{12}$.

Small-signal ac parameters specified for RF amplifiers are derived from S-parameters. These specifications are frequency-dependent. They are measured with a network analyzer and an S-parameter test set. The test circuit is shown in Figure 3.

Input and output VSWR $S_{11}$ and $S_{22}$

VSWR is a ratio and therefore a unitless quantity. It is a measure of how well the input and output impedances are matched to the source and load impedances. They should be as closely matched as possible to avoid reflections.

VSWR is defined as:

\[ \text{VSWR} = \frac{Z_{I/O}}{Z_S} \text{ or } \frac{Z_S}{Z_{I/O}}, \text{ whichever } > 1, \]

where $Z_{I/O}$ is the amplifier input or output impedance; and $Z_S$ is the test system source impedance. The ideal VSWR is equal to 1:1, but typical VSWRs will be no better than 1.5:1 for RF amps over their operating frequency range.

Measuring the input VSWR is a matter of measuring the ratio of the reflected power versus incident power on Port 1 ($S_{11}$) in Figure 3. A perfect match will reflect no power. Output VSWR is measured the same way at Port 2 ($S_{22}$).

An op amp’s input and output impedances are determined by external components selected by the designer. For this reason, VSWR cannot be specified on an op amp’s data sheet.

Return loss

Return loss is related to VSWR in the following way:

\[ \text{Return loss} = 20 \log \left( \frac{\text{VSWR} + 1}{\text{VSWR} - 1} \right) = 10 \log ((S_{11})^2) \text{ input} \]

\[ \text{or } = 10 \log ((S_{22})^2) \text{ output}. \]

$R_0$ is not a perfect match for $Z_L$ at high frequencies. The output impedance of the amplifier will increase as the loop

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Table 1. Scattering parameters

<table>
<thead>
<tr>
<th>SCATTERING PARAMETER</th>
<th>RF AMPLIFIER SPECIFICATION</th>
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</thead>
<tbody>
<tr>
<td>$S_{11}$</td>
<td>Input reflection Input VSWR</td>
</tr>
<tr>
<td>$S_{22}$</td>
<td>Output reflection Output VSWR</td>
</tr>
<tr>
<td>$S_{21}$</td>
<td>Forward transmission Amplifier gain and bandwidth</td>
</tr>
<tr>
<td>$S_{12}$</td>
<td>Reverse transmission Reverse isolation</td>
</tr>
</tbody>
</table>
gain falls off. This will change the output VSWR. A peaking capacitor, $C_O$, added in parallel with $R_O$, can compensate for this effect (Figure 4). Because op amp output impedance will be well defined, a fixed value usually can be substituted after experimentation determines the correct value.

Reducing the input impedance of the amplifier will extend the maximum usable frequency by swamping the effects of high-frequency parasitic components.

**Forward transmission $S_{21}$**

The forward transmission $S_{21}$ is specified over the operating frequency range of interest. $S_{21}$ is never specified on an op amp data sheet because it is a function of the gain, which is set by the input and feedback resistors $R_F$ and $R_G$, respectively. The forward transmission of a non-inverting op amp stage is:

$$S_{21} = A_L = \frac{V_L}{V_{IN}} = \frac{1}{2} \left( 1 + \frac{R_F}{R_G} \right).$$

The forward transmission of an inverting op amp stage is:

$$S_{21} = A_L = -\frac{V_L}{V_{IN}} = -\frac{1}{2} \left( \frac{R_G}{R_F} \right).$$

Op amp data sheets show open-loop gain and phase. It is the responsibility of the designer to know the closed-loop gain and phase. Fortunately, this is not difficult. The data sheets often include excellent graphs of open-loop bandwidth and sometimes include phase. Closing the loop produces a straight line across the graph at the desired gain, curving to meet the limit. The open-loop bandwidth plot should be used as an absolute maximum. The designer who approaches the limit does so at the expense of extensive compensation and complex PCB layout techniques.

**Reverse transmission $S_{12}$**

Op amp topologies, in particular current-feedback amplifiers, assume that both inputs are connected to low impedances. Therefore, the reverse isolation of op amp RF circuits is excellent.

Reverse isolation is somewhat better in non-inverting current-feedback amplifier configurations, because the output signal must also leak through the circuitry connecting the non-inverting and inverting inputs to get to the source.

**Phase linearity**

Often, a designer is concerned with the phase response of an RF circuit. This is particularly the case with video design, which is a specialized type of RF design. Current-feedback amplifiers tend to have better phase linearity than voltage-feedback amplifiers.

- Voltage-feedback THS4001: Differential phase = 0.15°.
- Current-feedback THS3001: Differential phase = 0.02°.

Look for Part 2 of this article and conclusions to be published in a future issue of *Analogue Applications Journal*.

**Related Web sites**

www.ti.com/sc/device/THS3001
www.ti.com/sc/device/THS4001

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**Figure 4. Output peaking capacitor**

![Output peaking capacitor](image)
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