Improve FET-based gain control

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One problem with standard FET gain-control circuits is increased noise when you use the FET as a part of a resistive attenuator in series with an op amp. This configuration attenuates the signal before amplification; hence, it requires much higher gain bandwidth and better noise performance from the op amp. When you substitute the FET for the gain-setting resistor in a noninverting op-amp circuit, distortion limits the circuit configuration to applications in which the input voltage is less than a few hundred millivolts. The FET imposes this limitation, because the channel-depletion layer is a function of V_{DG} and V_{GS}. The improved circuit in Figure 1 uses the FET as part of the feedback loop. The voltage across the FET is limited in this application, and the noise performance is good. An added bonus is improved linearity performance. The transfer function for the improved circuit is as follows (Reference 1):

$$-\frac{V_{OUT}}{V_{IN}} = -G = \frac{R_2 + R_3 + \frac{R_2 R_3}{R_4}}{R_1}.$$

When $R_2+R_3=R_1$ and $R_4=R_{DS}$ (FET drain-source resistance), the transfer function reduces to $-G=1+R_2||R_3/R_{DS}$. The minimum drain-source resistance for the FET on hand, J271, is 76Ω at $V_{GS}=0V$. The actual V_{DS} at the inception of distortion varies with each FET, but keeping V_{DS} lower than 200 mV usually prevents distortion. In the design in Figure 1, the FET drain-source voltage is limited to approximately 100 mV to prevent distortion. The divider action between R_3 and R_{DS} creates V_{DS} from the output voltage, according to the following equation:

$$V_{DS} = V_{OUT}\frac{R_{DS}}{R_{DS}+R_3} =$$

$$0.1V = 5\frac{0.076}{0.076+R_3}.$$

You can calculate R_3 as 24.5 kΩ and select 24 kΩ. The parallel value of R_2 and R_3 determine the maximum circuit gain. Selecting R_2 as 3 kΩ yields R_1 equal to 27 kΩ and a maximum gain of –37. The measured gain at $V_C=V_{GS}=0V$ is –36.1, which correlates well with the calculated value. R_A and R_B are feedback resistors that linearize the FET's V_{GS} versus R_{DS} transfer function. You can normally obtain adequate linearization with equal-value resistors, but you can also control the slope of the transfer function by setting the resistor ratio. The graph in Figure 2 shows that R_A modifies the transfer function and linear control-voltage range (V_{GS}). The p-channel FET, J271, requires a positive control voltage, but you can use a negative control voltage with an equivalent n-channel FET, such as the J210. The circuit is versatile and provides low distortion, wide range, good linearity, and low cost.

The TLC071 op amp has low input-bias currents and has provisions for input offset-voltage correction.

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Reference

1. Mancini, Ron, "Op amps for everyone," Texas Instruments, September 2000, pg 3.