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Op-Amp Audio

Realizing High Performance: Bandwidth Limitations

For this November *Analog Special* installment, we'll take a look at some of the very basic issues surrounding op amps used within high-quality audio circuits. A parameter which ultimately affects a gamut of op-amp performance specs is device gain-bandwidth. This is related to the device's open-loop bandwidth and gain in predictable ways. These interrelated issues, along with the nature of the feedback for a particular application, ultimately become major quality determinants.

The open-loop bandwidth problem: Virtually all conventional voltage-feedback-type op amps have a high open-loop gain (≅ 100 dB), and a relatively low open-loop bandwidth (10 to 100 Hz). By voltage feedback, we specifically mean the classic op-amp types with symmetrical ± inputs, and are excluding current-feedback types (at least for now). Of course, this voltage-feedback category includes audio-specialized types, as well as more conventional non-audio ones.

All such amplifiers are designed to be flexible and easily applied within an overall feedback system with closed-loop stability usually down to unity gain. For unity-gain stability, the application of feedback demands a controlled rate of open-loop roll-off. This roll-off is a uniform 6 dB/octave gain reduction with frequency. The associated 90° phase lag of such an open-loop response will guarantee closed-loop stability for any feedback level.

But herein lies the rub. What seems like a relatively simple system tradeoff in design philosophy may not actually be so. Why is this? Isn't any op-amp-based audio design more simple than a classic RC-coupled transistor gain stage? A more complete answer here is a rather complex one, and it involves an understanding of the feedback process. It also involves implications of applying the feedback around what can often be imperfect amplifier hardware. For example, a nonlinear op-amp input stage, combined with less-than-optimum-bandwidth.

We do know that an op-amp-based gain stage can be just about as simple as it gets system-wise—at least on the surface. It consists simply of the op-amp device itself, plus a pair of resistors to set the desired gain (*see the figure from Part 1,* ELECTRONIC DESIGN, *Sept. 1, p. 166*). Unfortunately, the underlying weaknesses of how such a feedback-based amplifier can degrade some aspects of overall performance often gets bypassed, particularly when there is pressure to employ only standard, low-cost ICs (such as 5532 types and their derivatives).

An op-amp gain stage is unrivaled in *utility*, a feature which is very compelling. But, it trades off open-loop gain for bandwidth, operating within the constraints of a constant gain-bandwidth product. For the 5532 mentioned, the applicable gain-bandwidth is 10 MHz, and the open-loop gain is 100 dB (10^5 V/V). Thus, the open-loop bandwidth is 100 Hz. Actually, a close examination of the 5532 data sheet shows more like 200 Hz, due to the fact that this particular topology uses a feedforward technique, which boosts gain-bandwidth at lower frequencies. But, in general, the available *small-signal* gain at any given frequency is defined by the op amp's gain-bandwidth. Note the emphasis here on the small-signal aspect. And, it's helpful to understand that the application of different feedback does not change a given device's basic gain-bandwidth—it only reallocates it to some different closed-loop gain and bandwidth.

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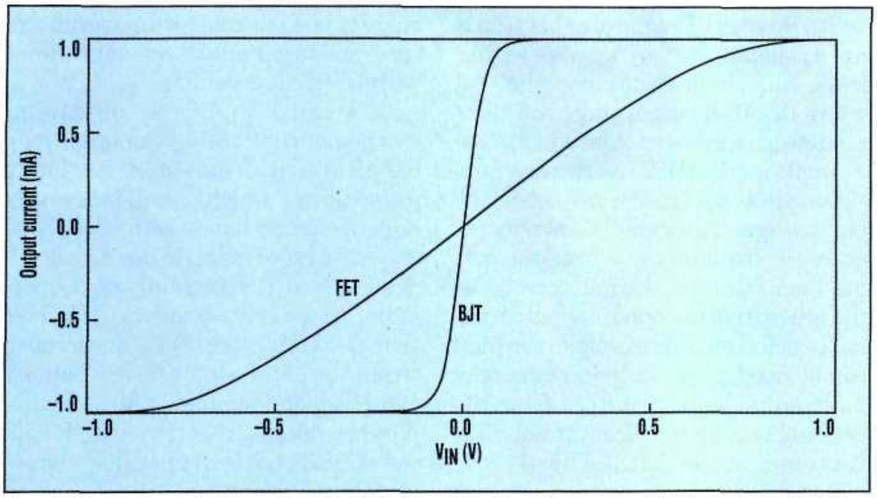
All of this may seem reasonable enough, until we go a step further, and consider the fact that the op-amp gain-bandwidth is based upon the small-signal transconductance (g_m) of the input-stage transistors, plus a fixed compensation capacitor (usually internal). If we consider this compensation cap fixed (for this discussion, at least), it should be obvious that the g_m of the input devices is also fixed, ideally. In other words, it doesn't vary with the input signal level.

But, within real devices, the g_m most certainly *does* vary. In fact, those devices that are best in terms of voltage noise performance—bipolar junction transistors (BJTs)—are worst in terms of their *transconductance linearity*. Barrie Gilbert has explored many of these non-ideal op-amp performance limitations in some recent *EDTN* columns.[1,2] Reference 2 includes a mathematical distortion analysis of an op amp. The analysis shows how an undegenerated BJT input stage (as just described) is actually quite poor in terms of standalone-mode distortion. The fundamental source of this distortion is the nonlinear g_m of the emitter-coupled BJT pair, which follows a hyperbolic tangent (tanh) function. Ideally this g_m would be highly linear, i.e., the inverse of a fixed resistance. While it isn't linear with a simple emitter-coupled BJT pair, it's much more so when the pair is operated with emitter-degeneration resistors, or the bipolars are replaced by JFET devices.

In an op-amp feedback circuit using such a nonlinear BJT input stage, the forward gain path typically includes the input stage as described, followed by an integrator stage which includes the aforementioned compensation cap, and a final output stage for load isolation.

When such an amplifier is placed within a simple, flat-frequency-response feedback setup, it's useful to contemplate what happens with a wideband audio signal passing through it. Consider, for example, a given input-signal level, and a flat voltage vs. frequency characteristic at the *output*. Increasing signal frequencies above the amplifier's open-loop corner frequency will result in a higher and higher input driving voltage to the op amp. (Not the signal input, but the actual voltage between the ± terminals.) This is a natural consequence of the feedback error correction, and the gain-vs.-frequency reduction within the op amp.

But, since the BJT input stage g_m is nonlinear, *and is followed* by a low-pass filter in the form of the integrator, higher signal frequencies require higher amplifier driving voltages to maintain the same output levels. This means higher frequencies must neces-



The relative transconductance characteristics for a ±1-V input range are displayed for both BJT and JFET differentially paired transistors. Both types use no emitter (source) resistance, and are biased by a fixed current of 1 mA. These curves were generated by PSpice, using 2N2222A and 2N5457 models available with that simulation package.

sarily drive the input stage harder, to counteract the filter roll-off. Because the input stage's g_m is different with a greater input drive, it produces a different corner frequency and phase shift (compared to lower frequencies, which require less amplitude drive). Considering just a case of one output level, this is a frequency-dependent nonlinear phase response.

When the output level is further increased, this phenomenon gets worse, until at some combination of amplitude and frequency, the op amp finally reaches its slew-rate limit. By definition, this occurs when the input stage is totally overloaded by the peak error voltage, at which point the output voltage from the op amp reaches its maximum rate-of-change.

So, in the absence of any corrective means, it can be shown that virtually all BJT-input-stage op amps (either IC or otherwise) can be limited in terms of input-overload sensitivity. And, they are nonlinear prior to their overload point. This is due to their extremely high and exponentially related g_m.

To put all of this in an overall perspective, a balanced BJT differential pair will develop around 1% THD for input signals which are just under 20 mV in peak amplitude. When such an input stage is used within a 10-MHz-gain-bandwidth op amp handling a 20-kHz, 10-V peak output signal, the actual amplifier driving signal will be 20 mV peak—it is just beginning to distort. If the amplifier were instead a 1-MHz "741-speed" device, the driving signal theoretically would be 200 mV peak. In practice, such an amplifier would more likely be operating in its slew-limited mode, and producing gross output distortion.

For today's audio op amps with bandwidths of 10 MHz or more, it could be argued that only the most extreme high-level, high-frequency audio signals even begin to push a non-degenerated BJT-input op amp into the nonlinear region. On the other hand, for digital signal byproducts, and other spurious out-of-band high-frequency components, the distinction may not be so clear. Here, an amplifier with more-linear input stages may be a better choice. And, if you've ever experienced spurious AM-band signal detection by a bipolar input stage op amp, you'll be able to relate to all of this, for sure!

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A positive aspect of this situation is that the BJT-input amplifier can easily achieve low input-noise performance, and it is good for low-level signals. But, the not-so-good side is that it can possibly show increasing distortion and phase shift effects for high-level, high-frequency signals above the open-loop corner frequency.

Comparing BJT/JFET g_m: Since op-amps are available with front ends consisting of either bipolar or JFET transistors, it is useful to compare them for overload. The g_m characteristics of both 2N2222A npn BJT and 2N5457 N-channel JFET differential-pair transistors make for a good comparison *(see the figure)*.

In these simulation plots, both transistor pairs are biased at the emitters (sources) by a 1-mA current source. The BJT-pair output is represented by the more steeply sloped trace in the center, with an input dynamic range of about ±200 mV for the ±1-mA output current. Also shown is the more-linear, gradually sloped g_m plot of the JFET pair, which has an input dynamic range of nearly ± 1V for the same output current. That is quite a contrast!

These data indicate the two major points just discussed above. Namely, that the BJT-device g_m is both higher and more nonlinear than that of the JFET. In fact, the degree of nonlinearity for the BJT case isn't readily apparent from this view, but it is easily revealed by comparing plots of differentiated data.

Extending open-loop bandwidth: Since the presence of an amplifier open-loop corner within the audio range, combined with feedback around a nonlinear BJT input stage, can give rise to dynamic phase shifts, a question arises: what can be done counteract it? Solutions are available in 3 forms.

1. One solution is by extending the effective open-loop bandwidth, so as to move the open-loop corner upward to 20 kHz or more. This step doesn't change the distortion in the input stage. But, it can reduce or remove the phase-modulation effects due to g_m variations—as the open-loop corner is moved upward to a region where (presumably) signals either do not occur, or they occur less frequently, or at lower levels.

The route to achieving this step can be as simple as adding one (or two) resistor(s) across the amplifier integrator. This damps the integrator and lowers the open-loop gain, thus moving the open-loop corner upward in frequency (again, within the constraints of the device's gain-bandwidth product). Practically, this step is not available on many amplifiers, but those with single-node comp pins and a zero-dc-offset output stage will allow a single such resistor to be added. One example is the AD829, with a compensation pin at pin 5, and a low-noise BJT input stage. Other amplifiers may require two resistors, one from the output back to one of the null terminals, the other from the opposite null terminal to common. For example, the 5534 can be used in this fashion with nominally equal value resistors from the two null pins. A significant trade-off of this approach is that the device's dc offset will almost surely be compromised by this inner-loop connection. This can in theory be corrected by a trim adjustment, but this step isn't likely to be practical.

Unfortunately, there are no common standards of what pin(s) are used for these secondary-bandwidth control functions, or what the relevant resistance(s) are, so some user experimentation is appropriate here, once given the proper amp.

Viewed from a system-level perspective, there's a more elegant and less compromising solution to optimizing the open-loop bandwidth of an op-amp circuit. Use multiple-stage feedback, so that the overall input-stage-to-integrator interface is controlled by local, signal-independent transfer characteristics.

Of course, this is a much more complex solution, and a useful working example will need to wait until a later installment. It also happens to be about the only practical way one can realistically implement the open-loop bandwidth control trick using dual (or quad) amplifier packages.

2. Use more-linear devices for the input transistors, which lessens the signal phase-modulation problem by reducing g_m nonlinearity. This is simply achieved by using a well chosen-op-amp. For example, one using a JFET input stage, either PFET or NFET. Both types typically have the desired lower g_m. A wide variety of general purpose FET input devices are available for this task, from the TL07X series of early JFET designs, to more recent devices such as the AD744 family, and the recent AD825 device. Of course, one does need to be selective here, as the JFET input stage is just one part of an overall picture, and other audio-relevant issues will also need screening.

3. A third (and truly optimum) method of controlling the open-loop bandwidth of an op-amp is to simply pick a device which has an inherently high open-loop bandwidth of (preferably) 20 kHz or more. While this is difficult indeed, it is certainly not impossible. And even a bandwidth of less than 20 kHz is more useful for desensitizing the phase shift effects than is a 100-Hz open-loop bandwidth. Examples are the just mentioned JFET input AD825, with an open-loop bandwidth of just under 10 kHz, or an AD817, with a similar bandwidth. The AD817 uses a BJT input stage with emitter degeneration, which gives it very good linearity.

On the downside, amplifiers that have lower-g_m input stages will typically tend to be more noisy than will their lower-noise, non-degenerated BJT cousins. This makes them useful for higher-level signals, as opposed to low-level front end applications. It is another of those system-level trade-offs a designer must make in honing a final high-performance design.

TIP: One or more of these bandwidth-extension and/or linearization methods can be useful in practice, and they are recommended to you for further experimentation. In a future column, we'll show an example of a multiple-feedback-stage design which uses method 1 above for bandwidth extension and input linearization.

References:

1. Gilbert, Barrie, "Op-amp Myths," *EDTN* web site, March 9, 1998, *www.edtn.com/analog/barrie1.htm.*

2. Gilbert, Barrie, "Are Op-amps Really Linear?" *EDTN* web site, June 10, 1998, *www.edtn.com/analog/barrie4.htm.*

Suggested Reading:

Otala, Matti, "Feedback-generated Phase Modulation in Audio Amplifiers," 65th Convention AES, 1980, London, U.K., Preprint # 1576.

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