

WALT JUNG

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 ($\cong 100$ 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 \pm 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 trade-off 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.

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.

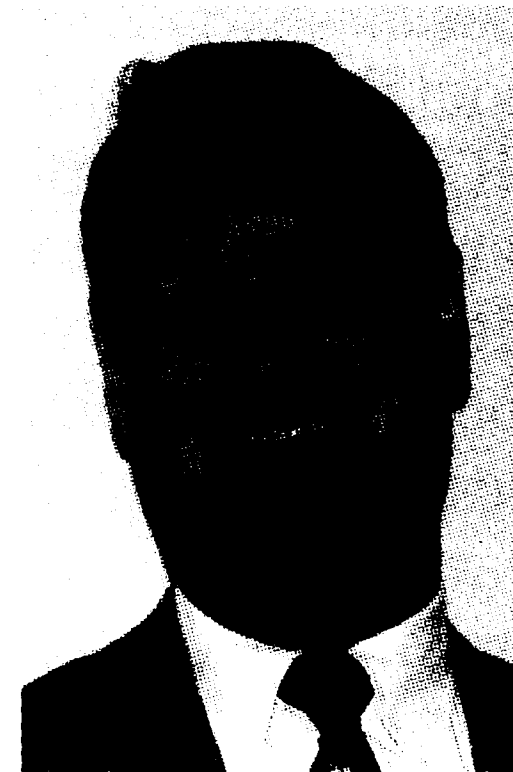
But, within real devices, the g_m most certainly *does* vary. In fact, those devices that are best in terms of voltage noise performance—bipolar junction transistors (BJTs)—are worst in terms of their *transconductance linearity*. Barrie Gilbert has explored many of these non-ideal op-amp performance 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

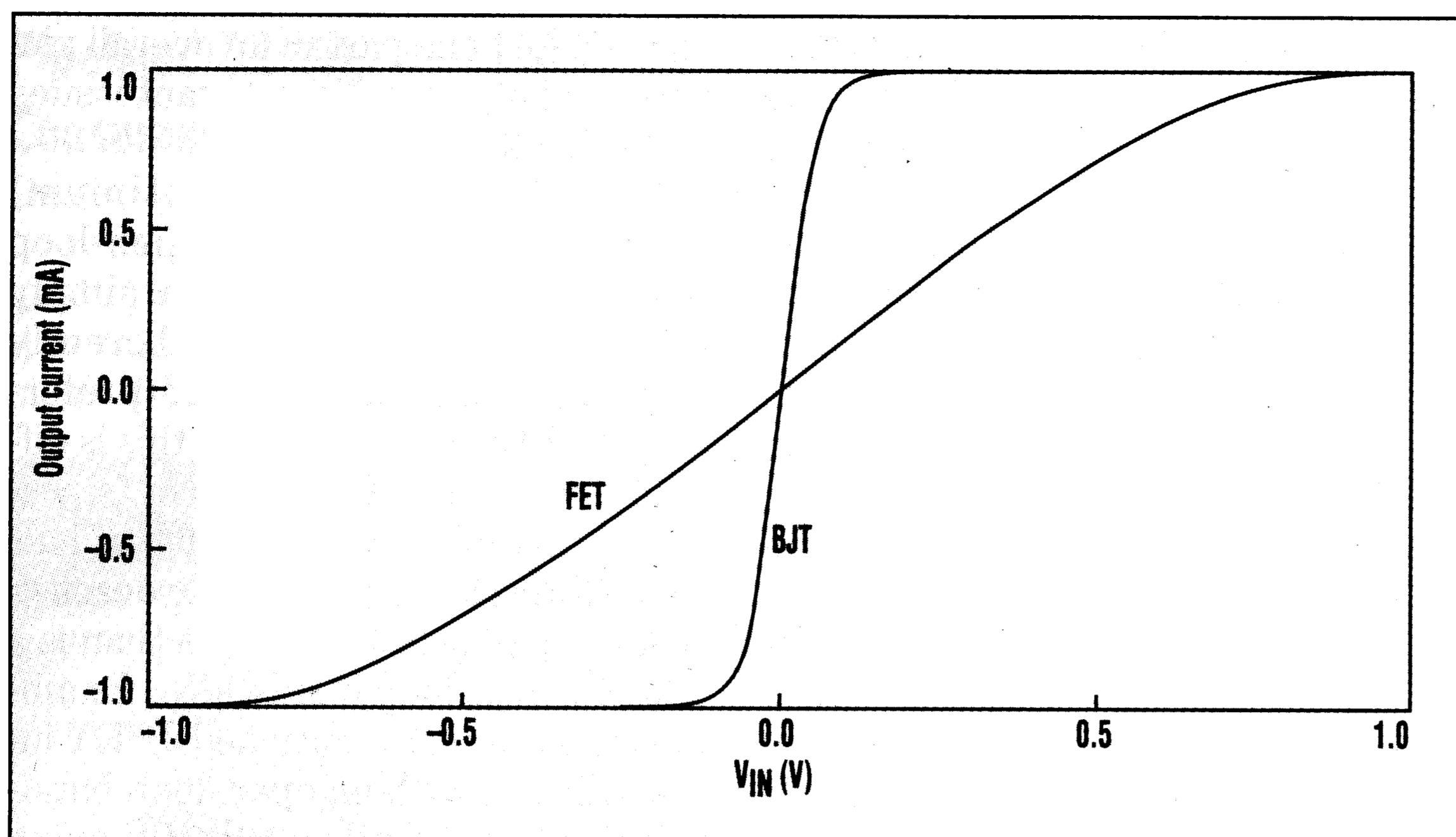
placed within a simple, flat-frequency-response feedback setup, it's useful to contemplate what happens with a wideband audio signal passing through it. Consider, for example, a given input-signal level, and a flat voltage vs. frequency characteristic at the *output*. Increasing signal frequencies above 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 \pm 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-



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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

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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!

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 ± 1 V 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 to 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-band-

