High Performance Balanced Audio Interface Design, Part 3

Balanced Line Receivers and Their Testing

By Bill Whitlock

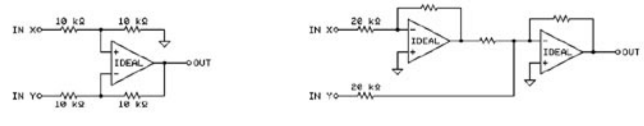
Part 3 is a logical continuation from part 2 (July/Aug. '07). After all, once the balanced output has been designed and built, it needs to feed a balanced receiver and be tested.

The overwhelming majority of audio equipment uses single-ended circuit topologies for *internal* signal processing. However, in professional equipment, we depend on balanced interfaces to link our equipment together in an electrically hostile outside world. In other words, we expect our balanced input to recover the differential audio signal while rejecting the common-mode voltages that are due to ground voltage differences or are induced into cables by ambient magnetic and electric fields. Performance of the differential line receiver is the most important determinant to *system* CMRR performance. A well-designed input stage can even minimize the effects of non-ideal behavior in source equipment, cables, and questionable grounding practices.

There are two basic types of balanced line receivers: differential amplifiers and transformers.

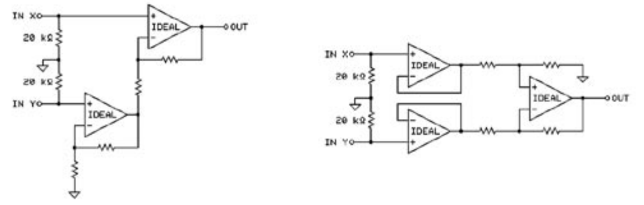
DIFFERENTIAL AMPLIFIERS

Differential amplifiers, sometimes called "active balanced" or "servo-balanced" inputs, are made of op amps and precision resistor networks to perform algebraic subtraction of signals presented to its two input terminals. The differential amplifier is realizable in numerous circuit topologies. The most common is the simple differential amplifier. These circuits are well known and have been analyzed and compared in some detail[11,12,13,14].



"SIMPLE" SINGLE OP-AMP

CURRENT MODE DUAL OP-AMP



VOLTAGE MODE DUAL OP-AMP

"INSTRUMENTATION" or TRIPLE OP-AMP

FIGURE 1: All these input stages have a common-mode input impedance of 20kΩ.

Figure 1 shows schematics of four popular topologies in their most basic form, stripped of AC coupling, RFI filtering, and so on. For discussion purposes, assume that op amps, resistors (and resistor ratios) are ideal and not a source of error. Because the common-mode input impedances, from either input to ground[15], are all 20kΩ, *these four circuits have identical CMRR performance*. Even when perfectly matched, these relatively low impedances are the downfall of these circuits when compared with input transformers. To quote Morrison[16]: "Many devices may be differential in character but not all are applicable in solving the basic instrumentation problem."

The plots in ***Fig. 2*** show how source impedance imbalance affects CMRR in any of these circuits. However, balanced inputs have traditionally been tested and specified with either perfectly balanced sources or shorted inputs (which makes the impedance imbalance zero). In real, mass-produced audio equipment, source impedance imbalances commonly range from 0.2-20Ω, resulting in system-level CMRR that's far less than that advertised in manufacturers' datasheets. When was the last time you saw a CMRR spec that specified how the measurement was made?

There are other problems, too:

1. The single and current-mode-dual op amp circuits must trade off common-mode input impedance for *noise*. For example, because of the 10kΩ resistors, the single op amp circuit will have a noise output of about -105dBu (0dBu = 775mV RMS). If it operates on ±15V rails, its maximum output will be about +20dBu, giving it a total dynamic range of 125dB. This might be marginal in some recording systems. If resistor values are increased, sensitivity to source impedance imbalance will be reduced, but noise will increase by 3dB for every doubling.
2. Many balanced input and output circuits use electrolytic coupling capacitors, which generally have loose tolerances (20% or worse) and change value with age, degrading the circuit's low-frequency CMRR by unbalancing the common-mode impedances.
3. Suppression of RF common-mode voltages to prevent subsequent demodulation by the op amps is another trade-off in

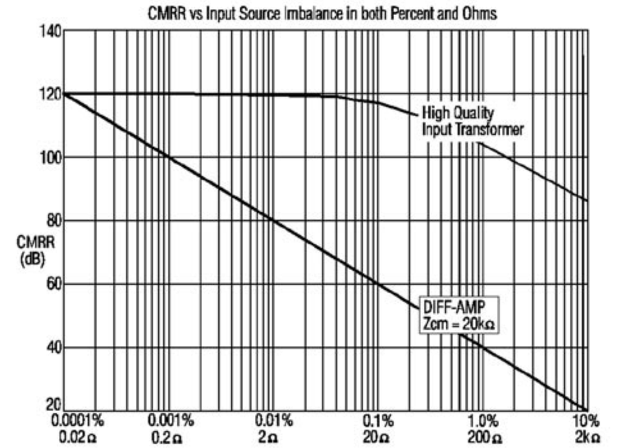


FIGURE 2: CMRR vs. source impedance imbalance for *Fig. 1* circuits vs. input transformer with extremely high common-mode impedance.

these circuits. Often 1000pF capacitors are added from each input to ground to attenuate RF. Unless these are precisely matched, they will unbalance the common-mode input impedance and degrade high frequency CMRR. Because they lower common-mode input impedance, they also increase sensitivity of CMRR to source impedance imbalance at high audio frequencies. This is a very tricky trade-off.

4. The common-mode voltage range is limited to between ±10 and ±15V for most circuits. *At high signal levels, common-mode range can approach zero because the limit applies to the* **sum** *of the peak signal and the peak common-mode voltages*[17,18]. This can cause problems in electrically hostile environments such as remote recording trucks or sound reinforcement systems operating near high-power lighting equipment or cables.

5. The single op amp design also has a property that seems confounding[19]. As shown in ***Fig. 3***, its common-mode input impedances are severely mismatched if the two inputs are tested separately with the other input grounded, yet matched if tested together (that is, the voltage is fed to both inputs X and Y, making the impedances-to-ground at the two inputs equal). Obviously, if driven from a zero-impedance balanced ground-referenced source, signal voltages at X and Y are forced to be identical. But real-world floating (high common-mode impedance) sources will also experience *signal* magnitude imbalances, typically about 3dB, when used with this receiver. In fact, if input X is driven by an *ideal* floating (infinite common-mode impedance) source, *all* signal voltage will appear at input X and none at input Y.

This phenomenon is an imaginary problem that has led some designers to "fix" it by adjusting resistor ratios. In their misguided quest for signal symmetry (which is irrelevant to a balanced output or input), they have inadvertently done massive damage to the CMRR of their input stage!

AUDIO TRANSFORMERS

An audio transformer couples a signal magnetically while maintaining an extremely high degree of electrical, or galvanic, *isolation* between input and output. It is an *inherently differential* device, requiring no trimming, and its differential properties are stable for life. ***Figure 4*** shows a circuit simulation model for a Jensen JT-10KB-D line input transformer. Its common-mode input impedances are determined by the 50pF capacitances of the primary to the Faraday shield (which is grounded), and small parasitic capacitances to the secondary (one end of which is usually grounded). These high common-mode input impedances, about 50MΩ at 60Hz and 1MΩ at 3kHz, are responsible for its relative insensitivity to source impedance imbalances, as shown in ***Fig. 2***.

Audio transformers tend to be much larger, heavier, and more expensive than op amps and resistors. Unfortunately, poorly designed audio transformers are widely available and can seriously harm audio signals. This has led some engineers to conclude that all transformers are inherently bad and shouldn't be considered for high-quality signal paths. But, as you can see, the transformer's major advantage is much higher CMRR in real-world systems. Input transformers have other advantages, too:

1. A transformer can transform (match) the impedance of the balanced line to the *optimum source resistance* for the subsequent amplifier to maximize signal-to-noise ratio. Noise figure is a measure of signal-to-noise degradation caused by a particular amplifier and it is always lowest when the amplifier is fed from its *optimum source resistance*[20]. Although this is especially relevant to microphone input stages, it's also an important consideration for wide-dynamic-range *line* input stages. A well-designed transformer-coupled line input stage operating from ±15V power rails can easily attain 140dB dynamic range!
2. RF common-mode attenuation is also inherent in transformers with Faraday shielding. Because it compares normal-mode to common-mode response, CMRR is not a useful measure of such attenuation. The normal mode -3dB frequency is about 180kHz for the Jensen JT-

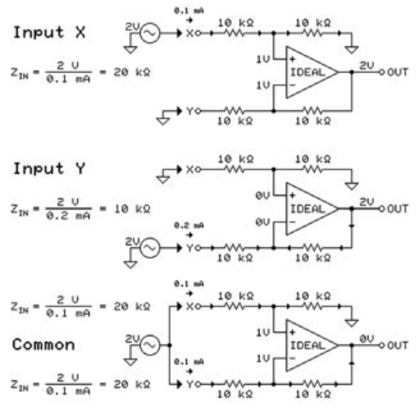
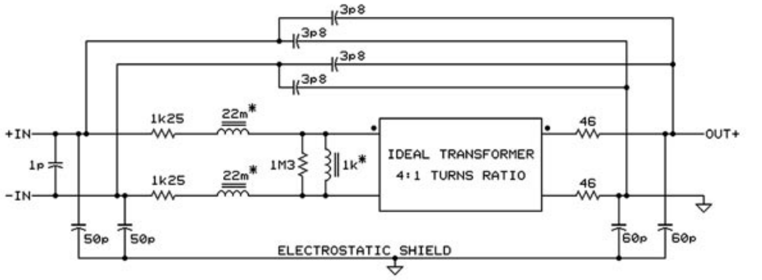


FIGURE 3: Confusing symmetry with balance leads some designers to fix an imaginary problem with the simple differential amplifier.



HIGH PERFORMANCE INPUT TRANSFORMER CIRCUIT SIMULATION MODEL

ALL RESISTANCE IN OHMS, CAPACITANCE IN FARADS, AND INDUCTANCE IN HENRYS.
UNIT PREFIX USED IN PLACE OF DECIMAL POINT: 3p8 = 3.8 pF, 1k25 = 1.25 kΩ, ETC.

INDUCTANCES MARKED* VARY INVERSELY WITH FREQUENCY, INCREASING AT ~3 dB PER OCTAVE DOWN TO ~1 Hz.
VALUE INDICATED AS 1 kH APPLIES AT 20 Hz, AND AS 22 mH APPLIES AT 100 kHz.

VALUES SHOWN ARE TYPICAL ONLY.

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FIGURE 4: Extremely high common-mode impedances of input transfomers make it insensitive to source impedance imbalances of real-world equipment outputs.

10KB-D. Its common-mode attenuation is typically over 30dB from 200kHz to 10MHz. RF attenuation can be further increased with an external low-pass filter network.

3. Input common-mode voltage range in a transformer depends only on the insulation materials used in its construction. Typical breakdown voltages exceed ±350V peak.

TESTING BALANCED LINE RECEIVERS

Noise rejection in a real-world balanced interface is often far less than that touted for the receiving input. That's because the performance of balanced inputs have traditionally been measured in ways that (conveniently) ignore the effects of impedance imbalances in the driving source (equipment output) and cable. As shown in ***Fig. 5***, for example, the old IEC method effectively "tweaked" the driving source impedance until it had *zero* imbalance. Another popular method, which simply ties the two inputs together and drives them with the generator, is equally unrealistic. Although the results of these tests are essentially meaningless, the tests are still used by many engineers.

This author is pleased to have convinced the IEC, with the help of John Woodgate, to adopt a new CMRR test that inserts realistic impedance imbalances in the driving source. The new test is part of the third edition of *IEC Standard 60268-3, Sound System Equipment—Part 3: Amplifiers*, issued in August 2000. It's very important to understand that noise rejection in a balanced interface is not simply a function of the receiver—actual performance in a real system depends on how the driver, cable, and receiver *interact*. M³

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FIGURE 5: Old and new IEC test for CMRR of balanced inputs for audio equipment. Both old and new tests use same normal-mode test shown here.