Op Amps in Line-Driver and Receiver Circuits

Part 2. Audio applications

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INTRODUCTION

The first article in this series (*Analog Dialogue 26-2*),* covering general line driving and buffer design considerations, gave examples of *video* line-driver and -receiver designs. In this article, we consider *audio* line drivers and receivers. The general techniques are still germane, in particular the amplifier tables and buffer design/selection guidelines. Capacitive load isolation is also important to audio drivers; long transmission lines appear capacitive because audio transmission systems do not tend to use terminated transmission lines. In general, the "housekeeping" rules on layout and bypassing are also strongly recommended for practical audio circuits of any type, especially drivers (and were followed for the examples in this article).

Transmitting audio signals between various components usually involves some form of tradeoff. For highest performance, fully differential or balanced transmission systems are best at rejecting low frequency and r-f noise. Figure 1 is a block diagram of a typical audio system using differential transmission. In concept, a variety of input/output coupling schemes are available for a balanced transmission system; they will be discussed briefly.

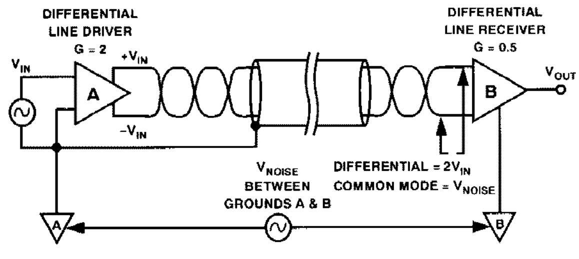

Figure 1. Audio balanced transmission system.

Transformers [1]-[4] have been a traditional input or output audio line-coupling element. While unexcelled in certain areas, they have well-known problems: noise pickup, poor frequency response, distortion, and limited operating level—problems that can be mitigated to some degree (often at fairly high cost).

The transformer's outstanding virtue is its ability to isolate galvanically voltages up to its windings' breakdown potential; signals can be transmitted between circuits with hundreds of volts of potential difference, a feature not easy to achieve with solid-state circuits. Quite high common-mode rejection (CMR) is also available, >100 dB over the audio range, less at high frequencies.

Figure 1 can use either transformer or active coupling to the line. The goal for either approach is to reproduce the input signal, V_{IN}, at the output, while rejecting noise between grounds A and B by 80-100 dB. A typical unity gain design uses a line drive of $\pm V_{IN}$ and a receiver gain of 1/2, to maximize receiver CMR.

AUDIO LINE RECEIVERS

A major purpose of this circuit and all line receivers is to reject common-mode noise, as might be picked up on a twisted-pair transmission line. A brief review of the topologies and pros and cons of active audio line receivers helps in understanding their evolution. The classic single-op-amp, 4-resistor subtractor circuit of Figure 2 can act as a differential amplifier. When the resistor ratios provide gain, the circuit is known as an instrumentation amplifier (IA). Some of today's IC audio line receivers, based on feedback circuitry, are direct descendants of this circuit. [5]-[9]

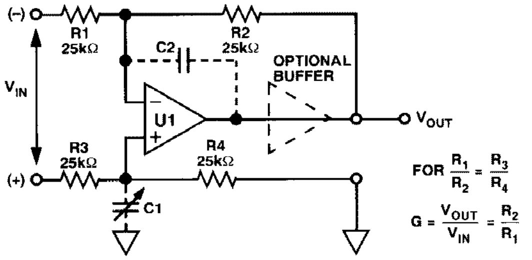

Figure 2. Simple line-receiver topology.

The simple line receiver

The circuit of Figure 2 is simple; the minimum ingredients are four matched film resistors and a good audio op amp. While it works functionally, its degree of common-mode rejection (CMR) may be problematical. The performance of such bridge-based difference amplifiers depends critically upon resistor-ratio matching—including source impedances in series with R1 and R3. The amplifier also contributes error, but with a high-quality op amp, noise rejection is limited by ac & dc bridge unbalance.

Selecting four discrete resistors from a same-vendor-same-batch lot, to ratio-match within 0.1%—or (more likely) using a purchased thin-film network with a 0.1% specified mismatch—results in CMR of 66 dB. In general, the worst-case CMR of this type of circuit (amplifier CMR ≥100 dB):

$$\mathrm{CMR\ (dB)} = 20 \log \frac{1 + R_2/R_1}{K_r}$$

where K_r is the net ratio tolerance in fractional form.[5] Clearly, for high and stable noise rejection with temperature tracking, thick- or thin-film resistors integrated on a single substrate with ratio matching to within 0.01% (from vendors such as Caddock and Vishay-Ohmtek) are preferred to selected individual resistors.

The Figure 2 topology is most effective when the resistors and amplifier are made simultaneously in a single monolithic IC. The Analog Devices 8-pin SSM-2141 and SSM-2143† are such ICs, designed and characterized as low distortion, high CMR audio line receivers with net gains of 1.0 (SSM-2141), and 0.5 (SSM-2143). The SSM-2141 has the same resistance values as in Figure 2, while the SSM-2143 uses 12-kΩ/6-kΩ resistors.

Amplifier protection is inherent in two ways: the input common-mode voltage (CMV) in the unity-gain case is halved at the amplifier inputs (and can be further reduced by resistors to ground), and the series resistance limits fault currents due to excessive

*Use the reply card. Circle 18 for *Analog Dialogue* 26-2, 19 for the article reprint.

†Technical data for the amplifiers mentioned in this article can be found in the *1992 Amplifier Reference Manual*, available at no charge. If you need a copy circle 10

CMV. Receiver circuits not needing input resistors may call for input resistors anyway for protection in practical circuitry.

Figure 2's working CM input range is $[1+(R_3/R_4)]\times V_{CM(U1)}$, and the differential input resistance is $R_1 + R_3$. Gain of the circuit isn't easily changed, because of the matched R-ratios.

For wideband audio uses, the bridge *impedance*-ratio match needs to be maintained for ac, to achieve flat CMR with increasing frequency. Capacitances at the R_2/R_1 and R_4/R_3 nodes need to be balanced. This is best achieved with very low and/or balanced parasitic capacitances at C_1-C_2.

Implementing the simple line-receiver function

For adequate input impedance, these receivers typically use input resistance ≥20 kΩ. With a well matched resistor network and low- or balanced parasitic capacitances, suggested amplifiers are the AD711 and AD744 (singles), and the AD712, AD746, OP-249 and OP-275 (duals). With 10-25 kΩ resistances, extremely low amplifier voltage noise is not a critical requirement, but high slew rate (SR) and husky output drive permit high amplitude levels, clean high-frequency response, and 600-Ω loads.

For circuits such as these, that resistively load the source, the line and source resistances, if unbalanced, can compromise CMR. For example, a mismatch of 2.5 Ω can easily occur in wiring; if it is not balanced out, CMR can be degraded to 86 dB. These circuits behave best when the sources are balanced and low-impedance.

Other issues with the simple line receiver

The circuit of Figure 2 has symmetry of a sort, but it is not really balanced. If a balanced pair of input voltages, $+V_{IN}$ and $-V_{IN}$, are applied to the two inputs, the currents in the two legs are different. Here, the current in the R3 leg is $V_{IN}/50$ kΩ and the current in the R_1 leg, because of the op-amp feedback action, is $[-V_{IN} - V_{IN}/2]/25\text{ k}\Omega = -3V_{IN}/50\text{ k}\Omega$, *three times as much*. Thus, the inputs load the source and the connecting lines differently. If the source is a transformer winding, the circuit will unbalance the line, driving the minus-input side to virtual ground.

Ideally, an audio line receiver should exhibit equal ac loading at the two inputs. With the simple line receiver of Figure 2, this goal is not met. Nevertheless, for a grounded symmetrical source and line pair, with a single receiver, loading of the source resistance will produce a gain error, but the asymmetrical current will not substantially affect the CMR because feedback will compensate for the greater voltage drop on the R1 side. But, in systems with numerous balanced transmission line pairs, the input current imbalance may be more serious; associated fields will not cancel as they do for completely balanced loading. Thus there is potential for crosstalk impairment in such systems.

While not optimum in large systems, the simple line receiver is nevertheless useful in more modest situations. With resistances R_1-R_3 relatively high (20 kΩ or more), it is quite adequate for small-scale or confined systems where I/O lines are relatively short or few in number—or are not cabled. Devices like the SSM-2141 and SSM-2143 serve well as efficient single-IC solutions.

A balanced form of line receiver

Birt, of the BBC, analyzing the simple line receiver topology, has described a balanced form[4]: in Figure 3, U1 uses an identical 4-resistor network, but the unity-gain inverter, U2, drives R4's previously grounded reference terminal at $-V_{OUT}$. This equalizes the input currents in the ± input legs and provides a choice of a balanced push-pull output with gain of R_2/R_1 or a single-ended output of either polarity with gain of 1/2 $[R_2/R_1]$ (one-half that of the Figure 2 circuit). Existing line receivers can be converted to the balanced topology by adding an appropriate inverter, U2, and doubling the gain ($R_2/R_1 = R_4/R_3 = 2$) if necessary. The common-mode range of this circuit is the same as for Figure 2, but common-mode rejection at V_{OUT} (or $-V_{OUT}$) is about doubled with all resistances nominally equal. The inverter resistance ratio, R_6/R_5 affects balance—but not CMR.

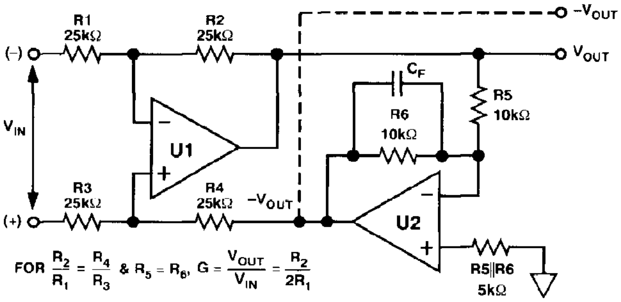

Figure 3. Balanced line receiver using push-pull feedback path.

Other balanced line receivers

Why not use an instrumentation amplifier [5-8] as a line receiver? Conventional high-input-impedance instrumentation amplifier circuits (including single-chip in-amps) can easily achieve the goal of fully balanced input loading. Too, they may specify high CMR —but generally at low frequencies. They may not be desirable for other reasons. For example, the input resistors of circuits like Figure 2 reduce common-mode voltage and limit fault currents, a necessary input-protection consideration in many real world audio systems. To add matched attenuators ahead of an in amp for this purpose degrades performance and adds cost.

An "all inverting" balanced line receiver

Figure 4, using only inverting amplifiers, can be configured for high CMV range and input resistance. The CMR of this circuit is limited essentially by the ability to match resistance ratios, since the amplifiers' CMRs are irrelevant. The maximum input voltage the circuit can handle is limited by the output range of U1, so R_1/R_2 can be increased to deal with higher common-mode input voltages. The differential input resistance is R_1+R_3.

Unlike the others, the gain of this circuit can be adjusted with a single resistance, R_5, without disturbing the CMR. Gain can be flexibly adjusted to values both greater and less than unity. As shown, the drive is a balanced signal, but note that it can be driven with single ended sources at either the (+) or the (–) terminal. Multiple inputs can be summed, by adding additional ratio-matched input-resistor pairs. This example shows a gain of 0.5.

In this improved version of the otherwise well-known circuit [5]-[8], phase lead compensation enhances high-frequency CMR. R_4 is shunted by a low capacitance (driven through an attenuator), chosen to compensate for the lag through U1; it maximizes phase matching of the ±CM signals at U2. The attenuator (R_6-R_7) can be used to avoid extremely low capacitance values. Its nominal division ratio is approximated by:

$$K_c = \frac{1}{2\,\pi\,\mathrm{BW(U1)}\,R_4\,C_1}$$

where K_c is the division ratio of R_6-R_7. For this example, with BW = 5 MHz (the closed-loop bandwidth of U1), K_c is about 0.6, providing an effective C_c of about 3 pF. Circuit parasitics,

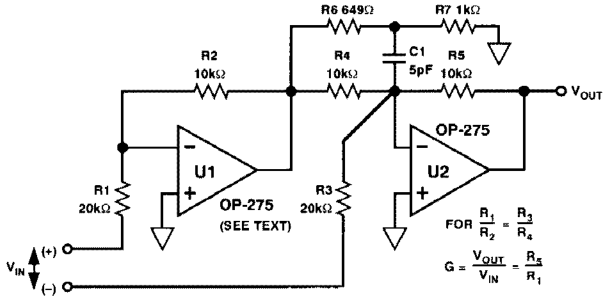

Figure 4. Dual-Inverter line receiver.

loading effects, and part variations make this inexact; but, once nominal compensation for a given layout and device is achieved, a 30-dB improvement in CMR at 10 kHz is possible.

Line-receiver performance

The balanced line receiver configurations of Figures 3 and 4 were tested for CM performance, with the common conditions of $G = 0.5$, $V_s = \pm 18V$, a balanced 600-Ω source, and a 10-V rms 20 Hz to 50 kHz input sweep, with filter bandwidth of 80 kHz. Figure 3 was implemented with an SSM-2141 and an OP-275 inverter, with $C_f = 68$ pF. Figure 4, implemented with an OP-275 and a resistor network matched to 0.005%, is shown with the phase-lead-network values for best high-frequency CMR.

The excellent results for both circuits are shown in Figure 5. CME is −100 dB or less for frequencies up to 1 kHz, with little sensitivity to source impedances of 50 Ω to 600 Ω (not shown). The Figure 4 topology offers better results at the higher frequencies, perhaps due to the trimming technique used (not applicable to Figure 3). The worst-case CM errors are still less than −80 dB at 10 kHz, still very good for an untrimmed circuit. CM data for Figure 4 were also taken for the other devices noted above, with good-to-excellent results, but the OP-275 is illustrated here because of the generally higher output drive. THD+N data, taken on both circuits, was mostly dominated by the noise floor of the circuit, at about 100 dB below 1 V rms.

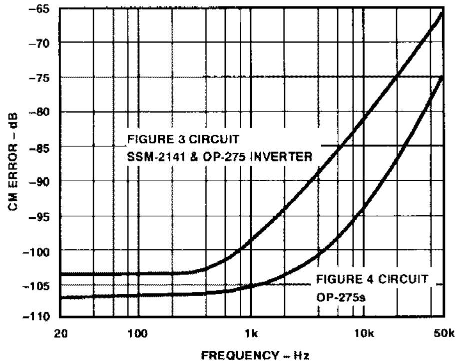

Figure 5. Balanced line receivers—CME vs. frequency (G=0.5, $V_S = \pm 18$ V, $R_S = 600$ Ω).

AUDIO LINE DRIVERS

Audio line driver principles do not differ substantially from those discussed in the first of this two-part series (*Analog Dialogue* 26-2). Indeed, many of the op amps mentioned as video drivers and/or buffers also do well for audio. Types already popular for audio include the AD845, AD846, AD847 and OP-42, while newer types such as the AD797, AD817, AD818 and OP-275 should upgrade performance in specific audio applications. The circuits shown here use series resistance to isolate capacitive loads; with 600-Ω lines, the compensatable gain error is <1 dB.

Single-ended line drivers

Single ended audio driver circuitry can be built using Fig. 2 of Part 1 as a starting point; indeed that circuit example (with appropriate op-amp choice and gain scaling) can serve well as an audio driver. Using the AD845, the circuit has low loaded distortion with high slew rate (SR) and output current.

A wide-dynamic-range ultra-low-distortion driver

Single-ended line drivers may seem simple; but, when pushed to their performance limits in dynamic range and distortion, they require careful device choice. One answer is the AD797, a new op amp (see page 18) with typical gain of 146 dB, <1 nV/√Hz noise, and a unique 50-mA distortion-cancelling output-stage design (patent pending).[11] Its buffered single-stage topology also results in improved bandwidth (450 kHz for gain of 1000), phase margin, and settling time (800 ns to 16 bits).

Figure 6 shows it in an application combining line driving with amplification (gain of ×10). Internally compensated to be stable at unity closed-loop gain, it delivers optionally improved performance at higher gains with a 50-pF capacitor connected between the output and its distortion-cancellation terminal, pin 8. The values for R1-R2 are recommended for best noise (select gain/source resistors with care; high values will degrade noise performance). For a 600-Ω load, typical THD in this application is −115 dB at 20 kHz at 3-V rms output, with ±15-V supplies—and the circuit's −3-dB bandwidth is 6 MHz.

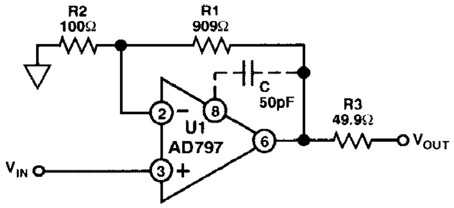

Figure 6. Ultra-low distortion ±50-mA driver.

A composite line driver

Another useful circuit technique [10] combines two amplifiers in a closed loop; the composite device forms a high-performance line driver, capitalizing on their individual strengths. In Figure 7, a low-distortion line driver combines the high input impedance of a FET-input IC and the power of a high-performance op amp that can deliver >100 mA. Here, the AD744's low bias current minimizes offset error over the range of adjustment of a 50-kΩ volume control. The wideband high-current AD811, fed back for gain of 2.5, boosts both current and voltage (i.e., power); it can drive 150-Ω lines with excellent linearity.

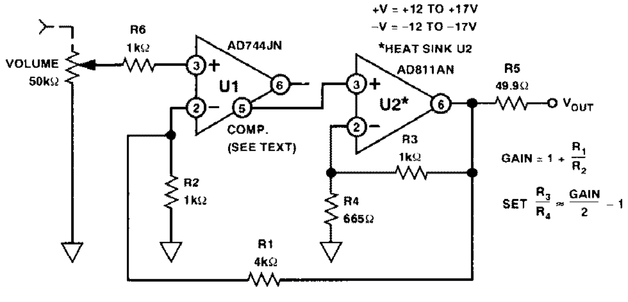

Figure 7. A low-distortion-composite ±100-mA line driver.

In an unusual connection (unique to the AD744), U1's output is (yes!) left open; pin 5 (the compensation terminal) drives U2's high-impedance input for increased overall phase margin. The gain-bandwidth and SR of U1 are boosted by the closed-loop gain of U2, an AD811 high-performance transimpedance amplifier. Though primarily intended for video, its high output-current drive capability enhances linearity in audio line driving.

As a non-inverting feedback amplifier, the circuit has an overall gain determined by R_1 and R_2, in this case the gain is 5× (i.e., 14 dB). The gain of the local loop around U2, determined by R_3 and R_4, reduces U1's output voltage drive and enhances overall stability. R_3 has the specified preferred value for U2 stability. Performance is rather good: for a typical audio load of 600 Ω —light loading for this circuit—THD+N at an output level of 5 V rms is of the order of 0.001% for frequencies below 20 kHz. For supply voltages of ±12 V or more, a clip-on heat sink is recommended for U2, as suggested in the earlier article.

Two contrasting balanced differential line drivers

"Inverter-follower" line driver

A balanced output signal, $\pm V_{IN}$ with respect to common, can be derived from an input, V_{IN}, by operating on it with side-by-side unity-gain amplifiers of opposing sense. The differential output voltage is $2V_{IN}$ (as in Figure 1). Other values of gain could be used to provide the amplification needed to the desired line level.

This "inverter/follower" driver is easily accomplished with a dual op amp, such as the OP-275, and an 8 × 20-kΩ film or discrete resistor network (Figure 8). U1A provides a gain of −1, and U1B operates at a gain of +1. The balanced differential output to the line is $2V_{IN}$, with a 100-Ω differential output impedance.

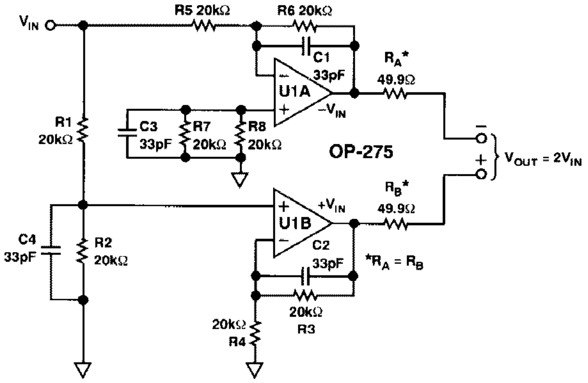

Figure 8. Simple differential line driver.

Readily available equal-value gain resistors are used around the U1 sections to provide symmetrical loading at the amplifier input terminals and matched noise gains for similarity of bandwidths and dynamics. Capacitors C1-C2, which cause the response to roll off at ultrasonic frequencies, enhance dynamic stability. This circuit provides good performance with simplicity and low cost, needing only U1, a resistor network, and 4-6 passive components.

A caveat should be kept in mind. Though the push-pull output circuit is simple and can achieve high performance in a limited class of systems (high-impedance, differential-input receiver circuits), some line destinations may incur problems. The outputs are not truly differential and floating—unlike a transformer, neither side can behave properly when grounded. The 49.9-Ω series resistors limit fault currents. Even though half the signal may be lost, damage is not likely.

Cross-coupled differential line driver

A more versatile gain-of-2 differential line driver uses a pair of cross-coupled differencing op amps. The circuit compares the voltage across the load with 2× the input voltage and ideally provides whatever values of current are necessary to maintain equality, regardless of the actual common-mode output voltage. Like a transformer, it works, even with grounded loads.[12]

Figure 9 shows a block diagram of the monolithic SSM-2142 balanced line-driver circuit. Inverter A1 provides a push-pull input of $2V_{IN}$ to the cross-coupled differencing amplifiers, to be compared with the differential load voltage fed back by the *sense* terminals. The *force* outputs, through 50-Ω isolating resistors, are driven to produce the correct voltage at the *sense* terminals.

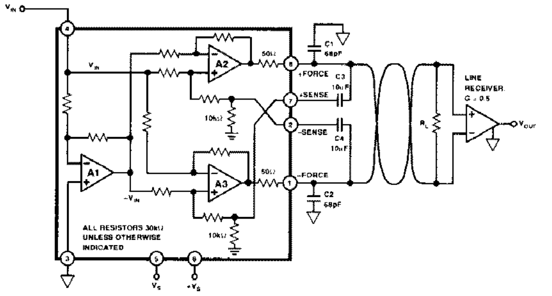

Figure 9. SSM-2142 differential driver system.

The SSM-2142, housed in an 8-pin mini-DIP, is designed to work into a 600-Ω load. In the simplest use, it is simply strapped with the appropriate force/sense pins tied together. Small capacitors (C1,C2) preload the IC for stability against varying cable lengths. Where dc offsets are expected, the optional 10-μF capacitors (C3,C4) may used to allow the outputs to maintain ac feedback over the audio band; the capacitors should be non-polar types unless the offset polarity is known.

In a system application, the SSM-2142 is used with a complementary gain-of-0.5 receiver, (an SSM-2143 or one of the other receivers mentioned). The circuit in Figure 9 comprises a complete unity-gain single-ended-to-differential-to-single-ended transmission system. Typical THD+N from 20 Hz to 20 kHz at 10-V rms output, driving 600 Ω, is of the order of 0.003% or less.

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