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# A New Balanced-Line Receiver Circuit and IC

*By Bill Whitlock*

[In part 2 (July/Aug. '07) we covered the generics of balanced line receivers and their testing. In this part, those concepts are applied to designing a high-performance circuit. DJW]

In a previous installment, I concluded that very high common-mode input impedances are extremely important if a balanced-line receiver is to have high noise rejection (CMRR) in real-world audio systems. Audio transformers enjoy a great advantage in this regard, and are widely used in systems operating in electrically hostile environments. You might ask, "Why not connect an input XLR directly to an instrumentation amplifier, since they have common-mode input impedances in the hundreds of megohms?" The answer is that an instrumentation amplifier balanced input requires a DC bias current for the "+" and "-" connection, and you can't depend on every signal source having DC paths to ground; for example, many have a capacitor- or transformer-coupled output.

Therefore, the DC paths must be part of the input circuit itself. But how can a balanced-line receiver provide relatively low resistance DC paths simultaneously with multi-megohm common-mode AC input impedances?

## THE NEW CIRCUIT

This question inspired me to produce a new circuit in 1994. It uses a technique known as "bootstrapping" to raise the AC common-mode input impedance of the receiver to >10MΩ at audio frequencies. ***Figure 1*** shows the basic technique.

By driving the lower end of R2 to nearly the same AC voltage as its upper end, AC 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-

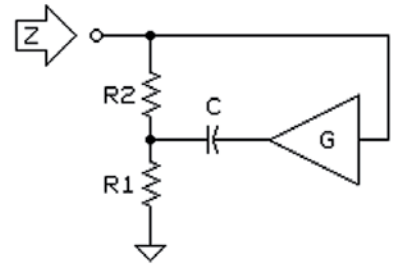

**FIGURE 1: Resistor bootstrapping.**

pass filter formed by C and R1, the effective value of R2 is increased and will approach infinity at sufficiently high frequencies.

For example, if R1 and R2 are 10kΩ each, the input impedance at DC is 20kΩ. 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 and bandwidth of amplifier G. Impedances greater than 10MΩ across the audio spectrum can be achieved.

Instrumentation amplifiers are widely used as balanced-line receivers. The circuit shown in ***Fig. 2*** is a standard instrumentation amplifier modified to have its input bias resistors, R1 and R2, bootstrapped.

Note 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 $R_G$. 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. Resistor R5 completes the DC path for bias currents.

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.

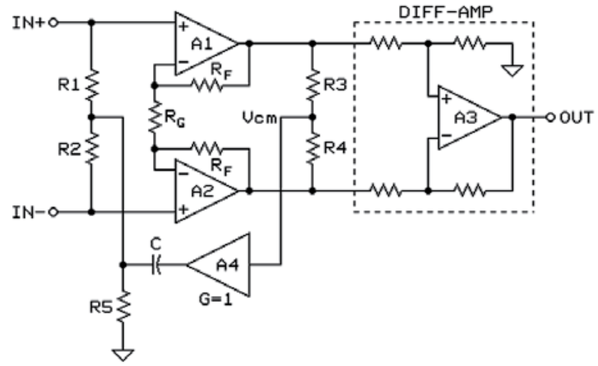

**FIGURE 2: Basic InGenius amp.**

The new circuit also has advantages in suppressing RF interference. Audio transformers inherently contain passive low-pass filters, removing most RF energy before it reaches the first amplifier. In well-designed equipment, RF-suppressing low-pass filters must precede the active input stages. A widely used circuit is shown in ***Fig. 3***.

At 10kHz, these capacitors alone will lower common-mode input impedances to about 16kΩ. This seriously degrades high-frequency CMRR with real-world sources, even if the capacitors are perfectly matched. A trade-off 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. The new circuit eases this problematic trade-off.

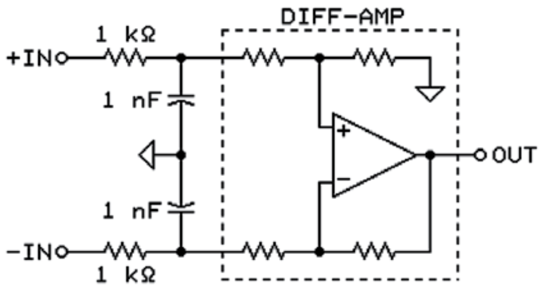

**FIGURE 3: Differential amplifier RF filter.**

The circuit in ***Fig. 4*** shows how bootstrapping can make the effective value of these capacitors small within the audio band, yet act at their full value at RF frequencies.

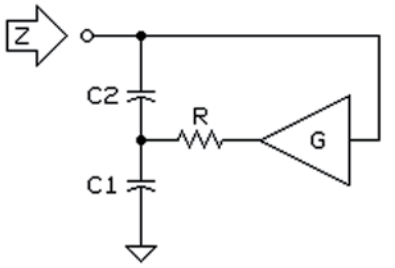

**FIGURE 4: Capacitor bootstrapping.**

By forcing the lower end of C2 to the same AC voltage as its upper end, current flow through C2 is greatly reduced, effectively decreasing its value. 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 = 2kΩ, C1 = 1nF, C2 = 100pF, and G = 0.99, the effective capacitance is only 15pF at 10kHz, but increases to 91pF at 100kHz or higher.

***Figure 5*** shows a complete input stage with bootstrapping of input resistors R1/R2 and RF filter capacitors C1/C2. Series filter elements X1 and X2 may be either resistors or inductors, providing additional RFI suppression. Another paper I wrote describes these circuits in much greater detail[8].

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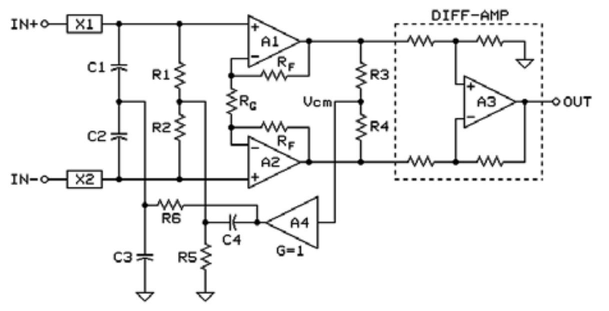

**FIGURE 5: InGenius with RF filter.**

## THE INGENIUS IC

The circuit was granted US Patent 5,568,561 in 1996, and is licensed to THAT Corporation (www.THATCorp.com). The silicon implementation differs from the discrete solution in many respects. Because all critical components are integrated, a well-controlled interaction between resistor values and metal traces can be duplicated with similar performance from die to die. However, the integration of certain components produces new challenges.

THAT Corporation uses a process called 40V complementary-bipolar dielectric isolation (DI) with thin film (TF) to fabricate the IC. The DI process has remarkable advantages. Truly high performance PNP and NPN transistors, as good as their discrete counterparts, can be made on the same piece of silicon. Each device is placed in a tub that's isolated from the substrate by a thick layer of oxide. This, unlike more conventional junction-isolated (JI) processes, makes it possible to achieve hundreds of volts of isolation between individual transistors and the substrate.

The lack of substrate connection has several advantages. It minimizes stray capacitance to the substrate (usually connected to the negative rail); therefore, wider bandwidths can be achieved with a simpler, fully complementary circuit design. Also, it makes possible stable operational amplifier designs with high slew rates. In fact, the typical slew rate of the InGenius line receiver is better than 10V/µs.

The op amp design topology is a folded cascode with PNP front end, chosen for better noise performance (NPN transistors are inherently noisier than PNP types). The folded cascode achieves high gain in one stage and requires only a simple stability compensation network. Moreover, the input voltage range of a cascode structure is greater than most other front ends. The output driver has a novel output stage that is the subject of US patent 6,160,451. The new topology achieves the same drive current and overall performance as a more traditional output stage, but uses less silicon area.

The InGenius design requires very-high-performance resistors. Most of the available diffused resistors in a traditional silicon process exhibit relatively high distortion and poor matching. The solution is to use thin-film resistors. The family of thin-film resistors includes compounds such as nichrome (NiCr), tantalum nitride (TaNi), and sichrome (SiCr), each best suited for a certain range of resistor values. In InGenius, SiCr thin-film is used due to its stability over time and temperature, plus sheet resistance that minimizes the total die area.

Thin-film on-chip resistors offer amazing accuracy and matching via laser trimming, but are more fragile than regular resistors, especially when subjected to electrostatic discharge (ESD). Careful layout design was required to ensure that the resistors can withstand the stress of ESD events.

The CMRR and gain-accuracy performance depend critically on matching resistors. The integrated environment makes it possible to achieve matching that would be practically impossible in a discrete implementation. In the Ingenius IC, typical resistor matching, achieved by laser trimming, is 0.005%, which delivers about 90dB CMRR. In absolute numbers, this means the typical resistor and metal error across all resistors is no greater than 0.35Ω! Discrete implementations with such performance are very difficult to achieve and would be extremely expensive.

Real-world environments require ESD protection for input and output stages, and putting it on the chip posed interesting challenges. The conventional solution is to connect reverse-biased protection diodes from all pins to the supply-rail pins. In the InGenius IC, this won't work for the input pins because they must accept voltage swings beyond the power supply rails. For those pins, THAT's designers developed a lateral protection diode with a breakdown voltage of about 70V, which could be fabricated using the same diffusion and implant sequences used for the rest of the IC. The IC is in full production and is currently used in products by TMH Labs (TMHLabs.com; Tom Holman was the first commercial InGenius user); Bag End Loudspeakers (www.BagEnd.com); Henry Engineering (www.HenryEng.com); and many others. Full specifications and application information on the IC is available from THAT Corporation at www.THATCorp.com/datashts/1200data.pdf.

NOTE: I'm happy to announce that the new Audio Precision (www.AP.com) APx520/525 analyzer is the first commercial instrument to incorporate CMRR testing per the new IEC method described in the previous installment of this series.

## REFERENCE

8. B. Whitlock, "A New Balanced Input Circuit for Maximum Common-Mode Rejection in Real-World Environments," Audio Engineering Society 101st Convention, 1996, Preprint #4372, see www.JensenTransformers.com/an/ingenaes.pdf.

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As president and chief engineer of Jensen Transformers, **Bill Whitlock** currently designs Jensen's audio, video, and other signal interfacing devices and handles much of Jensen's technical support. He also does consulting as time permits.