Op-Amp Audio

Minimizing Input Errors

For this second December issue, the column looks at a number of op-amp issues regarding their use in high quality audio circuits. For now, this wraps up the series on this topic. As noted below, this final 1998 installment also marks my departure from this regular monthly column, in order to partake in a new project.

Op-amps and audio: Recalling the imperfect op-amp gain stage model printed in the Sept. 1 column, we will first review it with regard to the error sources, V1-V5 *(Fig. 1)*. There is an errata note for the OP177 data sheet circuit originally referenced. It was Figure 3 on early revisions, but Figure 24 now.

In the first two parts of the series, we discussed using buffers (both IC and discrete), along with their role in minimizing output-to-input power-related errors. This error source is symbolized by V5, with the dotted coupling indicated. With the use of an appropriate U2 buffer or load-immune op amp U1, we'll consider V5 errors negligible, and then move on to the others.

The remaining errors are V1-V2 and V3-V4, four in all. But note that these are *paired* error sources, so if you understand how to deal with one of the pair, you also can deal with its twin. In essence, these pairs reduce to two basic types of error sources, each with distinct minimization solutions.

V1-V2 source-impedance-related errors: V1 and V2 are ac errors, and they are proportional to the impedances seen at the op amp's (+) and (–) inputs (again as indicated by the dotted coupling). Understanding a very basic semiconductor distortion mechanism is helpful here.

A byproduct of semiconductor manufacture is the fact that often, the junction capacitance is a nonlinear function of applied voltage. Applied ac (audio) modulates this capacitance, which gives rise to even-order harmonic distortion. You can see the basis of this by studying various transistor data sheet C/V curves. Note that it doesn't matter if such junctions are within a discrete transistor or an IC, the result is the same.

For audio circuits, taking various steps can help to minimize distortion due to this nonlinear capacitance. One is to bias the capacitance to a high dc voltage. Another is keeping the ac signal swings small. A third step is to choose devices with less raw capacitance (and therefore, less sensitivity), and, finally, operating with low source impedances.

In op-amp circuit configurations, it is important to note this input stage distortion mechanism applies to *noninverting-mode operation*, such as in Figure 1, where the applied common-mode (CM) voltage is highest. And, in terms of susceptible device categories, by and large it is found in op amps using *junction-isolated* FETs (JFETs). Note also that it is not a factor in inverting mode circuits, since by nature these don't see CM voltage.

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Within JFET-input op-amps there are actually two such capacitors present, corresponding to V1 and V2 errors. They are directly in the signal path, with one appearing at each input terminal, i.e., the gate of the FET input devices. The capacitance is formed as part of the manufacturing process. It electrically appears between the corresponding input and one supply rail, or ac common (for p-channel FET amplifiers the rail is typically $-V_S$).

In Figure 1, source resistance R_S and the internal nonlinear capacitance of U1 form a low pass filter at some high frequency—usually well above the audio bandwidth. However, this seemingly innocuous relationship doesn't fully reveal what can happen in sensitive, low-distortion circuits, or if R_S is high. Or, worse yet, when the op amp has appreciably higher input capacitance (as it might in the case of large-junction, low-noise input transistors). All these factors exacerbate the distortion generation.

Normally it is an audio rule-of-thumb to use low feedback resistances to minimize noise contribution. In Figure 1, the feedback source resistance ($R_S(-) = R_F \parallel R_{IN}$) is <1 kΩ, but the input R_S may be higher, so the amplifier's $R_S(+)$ and $R_S(-)$ aren't necessarily equal. In practice, given the very-low-distortion capability of today's op amps, (THD+N of –100 dB or better), it is easily possible to see distortion effects due to mismatched $R_S(+)$.

Fortunately a neat distortion solution is at hand, involving profitable use of the op amp's basic nature. Any such op amp always has *two* similar nonlinear capacitances, and with the input devices matched, it can be assumed the capacitors are the same. So, the distortion effects can be balanced and nulled, if within the external circuit, $R_S(-)$ is made equal to $R_S(+)$. Or, more precisely, when the total impedance seen looking out of the (–) input is made equal to that at the (+) input.

With an equal source impedance condition, the two sets of distortion components generated by the nonlinear capacitances match, or V1 = V2. Since this distortion is CM to the op amp (not differential), it is rejected. A distinct operational "sweet spot" occurs, with even-order output THD going to a minimum.

Therefore, to optimize noninverting op-amp circuits against V1-V2 errors, choose R_{IN} and R_F so their Thevenin equivalent value is equal to R_S, which minimizes distortion. C_F, if used, can upset exact high-frequency balance. For such cases, a compensating value can be used, from pin 3 to ground.

Wondering about your favorite op amp's susceptibility to this distortion? A good test for it is a noninverting gain stage of 2X (with $R_S(-)$ <1 kΩ), and R_S switchable between <$R_S(-)$, =$R_S(-)$, and >$R_S(-)$.With V1-V2 errors, THD+N plots vs. R_S can reveal higher distortion for mismatches.[1]

Extrapolating JFET-input op amps to even more sensitive topologies leads us to Sallen-Key active filters, which, by definition, use noninverting amplifiers (often unity-gain, JFET-based followers). For absolutely lowest distortion here, a mirror-image network "$Z_S(-)$" can be used in the feedback path, in lieu of a direct connection. $Z_S(-)$ is simply a dummy RC component set, to mimic the real $Z_S(+)$ filter elements, as seen looking out from the op amp's (+) input.[2] Other JFET-input op-amp circuits also can optimize R_S, as described below.

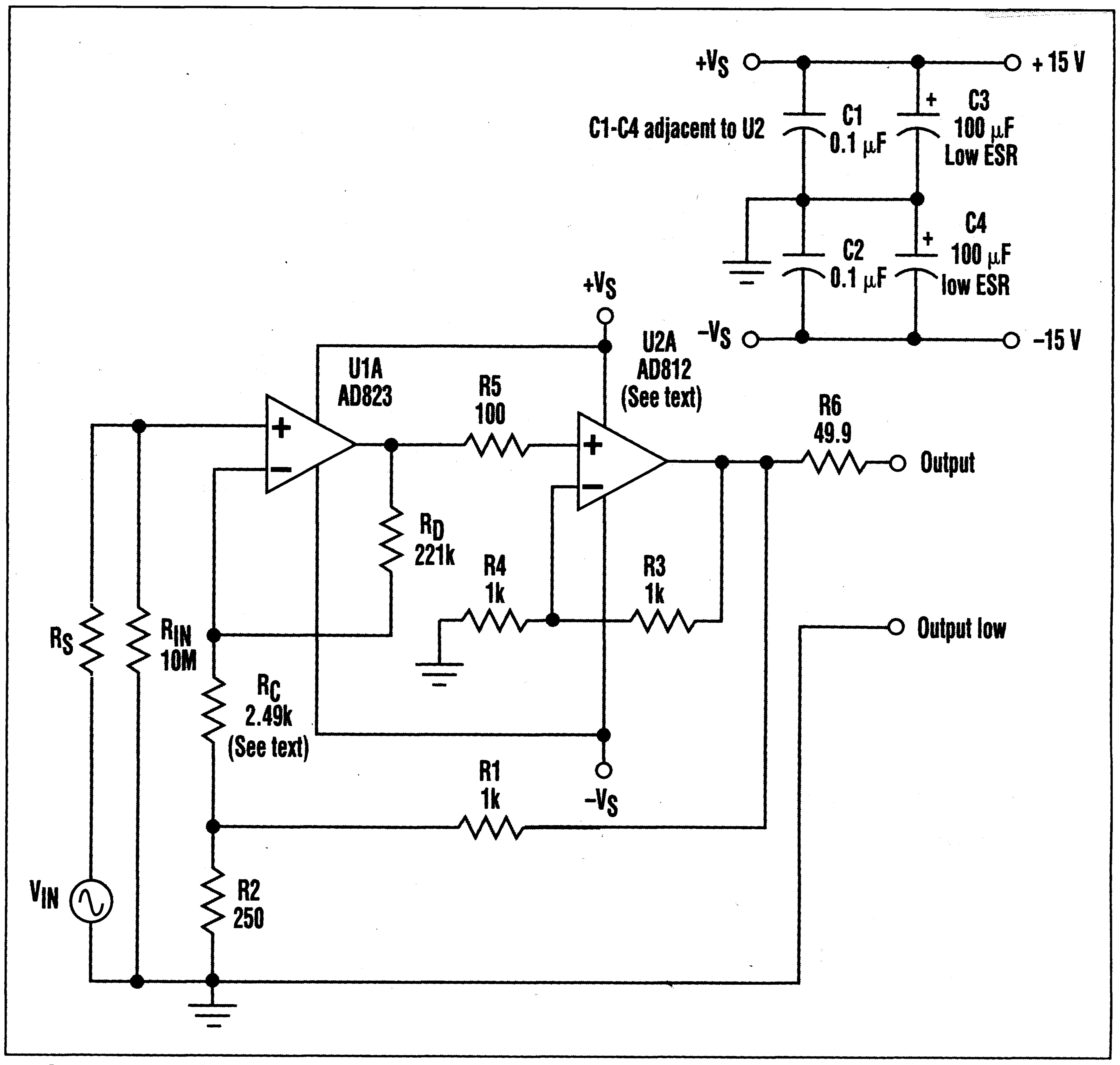
V3-V4 power-supply-related errors: The two remaining errors are V3-V4, which relate $+V_s$ and $-V_s$ supply-rail noise to the amplifier inputs. These power supply rejection (PSR) errors are usually given in dB. Some might think these errors straightforward. But in real life, things are a bit more complex. Let's see why.

If you study a typical op-amp data sheet, you'll notice that there is a PSR spec for both $+V_S$ and $-V_S$, as well as one for common-mode rejection (CMR). But, close inspection reveals that *these are dc specs.* Over audio frequencies, typical PSR behavior is plotted, and it degrades with frequency at 6 dB/octave. Common values are 100 dB or more of dc PSR (or CMR), dropping to 80 dB at 1 kHz. Ironically, such popular audio op amps as the 5532 and 5534 don't provide their users PSR and CMR curves!

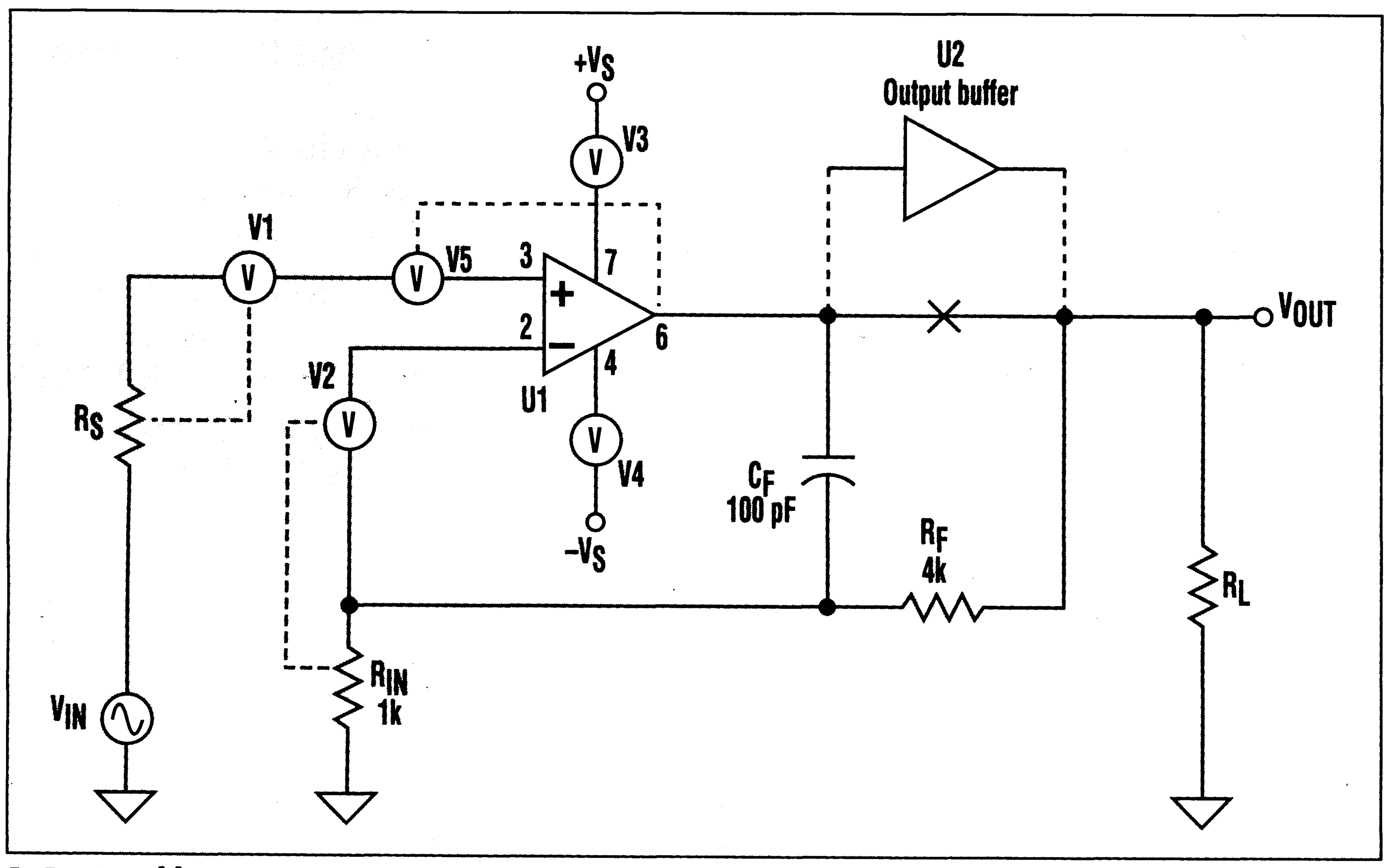
Also, note that PSR will often be poorer for one of the supplies, sometimes noticeably so. CMR and PSR are related—both measuring front-end response to signals common to the normal inputs, or via the rail(s) as a signal source. It is typical to specify PSR for symmetrically varying (±) supply voltages. Unfortunately, real-world power sources don't always vary neatly. So, a realistic audio consideration would be to analyze things in terms of the *worst* PSR/CMR curve from the data sheet, and use that data at various frequencies. We'll assume an 80 dB/1 kHz PSR error in an example calculation.

An error 80dB down may sound good, until we add some mitigating factors. In Figure 1, for example, the 5X noise gain makes an 80 dB/1 kHz error about 14 dB worse, or 66 dB/1 kHz, *as referred to the output.* And in almost every case with conventional op amps, this still gets worse by 6 dB/octave with increasing frequency.

Putting it in perspective with an actual output signal, we'll talk in terms of op-amp input-referred errors (since that's where PSR errors couple). Assume 1 V p-p output at 1 kHz, and an op amp gain-bandwidth of 10 MHz. This means that to produce the 1 V p-p, the amplifier's input signal will be 100 µV p-p. If the supply rail sees a 1 mV p-p/1 kHz noise (for whatever reason), this noise referred at the amplifier input will be 0.1 µV p-p. The ratio of the desired signal to the noise is 60 dB—*not* such a good ratio. Also, consider the possibility that CMR or PSR could be worse than 80 dB, or the power-rail noise higher.



2. This example design applies all the concepts of the audio series, in an optimized gain-of-five stage. In addition to minimizing V1-V5 errors, it also eliminates thermal distortion and crosstalk in output stage U2. Open-loop bandwidth of the first stage is set by local feedback, and is about 100 kHz.



1. Depicted here is a noninverting op-amp gain stage with five error sources, V1-V5. Output buffering or a load-immune op amp minimizes V5. V1-V2 are minimized by matching source impedances, and V3-V4 are minimized by careful power-supply design.

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Another subtle point is that the PSR frequency-response corners for the $+V_S/-V_S$ rails may vary from one another, and may also vary with respect to the open-loop-gain corner. Thus, the sample numbers used here could be different in reality.

The example assumed a 10-MHz gain-bandwidth op amp. But, if we consider an op- amp with ten times the gain-bandwidth (100 MHz), the input signal reduces ten-fold, to 10 µV p-p. With the same power-rail noise, this tends towards an effect of PSR errors of similar order (80 dB) being much more serious. In practice, such a higher gain-bandwidth op amp will very likely also have greater PSR.

The main general point being made is that real-world PSR and CMR errors can be much worse than a casual glance at a data-sheet curve may suggest. In fact, a better way to look at the topic of V3-V4 errors is to consider the rails of an op amp simply as another signal input, and proceed accordingly. Good supply regulation and bypassing will go a long way toward minimizing and controlling these errors. In fact, it isn't unrealistic to set V3-V4 error goals referred to a working op-amp input signal of –100 dB (or better). This will generally require some careful supply regulation, since you can't always count on an op amp providing 100 dB of V3-V4 error isolation over the applicable frequency range. Current-feedback types, for example, have typical PSR and CMR of 60-70 dB.

An optimized amplifier example: To illustrate all of the error-minimization and bandwidth-extension principles discussed in this series, the circuit of Figure 2 is offered. It can be recognized as a cousin to a previous 0.5-A line-driver/headphone amplifier.[3] It also has similar thermal-distortion suppression, as the U1 stage servos out U2 thermal errors. Three distinct feedback paths are used.

This line-driver circuit has an overall gain of about 5X, as set by the R1-R2 loop. U2 is a dual current-feedback amplifier, allowing 50 mA or more of output while buffering U1.

Compensation for V1-V2 errors in U1 (a JFET-input op amp) is provided by R_C, set equal to R_S. With a variable R_S such as a volume control, a nominal gain value is used, in this case 2-3 kΩ.

First-stage open-loop bandwidth control is exercised in this circuit, as it applies to U1 and the local feedback loop R_D-R_C. For the values shown, U1's open-loop bandwidth is about 100 kHz. Were R_D open, the U1 stage would function as a more-conventional (narrow bandwidth) op-amp.

Control of V3-V4 errors is not integral to this amplifier, except for the local bypassing shown. Tight regulation of $\pm V_S$ will aid this, and is recommended for noise minimization.

Summary of audio op-amp series notes: The discussions above wrap up our look into various op-amp and circuit issues which help determine high audio performance. Over the years, I have found all of these techniques useful for improving audio circuits, and hope you will also.

Some parting comments: This column wraps up a two-year run of "Walt's Tools and Tips," an experience I have enjoyed immensely. I hope you have as well, and I thank all those who have contributed comments.

Over the next year (or more), I will be embarking on a major new project. Unfortunately, this will preclude the time expenditure it takes to put together the kind of material I like in this column. Therefore, I am taking a column sabbatical for a period of time. I hope to return to these pages sometime soon to continue these analog-oriented talks. Happy Holidays to all.

References:

1. Jung, Walt, "Op-amp Device/Topology Related Distortions" of 'Audio Line Drivers and Buffers,' part of Chapter 8 of *System Applications Guide*, Analog Devices, 1993.

2. Wurcer, Scott, "An Input-Impedance Compensated Sallen-Key Filter," Analog Devices AD743 data sheet.

3. Jung, Walt, "Composite Line Driver with Low Distortion," *Electronic Design* Analog Special Issue, June 24, 1996, p. 78.

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Walt, it's been a real pleasure Tooling and Tipping with you. We'll miss you.—*Bob Milne, Managing Editor*