Technical Article

Achieving Faster Composite Op-Amp Dynamics by Expanding the Frequency Bandwidth

one hour ago by Dr. Sergio Franco

This is Part 3 of the series of articles about composite amplifiers. In this section, we are going to show how to achieve faster op-amp dynamics by expanding the frequency bandwidth.

In Parts 1 and 2 of a three-article series on composite amplifiers we have investigated how to boost the output current drive capability of an op-amp and simulate our example voltage buffer in PSpice.

Now, we are going to show how to achieve faster op-amp dynamics by expanding the frequency bandwidth.

Expanding the Frequency Bandwidth

The open-loop gain of most op-amps exhibits a constant gain-bandwidth product (constant GBP). The most salient consequence of this constancy is the fact that the higher the noise gain of an op-amp circuit is, the lower the closed-loop bandwidth. For instance, if we configure the op-amp as a noninverting amplifier, in which case the noise gain coincides with the closed-loop gain A, then the closed-loop bandwidth is

$$f_B = \frac{GBP}{A}$$

Equation 1

So, if we use an op-amp with GBP = 1 MHz and configure it for a noninverting gain of A = 10 V/V, then we get $f_B = 10^6/10$ = 100 kHz. For A = 100 V/V we get f_B = 10 kHz, and for A = 1,000 V/V we get f_B = 1 kHz.

What if we wanted to use this op-amp as an *audio preamplifier* with a gain of 1,000 V/V and a bandwidth of f_B = 20 kHz, which represents the upper limit of the audio range?

Clearly, a single 1-MHz op-amp won't do it, so let's see if we can enlist the help of a second, similar op-amp to raise f_B from 1 kHz to 20 kHz. Figure 1 shows a popular realization of this concept.

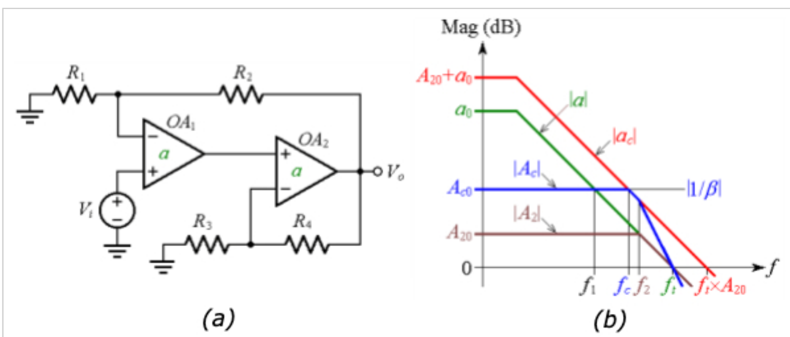

Figure 1. (a) Composite amplifier to achieve a wider bandwidth. (b) Straight-line Bode plots

In the figure, you can see (a) a composite amplifier to achieve a *wider bandwidth*. and (b) straight-line Bode plots where:

- $|a|$ is the open-loop gain of each op-amp, and f_t is the transition frequency (f_t = GBP in the present rendition)
- $|a_c|$ is the composite amplifier's open-loop gain; $|A_2|$ is the closed-loop gain of OA_2, and f_2 is its –3-dB frequency
- $|A_c|$ is the composite amplifier's closed-loop gain, and f_c is its –3-dB frequency
- $|\beta|$ is the feedback factor around the composite amplifier
- a_0, A_{c0}, and A_{20} identify the DC values of the above gains.

Here, OA_1 is the primary op-amp and OA_2 is the secondary op-amp, both having an open-loop gain of a. OA_2 is configured as a noninverting amplifier with a closed-loop gain of A_2 with a DC value of

$$A_{20} = 1 + \frac{R_4}{R_3}$$

Equation 2

By Equation 1, with GBP replaced by f_t, the closed-loop bandwidth of OA_2 is

$$f_2 = \frac{f_t}{A_{20}})$$

Equation 3

Together, OA_1 and OA_2 form a composite amplifier with an open-loop gain of

$$a_c = a \times A_2$$

Equation 4

The presence of OA_2 inside OA_1's feedback loop has two effects:

- It expands the open-loop gain from a to a_c. Due to the logarithmic nature of decibels (the log of a *product* equals the *sum* of the logs), the DC values a_0 and A_{20} *add up* in the manner shown.
- It establishes a pole frequency at f_2, which causes the slope of the $|a_c|$ curve to change from –20 dB/dec to –40 dB/dec, as shown. This pole frequency will erode the phase margin of the loop around OA_1, so we must be vigilant that the overall circuit does not get destabilized.

The composite amplifier of Figure 1(a) is in turn configured as a noninverting amplifier with a feedback factor of $\beta = R_1/(R_1 + R_2)$. The reciprocal 1/β is called the *noise gain*, and

$$\frac{1}{\beta} = 1 + \frac{R_2}{R_1}$$

Equation 5

(Recall that for a noninverting op-amp the noise gain and the closed-loop gain coincide, so $A_{c0} = 1/\beta$). Were OA_1 operating alone, its closed-loop bandwidth would be f_1 (see Figure 1(b)).

However, the presence of OA_2 expands the closed-loop bandwidth from f_1 to f_c, where f_c is the *crossover frequency* of the $|a_c|$ and $|1/\beta|$ curves. It is precisely this bandwidth expansion that we wish to exploit.

To gain better insight, consider the PSpice circuit of Figure 2, simulating a composite amplifier with a closed-loop gain of 1,000 V/V, or 60 dB.

Scroll to continue with content

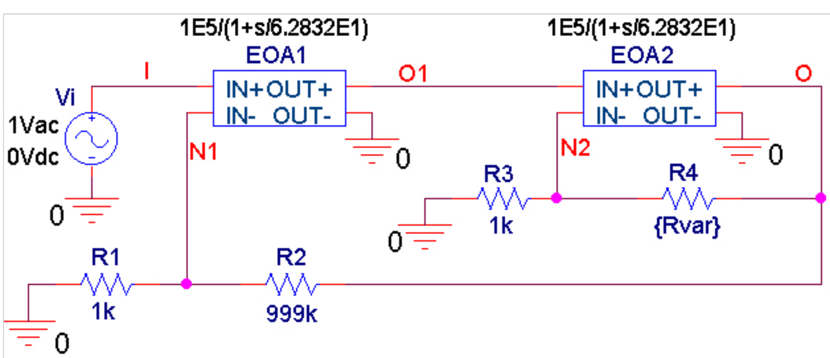

Figure 2. PSpice circuit for a composite amplifier using Laplace blocks to simulate 1-MHz op-amps.

Figure 3(a) shows the effect of stepping EOA2's closed-loop gain |A2| in 10-dB increments via R4. For |A2| = 0 dB things go as if EOA1 were operating alone, giving a closed-loop DC gain of 1,000 V/V (= 60 dB) with a closed-loop bandwidth of 1 kHz.

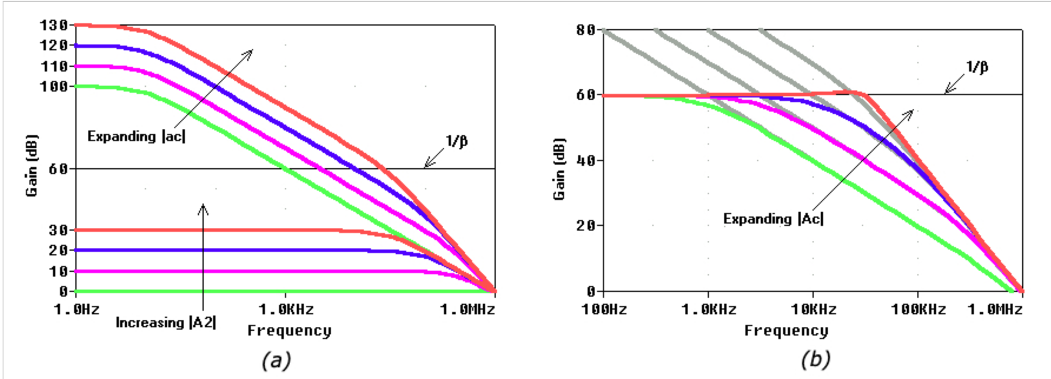

Figure 3. Visualizing the effect of 10-dB increments in EOA2's closed-loop gain |A2| in the circuit of Figure 2. Effect on the composite amplifier's (a) open-loop gain |ac|, and (b) closed-loop gain |Ac|.

Increasing |A2| *expands* the composite amplifier's open-loop gain |ac| along both the vertical and the horizontal axes, while at the same time *reducing* EOA2's closed-loop bandwidth f_2, as per Equation 3.

Figure 3(b) shows the effect on the composite amplifier's closed-loop gain A_c: all curves exhibit the same DC value of 60 dB; however, the bandwidth increases with |A2|.

It is interesting to observe, in Figure 4(a), how **OA1** and **OA2** cooperate, in complementary fashion, to maintain a constant DC value of 60 dB.

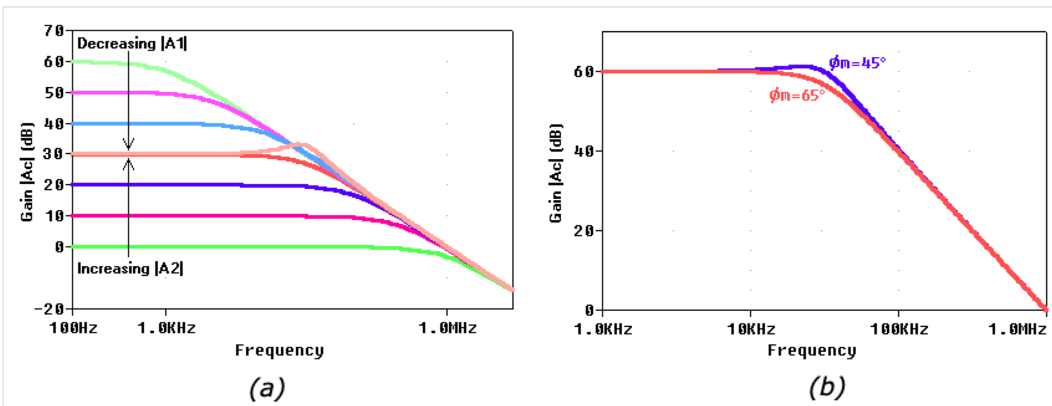

Figure 4. Visualizing the effect of 10-dB increments in EOA2's closed-loop gain |A2| upon EOA1's closed-loop gain |A1| in the circuit of Figure 2 (b). The composite amplifier's closed-loop gain |Ac| for phase margins of 45° and 65°.

As |A2| rises, |A1| drops in such a way that their DC values keep adding up to 60 dB as 0 + 60, or 10 + 50, or 20 + 40, or 30 + 30. However, also **OA2**'s pole frequency f_2 drops, and in so doing it gradually erodes **OA1**'s phase margin. How far can we raise |A2| before f_2 destabilizes the composite amplifier? This depends on the phase margin we are willing to accept.

In the absence of OA_2, the circuit would conform to the situation corresponding to the $1/\beta_1$ curve of Figure 2 of Part 1, indicating a phase margin of $\varphi_m = 90°$. With OA_2 present, φ_m gets eroded according to

$$\phi_m = 90^\circ - tan^{-1}\frac{f_2}{f_c}$$

Equation 6

Now, exploiting the constancy of the GBP on the |*a*| curve of Figure 1(b), we write

$$A_{c0} \times f_c = f_t \times A_{20}$$

Equation 7

Combining with Equations 3 and 7 and solving for the f_2/f_c ratio gives φ_m in terms of the DC gains A_{20} and A_{c0}

$$\phi_m = 90^\circ - tan^{-1}\frac{A_{20}^2}{A_c0}$$

Equation 8

Turning around Equation 8, we can find how far we can increase A_{20} for a given φ_m and A_{c0}

$$A_{20} = \sqrt{A_{c0} \times tan(90^\circ) - \phi_m}$$

Equation 9

A popular strategy is to impose $f_2 = f_c$, a situation corresponding to the $1/\beta_2$ curve of Figure 2 of Part 1, for which $\varphi_m = 45°$. This is achieved by making $A_{20} = (A_{c0})^{1/2}$. So, for the PSpice circuit of Figure 2, we need $A_{20} = (1{,}000)^{1/2} = 31.6$ V/V, which we implement with $R_4 = 30.6$ kΩ. As shown in Figure 4(b), the ensuing closed-loop gain exhibits some peaking around 22 kHz, and a –3-dB frequency of about 40 kHz.

If the application calls for the absence of peaking, then we shoot for $\varphi_m = 65°$, which marks the onset of peaking. Using Equation 9 we find $A_{20} = 21.6$ V/V, which we implement with $R_4 = 20.6$ kΩ in our PSpice circuit of Figure 2. The ensuing response has a –3-dB frequency of about 30 kHz. This is considerably higher than the bandwidth of 1 kHz that OA1 would yield if acting alone.

It is worth pointing out that besides expanding the bandwidth, the presence of OA_2 also raises the DC loop gain by A_{20}. In our circuit example of Figure 2, without OA_2 we would have $f_B = 1$ kHz and a DC loop gain of $T_0 = \beta a_0 = 10^{-3} \times 10^5 = 100$. With OA_2 present and configured for $A_{20} = 21.6$ V/V to give $\varphi_m = 65°$, f_B gets raised from 1 kHz to 30 kHz, and T_0 gets raised from 200 to $200 \times A_{20} = 200 \times 21.6 > 4{,}000$, thus improving the DC precision considerably.

You can readily implement the composite amplifier under discussion using a dual op-amp package.

In the next article, we'll talk about another method of achieving faster op-amp dynamics: raising the slew-rate.