A NEW BALANCED AUDIO INPUT CIRCUIT FOR MAXIMUM COMMON-MODE REJECTION IN REAL-WORLD ENVIRONMENTS

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A new patented balanced input circuit emulates the extremely high common-mode input impedances which give a quality audio transformer its hum and buzz rejecting advantage in real-world audio systems, where driving source impedances are rarely perfectly balanced. Compared to traditional "active balanced" circuits, the new circuit can produce CMRR improvements up to 80 dB but is only slightly more complex and requires no additional closely matched components.

INTRODUCTION

With rare exception, when it comes to audio <u>system</u> performance, the whole is much <u>less</u> than the sum of its parts. When audio components are interconnected to form a system, it usually has far more noise and distortion than would be predicted from test bench measurements on each component. The degradation occurs because the vast majority of component manufacturers don't adequately consider real-world conditions when designing interfaces. Tests are performed and specifications are written as if all equipment were operated in an ideal laboratory environment. For example, have you ever seen an output specified for impedance <u>imbalance</u> limits, an input specified for CMRR when driven by a source with a realistic <u>imbalance</u>, or even cable specified for capacitance <u>imbalance</u>? All too often, the end user is left with the thankless job of "fixing" the system to work the way it should have "out of the box". Most system designers and technicians assume that the use of "balanced" outputs, cables, and inputs can be relied upon to eliminate the hum, buzz, and other artifacts usually blamed on so-called "ground loops".

Although it seems simple, the task of transferring an audio signal from one system component to another while avoiding audible contamination is anything but trivial. The existence of significant ground voltage differences between system components <u>must</u> be accepted as a fact of life. Equipment designers <u>must</u> be aware of the noisy currents which flow through shields from one chassis to another, avoiding the "pin 1 problem" with a well reasoned internal ground system.[1] Carefully designed and executed system grounding schemes can reduce ground voltage differences but cannot eliminate them. By far, the most dominant factor in the success or failure of a balanced interface to reject ground noise is the *actual* CMRR (common-mode rejection ratio) realized from the balanced line receiver or input stage. Audio transformers have been used for this purpose for over 50 years, so long that their 100 dB plus CMRR at 60 Hz has become taken for granted. Transformers still consistently outperform their active counterparts in real-world systems for reasons that need to be widely understood and appreciated. It will be shown that the most important advantage of a transformer stems from its inherently high common-mode input impedances.

Traditional active line receivers are widely used because they are far cheaper, smaller, and lighter than a quality transformer. This paper will describe a new active line receiver circuit which has the high common-mode input impedances, and resulting high in-system CMRR, previously associated only with transformers. Compared to traditional active receivers, the new circuit is only slightly more complex, requires no additional tightly matched or trimmed components, and lends itself to very effective and novel RFI suppression circuitry.

BALANCED AUDIO INTERFACES

The goal of modern audio interfaces is to transfer maximum signal <u>voltage</u> while, of course, rejecting ground voltage differences and interference from external electrostatic and magnetic fields. To accomplish this requires a balanced interface with low differential output impedance at the driver and high differential input impedance at the receiver. This method, sometimes called "voltage matching", should not be confused with *impedance matching* where output and input impedances are made equal, wasting half the driver voltage in order to transfer maximum <u>power</u> to the receiver. Line drivers with low differential output impedance generally have inherently low common-mode impedances (usually half the differential or "output" impedance). Because of normal tolerances in the resistors and capacitors which usually determine a driver's output impedance, imbalances up to about 20 Ω should be routinely expected. This defines a "real-world" source.

In a previous paper, this author has examined balanced audio interfaces in some detail, including performance comparisons of various receiver types.[2] It was concluded that, regardless of their circuit topology, popular active receivers have very poor CMRR when driven from real-world sources. This poor performance is a direct result of their low common-mode input impedances.

The theory underlying balanced interfaces seems to be misunderstood by a very large number of audio equipment designers. The widespread use of the simple differential amplifier as a panacea is evidence of this. Over the years, so-called "improvements" to this simple circuit have appeared. One of them attempts to balance *signal* input impedances by mismatching input resistor values, presumably in quest of perfect signal symmetry. This mismatch grossly *unbalances* the common-mode impedances, which destroys the CMRR for any real (non-zero impedance) source. This and other misguided "improvements" completely ignore the importance of common-mode input impedances. Apparently, an alarming number of designers test the CMRR of receiver circuits by driving the inputs shorted to each other, which is both unrealistic and misleading. As this author has said before, noise rejection in a balanced system has NOTHING to do with signal symmetry. It is the balance of <u>common-mode impedances</u> that defines a balanced system.
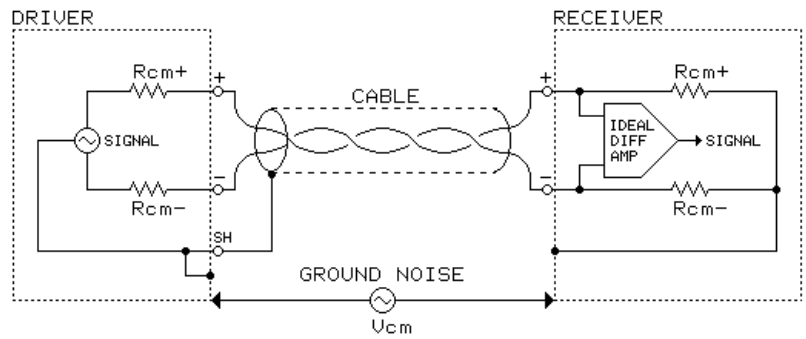

Figure 1
The Balanced Interface

A BALANCED SYSTEM IS A BRIDGE

In the basic balanced interface of Figure 1, the output impedances of the driver and the input impedances of the receiver effectively form the Wheatstone bridge shown in Figure 2. If the bridge is not "balanced" or "nulled", some of the ground noise Vcm will be "converted" to a differential signal on the line. Rejection or nulling of the common-mode voltage is critically dependent on the ratio matching of the driver/receiver common-mode impedances in the two circuit sides or branches.
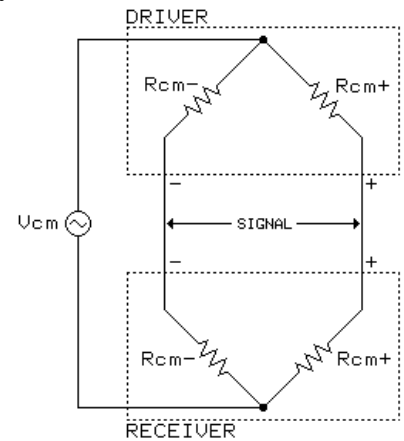
The bridge is <u>most</u> sensitive to small fractional impedance changes in one of its arms when all arms have the same impedance. It is <u>least</u> sensitive when upper and lower arms have widely differing impedances, for example when upper arms are very low and lower arms are very high. Impedances must be changed in *pairs* because the impedance ratios of the two sides must match in order to null the bridge. Therefore, we can minimize the sensitivity of a balanced system (bridge) to impedance imbalances by making common-mode impedances very <u>low</u> at one end of the line and very <u>high</u> at the other. This condition is consistent with the previously mentioned requirements for "voltage matching".
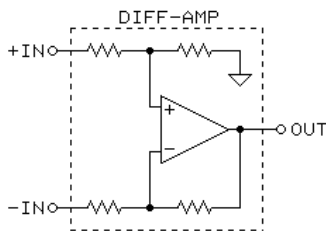

Figure 2
The Balanced Interface as a Wheatstone Bridge

Figure 3
Basic Differential Amplifier

Most active line receivers, including the simple differential amplifier of Figure 3, have common-mode input impedances in the 5 kΩ to 50 kΩ range, which is inadequate to maintain high CMRR with real-world sources.

With common-mode input impedances of 5 kΩ, a source imbalance of only 1 Ω, which could arise from normal contact and wire resistance variations, can degrade CMRR by 60 dB. Under the same conditions, the CMRR of a quality transformer would be unaffected because of its 50 MΩ common-mode input impedances. Figure 4 shows calculated CMRR versus source imbalance for different receiver common-mode input impedances. Thermal noise and other limitations place a practical limit of about 130 dB on actual CMRR measurements. Note that, for the 50 MΩ common-mode input impedances of a transformer, 94 dB of ground noise rejection is attained from an <u>unbalanced</u> 1 kΩ source, which is typical of consumer equipment. If common-mode input impedances are sufficiently high, an input can be
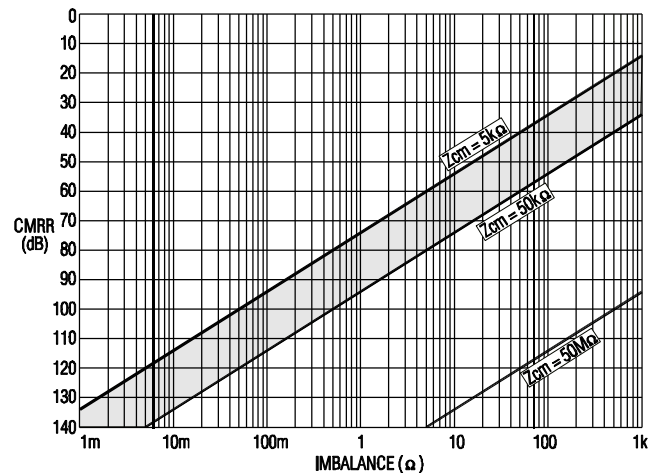

Figure 4
CMRR vs Source Imbalance vs Receiver Input Zcm

considered "universal", suitable for any source whether balanced or unbalanced.

THE NEW CIRCUIT

The new circuit uses a technique called "bootstrapping" to raise the common-mode input impedances of the receiver. Figure 5 shows the resistor ac bootstrap technique. By driving the lower end of R2 to nearly same ac voltage as the upper end, current flow through R2 is greatly reduced, effectively increasing its value. At dc, of course, Z is simply R1 + R2. If gain G is unity, for frequencies within the passband of the high-pass filter formed by C and R1, the effective value of R2 is increased and will approach infinity at sufficiently high frequencies. Input impedance Z_i at frequency f is described by the following equation:

$$Z_i = (R_1 + R_2) \sqrt{\frac{1 + \left(\dfrac{f}{f_N}\right)^2}{1 + (1-G)^2 \left(\dfrac{f}{f_D}\right)^2}}$$

Figure 5
Bootstrapped Resistor

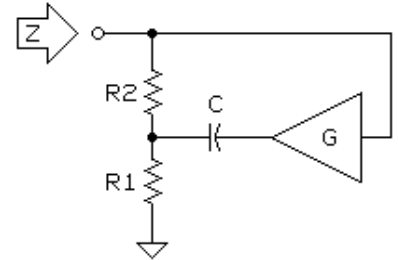$$\text{where} \qquad f_N = \frac{1}{2\pi \left(\dfrac{R_1 \cdot R_2}{R_1 + R_2}\right) C} \qquad\qquad f_D = \frac{1}{2\pi \, R_1 \, C}$$

For example, if R1 and R2 are 10 kΩ each, the input impedance at dc is 20 kΩ. This resistance provides a dc path for amplifier bias current as well as leakage current that might flow from a signal source. At higher frequencies, the bootstrap greatly increases the input impedance, limited ultimately by the gain of amplifier G, which may decrease with increasing frequency. Using readily available IC op-amps, input impedances greater than 10 MΩ across the audio spectrum can be achieved.
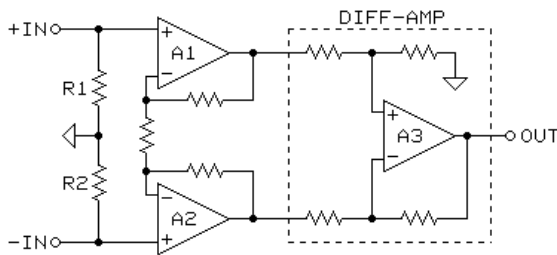

Figure 6
Conventional Instrumentation Amplifier

Figure 7
New Circuit Bootstraps R1 and R2

An interesting property of the standard instrumentation amplifier of Figure 6 is that its common-mode gain, from inputs to outputs of A1 and A2, is unity regardless of any differential gain that may be set by R_F and R_G. In Figure 7, the common-mode voltage appearing at the junction of R3 and R4 is buffered by unity gain buffer A4 which, through capacitor C, ac bootstraps input resistors R1 and R2. To ac common-mode voltages, the circuit's input impedances are 1000 or more times the values of R1 and R2, but to differential signals, R1 and R2 have their normal values, making the signal input impedance R1 + R2. Note that capacitor C is not part of the differential signal path, so signal response extends to dc. The bootstrapping does not become part of the (differential) signal path.
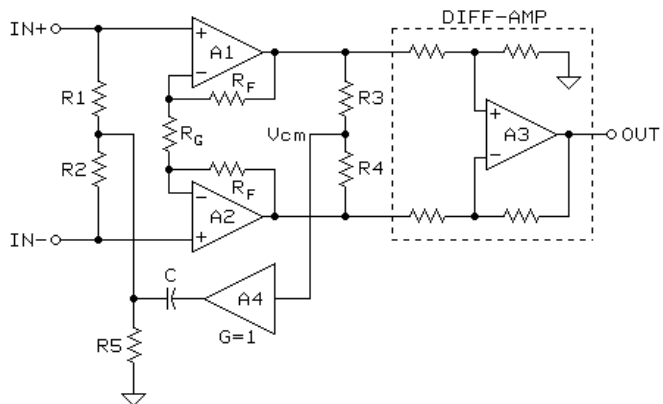
ELECTROMAGNETIC COMPATABILITY (EMC)

Equipment designers must, by law in some juridictions, concern themselves with issues of electromagnetic compatability, which includes both radiation/conduction of electromagnetic energy *from* a device and susceptability of a device *to* such energy from external sources. A potential problem with any audio input stage is susceptability to radio frequency interference (RFI). When driven with sufficient "out of band" (over 20 kHz) voltage, most amplifiers will function as AM detectors because of asymmetrical slew rates or other mechanisms. Symptoms may include voices or music from AM broadcast or CB transmitters, buzz from TV transmitters or equipment producing power line synchronized bursts of RFI,

or random pops, clicks, or whines from spark producing switches, relays, or motors.

Insufficient suppression of RFI can also result in more subtle signal degradation. RFI which enters the signal path, even at very low levels, can cross-modulate with ultra-sonic harmonics of the desired signal in downstream amplifiers, producing subtle in-band artifacts usually called "distortions". Jensen and Sokolich called this phenomenon "spectral contamination".[3]

Audio transformers inherently contain passive low-pass filters, removing much RFI before it can reach the first amplifier stage, which most often becomes the "detector". When RFI suppressing low-pass filter networks are added to active input stages, they are often rather "heavy handed". Many common circuits connect 1 nF capacitors from each input to ground as shown in Figure 8. At 10 kHz, these capacitors alone will lower common-mode input impedances to about 16 kΩ. This seriously degrades high frequency CMRR with real-world sources, even if the capacitors are perfectly matched. A tradeoff exists because shunt capacitors must have values large enough to make an effective low-pass filter, but small enough to keep the common-mode input impedances high.
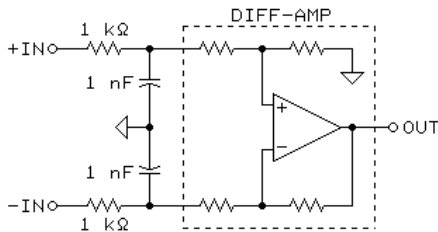

Figure 8
Conventional RFI Suppression

The new circuit makes the tradeoff easier. The same bootstrapping that made the input resistors "look" large can make these capacitors "look" small within the audio band yet become their full value to out of band RFI. Figure 9 shows the basic concept. By forcing the lower end of C2 to the same ac voltage as the top, current flow through C2 is greatly reduced, effectively decreasing its valu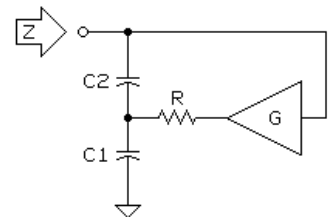e. If gain G is unity, at frequencies below the cutoff frequency of the low-pass filter formed by R and C1, the effective value of C2 will approach zero. At very high frequencies, of course, the effective capacitance is simply that of C1 and C2 in series (C1 is generally much larger than C2). For example, if R = 2 kΩ, C1 = 1 nF, C2 = 100 pF, and G = 0.99, the effective capacitance is only 15 pF at 10 kHz, but increases to 91 pF at 100 kHz or higher.

Figure 9
Bootstrapped Capacitor

A complete input stage with RFI filtering is shown in Figure 10. While series filter elements X1 and X2 can simply be resistors, they may add undesirable noise in low level circuits. A common-mode choke may be more appropriate since its resistance is generally lower and adds no significant noise. The choke will also provide additional RFI suppression.
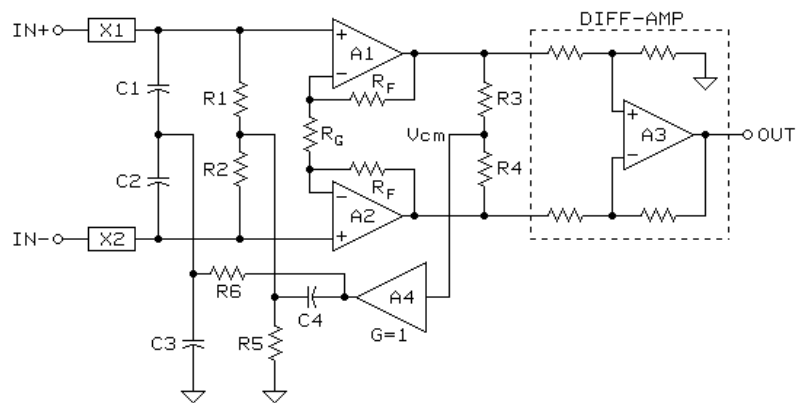
ADVANTAGES AND CONCLUSION
When used in the real world, the most important advantage of the new circuit is its greatly improved common-mode rejection, which is comparable to that of a very high quality transformer and several orders of magnitude higher than existing active input circuits. Like a quality transformer, it has outstanding noise rejection even when driven from unbalanced sources.

Figure 10
New Circuit with Bootstrapped RFI Suppression

Like the conventional "instrumentation" amplifier, the new circuit will generally have less wideband noise (hiss) than the simple differential amplifier because the four differential amplifier resistors can be significantly reduced in value. This reduces both thermal noise and op-amp input current noise contributions.

In a microphone preamplifier, the new circuit can eliminate the CMRR degradation due to the resistors which pass "phantom power". These resistors severely reduce the common-mode input impedances of the preamplifier. In Figure 9, if the grounded end of R5 is connected to phantom power, dc power will flow through R5, R1, and R2 to the microphone, but R1 and R2 will effectively disappear to the ac common-mode input voltage. If high voltage op-amps are used to extend the input common-mode voltage range, a completely dc coupled mic preamp with "phantom power" is possible.

As with any active circuit, input common-mode voltages are limited to those tolerated by the amplifiers used. For most system environments, the ± 15 volt range obtainable with inexpensive op-amps operated from ± 18 volt power is adequate. The transformer, with its common-mode voltage range of ± 250 volts or more, remains the input device of choice for the most electrically hostile systems.

REFERENCES

[1] **Neil Muncy,** *Noise Susceptibility in Analog and Digital Signal Processing Systems*, **AES Journal Vol 43, No 6, 1995, pp. 435-453.**

[2] **Bill Whitlock,** *Balanced Lines in Audio — Fact, Fiction, and Transformers*, **AES Journal Vol 43, No 6, 1995, pp. 454-464.**

[3] **Deane Jensen & Gary Sokolich,** *Spectral Contamination Measurement*, **AES 85th Convention Preprint 2725, 1988.**