Transient simulation helps engineers optimize logarithmic amps

Claus Kühnel

Some measurement devices exhibit large dynamic ranges ($>1:10^6$) and nanosecond risetimes. These types of current-output devices—which include photomultiplier tubes, photo diodes, ion chambers and ionization gauges—require logarithmic amplifiers to accurately buffer input signals to downstream measurement circuits or A/Ds. Log amps compress large dynamic excursions into a smaller signal range, which linear circuits can then handle accurately.

Although the basic design of a log amp is quite straightforward (Fig 1) and builds upon the exponential relationship of a bipolar transistor's collector-emitter current to base-emitter voltage, obtaining accurate transient response requires careful attention to circuit parameters. However, because log amps are *nonlinear*, an analytical solution isn't possible.

To accurately predict a log amp's transient response and stability, circuit simulation with Spice is the best approach. Using example circuits for logarithmic current/voltage amplifiers, this article discusses small- and large-signal transient modeling using the Design Center from MicroSim Corp (Irvine, CA (800) 245-3022), a Spice-based analog circuit simulator.

Core equations

Before delving into the specifics of log-amp design, first review bipolar-transistor operation. The following formula expresses the exponential relationship between collector-emitter current (I_c) and base-emitter voltage (V_{be}):

$$I_c = I_s \exp(V_{be} / V_t)$$

where I_c equals collector-emitter current, I_s corresponds to base-emitter saturation current and V_{be} represents base-emitter voltage. In addition, $V_t = k \cdot T / e$ where k is Boltzmann's constant ($1.381 \cdot 10^{23}$), e equals the elementary charge of an electron ($1.602 \cdot 10^{-19}$), and T is the absolute temperature measured in °K. For calculations of V_t at room temperature (approximately 300 °K), $V_t =$ 29.5 mV.

Now extend the basic transistor to log-amp operation. Simply stated, a log current/voltage amp outputs a voltage proportional to the log of the input current. For operation of the log amp in Fig 1, the transistor's base connects to ground, the emitter connects to the op-amp output, and the collector connects to the signal input at the amp's inverting input. Thus, for the circuit in Fig 1, the op-amp output voltage (referenced to ground) equals $-V_{be}$, the base emitter voltage.

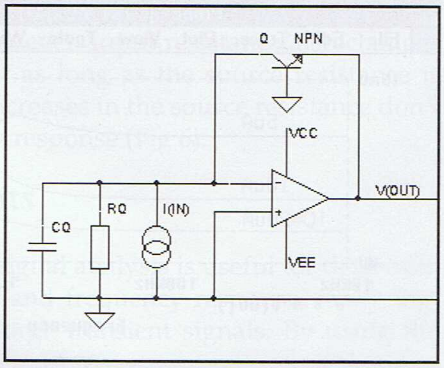

Fig 1—The basic log-amp design places a bipolar transistor within the feedback loop of an op amp, which builds upon the transistor's exponential relationship between collector current and base-emitter voltage.

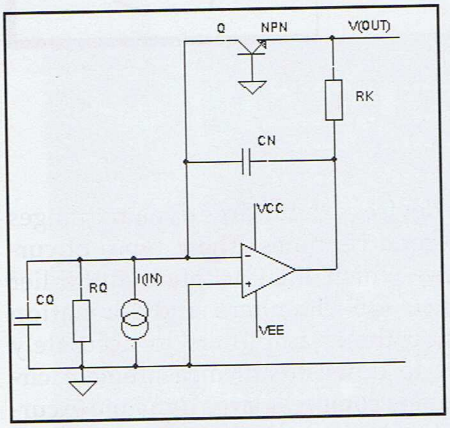

Fig 2—Frequency compensation is essential for real log-amp designs. Here, R_K and C_N stabilize the log amp's transient response.

Taking the log of the first equation and rearranging it yields the following expression, which describes the log current/voltage operation:

$$V_{be} = V_t \cdot \log(I_c / I_s)$$

where I_c is the input current. Because the transistor saturation current, I_s exceeds zero under all conditions, it isn't necessary to constrain input values for the equation.

For approximate calculations, I_s (base-emitter saturation current) is relatively constant for small changes in V_{be}. For bipolar transistors, I_s depends primarily upon transistor design and temperature. Later in this article, we'll cover more advanced circuits that account for temperature variation of transistor parameters through the use of matched transistors.

Small-signal stability

Although the dc operation of the circuit in Fig 1 might suffice for simple applications, transient stability of the log amp requires additional components as the circuit in Fig 2 shows. An analysis of small-signal behavior requires calculation of the conductance for the feedback loop. Differentiating the first equation defines bipolar-transistor operation:

$$g_n = \partial I_c / \partial V_{be}$$

$$g_n = (1/V_t) \cdot I_s \exp (V_{be} / V_t)$$

Substituting I_c (using $I_s\ e^{(Vbe\ /\ Vt)}$) yields the final equation for g_n

$$g_n = I_c / V_t$$

That final equation for g_n describes the operation of the current-dependent op-amp feedback because the collector current of the feedback transistor equals the current of the signal source (Fig 2). The equation also shows how base current doesn't affect the accuracy of the log operation.

Now you can analyze small-signal transient operation of Fig 2 by including the circuit's source impedance. At this point, the most direct approach isn't a theoretical analysis but rather simulation. Simulation first requires capturing the circuit diagram and using Spice to generate data for a plot of frequency-dependent operation.

Drawing the schematic and supplying specific values for the components yields Fig 3. A second op amp and diode-connected transistor Q_2 (and associated 120-kΩ resistor to V_{ref}) compensates for temperature variations in V_{be} of Q_1. Close thermal matching between Q_1 and Q_2

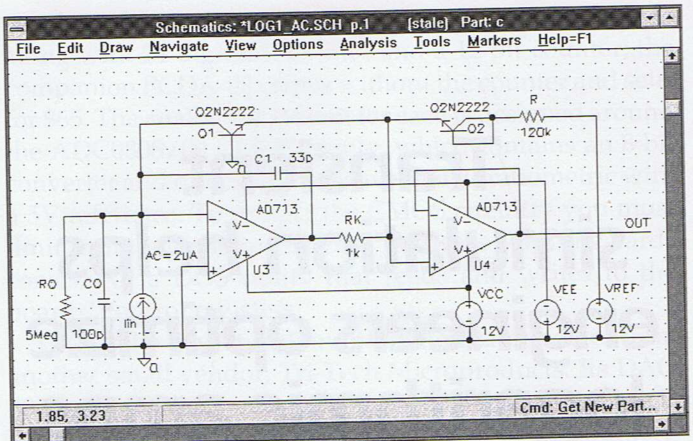

Fig 3—In addition to frequency compensation, practical log amps require temperature stabilization as well. The additional op amp (U_4) and transistor (Q_2) compensate for temperature-dependent variations in base-emitter voltage.

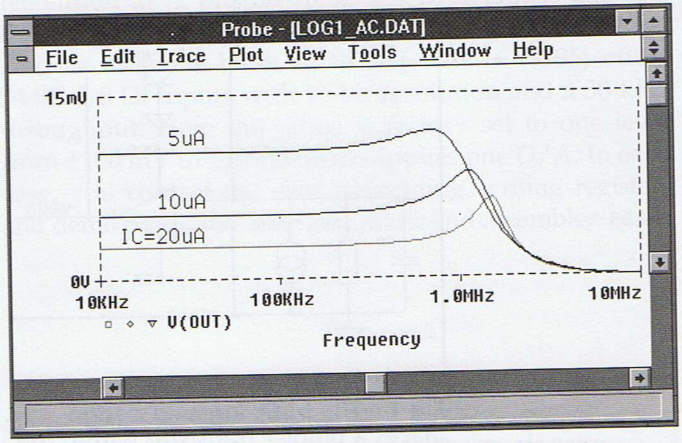

Fig 4—Like most bipolar transistor circuits, log-amp frequency response depends upon dc collector current. The plots show log-amp frequency response for 5-µA, 10-µA and 20-µA dc collector currents; dc current levels above 20 µA lead to instability.

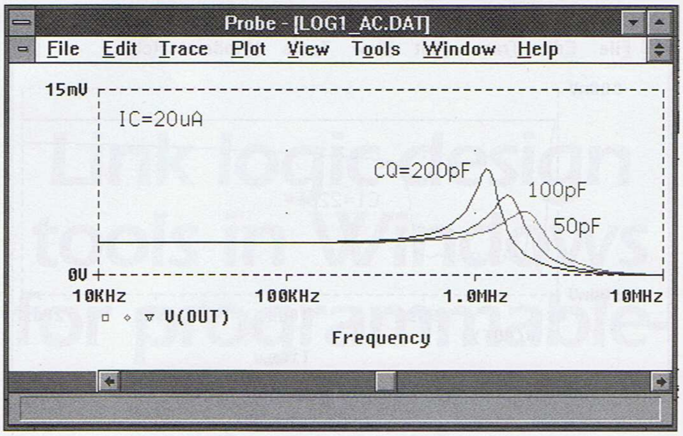

Fig 5—Source impedance also influences log-amp frequency response. For dc collector current of 20 μA, low-input capacitance offers flat frequency response.

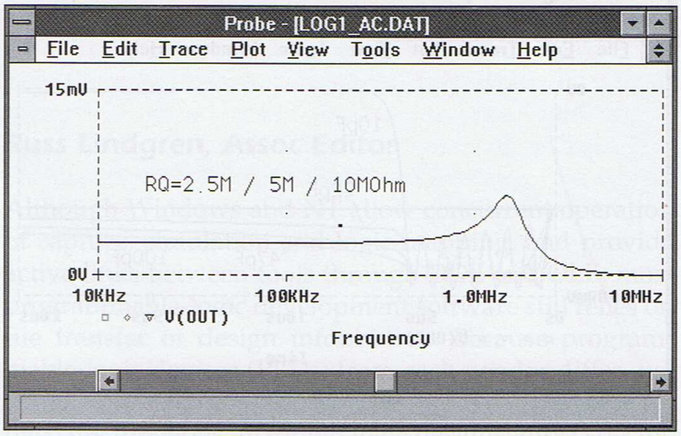

Fig 6—Although input resistance also influences frequency response, input resistances ≥ 2.5 MΩ cause little change.

improves circuit accuracy.

Although temperature-dependent circuit parameters affect dc operation, different circuit parameters alter ac operation. For instance, Fig 4 illustrates that dc-input current levels impact frequency response for ac signals. It plots circuit responses for a 2-μA ac-input current for dc-input current levels of 5 μA, 10 μA and 20 μA. The g_n equation describes this operation because, with decreasing input currents, the impedance of the feedback loop for the first op amp increases. Due to the influence of dc current on the circuit's frequency pole and Q value, setting dc-input current > 20 μA leads to instability.

The input impedance of the signal source also alters circuit-frequency response and stability. Fig 5 illustrates the effects of varying input capacitance. Note that higher values reduce signal-range reserve, thereby decreasing circuit stability. However, input resistance also changes circuit stability, but as long as the source resistance is ≥ 2.5 MΩ, further increases in the source resistance don't influence frequency response (Fig 6).

Large transients

Although small-signal analysis is useful for determining circuit stability and frequency response, many log-amp apps handle large transient signals. By using the maximum stable values for input capacitance and stimulating the circuit with a large current pulse that ranges over three decades, you can determine the optimum value for the compensation capacitor C_1 (Fig 7). Consider that simulation runs with C_1 set to 10 pF, 22 pF, 47 pF and 100 pF. Inspecting the input current source in Fig 7, you can see the input signal ranges from 10 nA to 20 μA. This 2000X pulse in input current creates an output change of 197 mV.

The large range of the 10- to 20-μA current pulse also requires a designer to analyze the input-current specifications for the op-amp model in the Spice simulation. Fig 7 uses the Analog Devices AD713, which features input offset and input bias currents < 150 pA. (A later section covers how op-amp input currents affect circuit performance). These low values for input current qualify this device for use in a log amp. In addition, the IC vendor provides a Spice model of the AD713 on the Spice Model Library Release H (dated July 1993). (Engineers can request the model by calling the device vendor at (617) 329-4700 and asking for semiconductor products tech support.)

After defining important specifications for C_1 and U_1, you're ready to simulate large-signal transient response; Fig 8 show the results. Clearly, 10 pF is too small a value

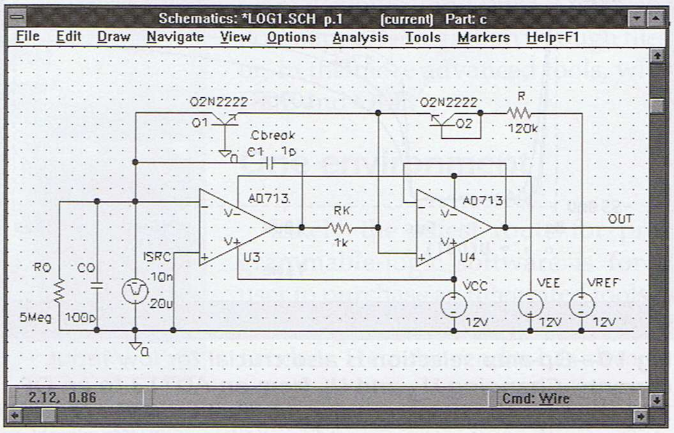

Fig 7—To simulate the log amp's large-signal transient response, modify circuit parameters for frequency compensation (C_1) and input current (I_{SRC}).

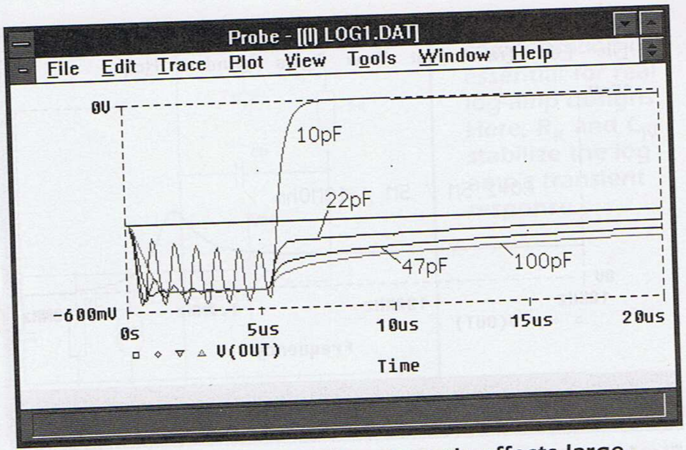

Fig 8—Log-amp compensation strongly affects large-signal frequency response and simulation helps determine C1's optimal value. With 10-pF compensation (C1), a 20-µA current pulse causes ringing and overshoot. Therefore the minimum stable value is 22 pF.

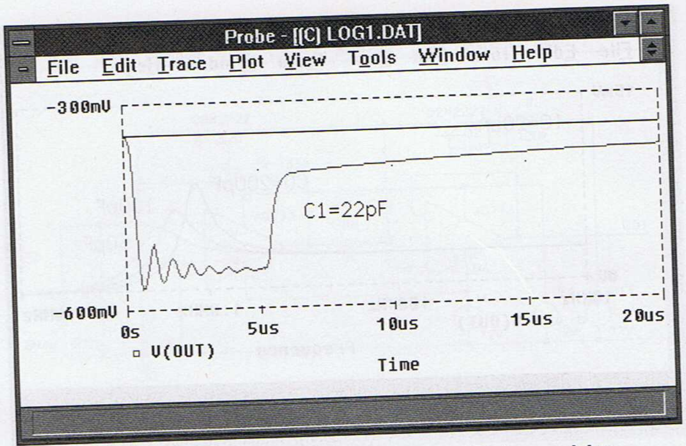

Fig 9—Although 22-pF compensation (C_1) provides critically damped circuit response for large-signal transients, the circuit takes a long time to return to a quiescent output level of -347 mV (horizontal line). Thus, the circuit accurately handles low-repetition-rate signals.

for C_1 because the circuit oscillates and then saturates at 0V, while the other values for C_1 (22 pF, 47 pF and 100 pF) offer accurate behavior with the output signal ranging from -347 mV (for 10 nA) to -544 mV (for 20 µA).

Clearly, the minimum standard-component value for C_1 is 22 pF, but due to the small quiescent input current of 10 nA, the circuit takes quite a while to return to its original zero-level state. Expanding the range of the prior simulation for just the C_1 = 22 pF plot, you can see in Fig 9 that the circuit takes much longer than 20 µsec to return to its quiescent output value of -347 mV. Thus, it works best for events with low repetition rates. Depending upon accuracy requirements, you'd have to modify the log amp with reset circuitry to handle events that occur < 200 µsec apart.

Just as you've seen how low-level (10-nA) input background current affects circuit application, op-amp specs also change circuit operation. What happens if you replace the low-input-current AD713 to an op amp with higher input and bias currents? For example, selecting an OP-275 (available from Analog Devices and also on the Spice Model Library disk), which offers input and bias currents of 150 nA, causes several important changes in circuit response (Fig 10). First, notice how the minimum output voltage from the log amp becomes -405 mV, whereas the prior circuit offered -347 mV value. Clearly, the log amp is losing signal range due to the op amp's increased input current. Thus, for low-level signals of < 150 nA, the OP-275 is a poor choice. For low-level input currents, you need an op amp with low bias and offset currents, most likely using a FET input stage. However, because FETs tend to drift over temperature, you must decide how to trade off low drift or low input currents—you can't get both.

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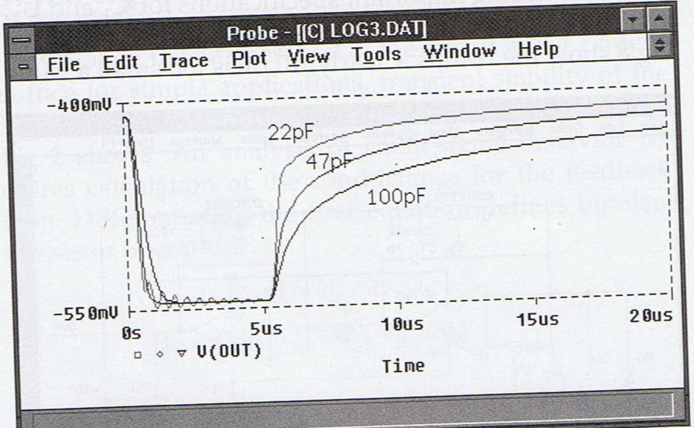

Fig 10—Op-amp selection is also crucial for low input currents. Changing U_3 and U_4 from an AD713 to an OP-275 changes the quiescent output level to -405 mV. This change reflects the increased input bias and offset currents of the OP-275 and reduces circuit sensitivity to low input currents.

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Claus Kühnel (kuehnel@dial.eunet.ch) received his MSc and PhD in electrical engineering from the Technical Univ in Dresden, Germany and currently resides in Switzerland. He's developed DSP and microcontroller applications for traffic control circuits, which use DSPs to monitor traffic speed. He's also designed measurement circuitry for sports events.