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New Balanced-Input Integrated Circuit Achieves Very High Dynamic Range In Real-World Systems

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ABSTRACT

Limited Common-Mode Rejection Ratio (CMRR) in balanced interfaces often limits dynamic range in real-world audio systems. Conventional differential amplifier input circuits suffer serious CMRR degradation when driven by real system signal sources instead of laboratory generators. An ideal audio transformer, because of its extremely high common-mode impedances, is virtually immune to this degradation. A new Integrated Circuit (IC) is described that uses a patented topology to achieve common-mode impedances comparable to those of an ideal transformer. As a result, the IC enables signals with very high dynamic range to be transported without contamination by system ground-voltage differences or other sources of common-mode interference. Other features of the IC, which relate to audio signal quality, are also detailed.

INTRODUCTION

The task of transferring an analog audio signal from one system component to another while avoiding audible contamination is anything but trivial. The trend in modern audio systems is toward increasing dynamic range, fueled largely by increasing resolution in available digital converters. To realize a wide dynamic range of analog signals, noise artifacts such as hum or buzz must be kept to an absolute minimum. Especially in large or complex audio systems, residual hum or buzz is often a serious and confounding problem. These noises are predominantly caused by ground voltage differences or "ground noise" between the system components. Carefully designed and executed system grounding schemes can reduce ground voltage differences but cannot eliminate them. It is tantalizing to assume that the use of "balanced" outputs, cables, and inputs can be relied upon to virtually eliminate such noise contamination.

It is a fact that noise rejection in each and every balanced interface depends critically on how the common-mode impedance imbalances of the driver and receiver interact. Quality input transformers have very high common-mode input impedances, and this inherent property makes them extremely tolerant of impedance imbalances in driving sources. Such transformers have been used in balanced input stages for over 60 years – so long that their 100 dB plus noise rejection is taken for granted and the reasons for it are all but forgotten.

Designers of conventional active transformer-less input stages fail to consider this interaction when they test their inputs with laboratory signal generators. Equipment is routinely tested and specifications are written as if the equipment will be driven by a laboratory signal generator. But, unlike such generators, real equipment outputs have significant impedance imbalances - and this often seriously degrades the noise rejection of the interface. Therefore, when real audio components are interconnected to form a system, it usually has far more noise than would be predicted from test bench measurements on each component.

BIT OF BALANCED INTERFACE THEORY

The purpose of a balanced audio interface is to efficiently transfer signal voltage from driver to receiver while rejecting ground voltage differences between them and interference caused by external electrostatic and magnetic fields acting on the cable. The theory underlying balanced interfaces is widely misunderstood. A balanced line consists of two conductors whose ***impedances*** are equal with respect to ground. It's critically important to understand that these impedances are affected by *everything* connected to the lines, therefore every component connected to a balanced line must rigorously maintain its "balance" in order to realize maximum *system* benefits. This includes the line driver, the line or cable itself, and the line receiver. This is especially true if we wish to freely interconnect various devices and interchange cables, as is usually the case. It should be strongly re-iterated here that **noise rejection in a balanced system has absolutely NOTHING to do with signal symmetry** (equal and opposite signal voltage swings). It is the balance of common-mode **impedances** that defines a balanced system!

A balanced line receiver uses a differential amplifier to reject common-mode voltages. It produces an output *only* in response to a voltage difference between its input terminals. Voltages that are common to both input terminals (i.e., identical) theoretically produce no output. Common-mode rejection or CMRR is the ratio of output produced from a differential input voltage compared to that produced with the same input applied as a common-mode voltage. It is generally expressed in dB, where higher numbers indicate better rejection of common-mode.

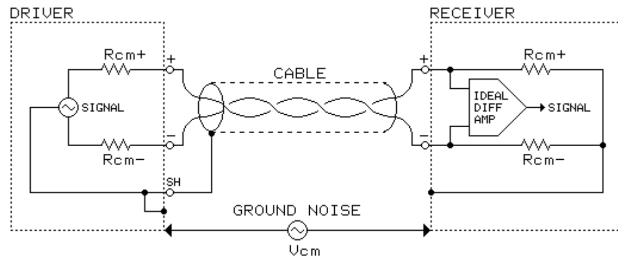

Figure 1: The Balanced Interface

In Figure 1, the ground noise will appear as common-mode voltage at the receiver. Rejection or CMRR will be *infinite* as long as the common-mode voltages at the inputs of the receiver are *exactly* equal. Anything that attenuates these voltages ***un***equally will degrade CMRR. This unequal attenuation process is called ***mode conversion*** since it converts a fraction of the *common-mode* noise to a *normal-mode* signal via the impedance unbalances in any of the "balanced" system components. Figure 2 shows the circuit rearranged to show that it forms a Wheatstone bridge.

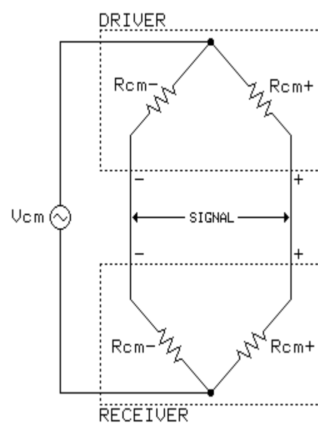

Figure 2: The Balanced Interface as a Wheatstone Bridge

The sensitivity of this null to impedance variations, such as resistor tolerances or contact resistance, can be minimized by making driver (output) common-mode impedances very small and receiver (input) common-mode impedances very large. In traditional equipment, a typical line driver *common-mode* output impedance is 100 Ω and line receiver *common-mode* input impedances typically range from 5 kΩ to 50 kΩ as shown in the shaded area of Figure 3. With a conventional receiver at 10 kΩ, a driver output

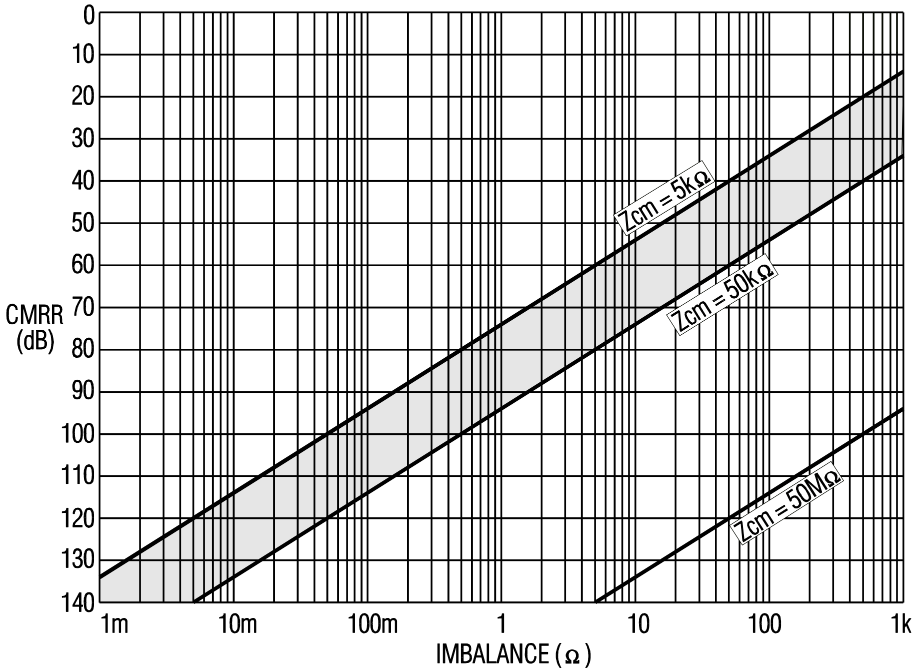

Figure 3: CMRR vs Source Imbalance vs Receiver Input Zcm

impedance imbalance of only 1Ω could degrade systemCMRR by 40 dB, reducing it from 120 dB to 80 dB. Equipment imbalances of 10 Ω are not uncommon.

A common-mode input impedance of about 50 MΩ is typical of an input transformer (at 60 Hz). Its CMRR is essentially unaffected until imbalance reaches nearly 100 Ω. In fact, 94 dB of noise rejection is attained from an unbalanced 1 kΩ source, which is typical of a consumer output. If common-mode input impedance is high enough, inputs are universal, suitable for any source-balanced or unbalanced.

A previous paper by Whitlock examined balanced interfaces in considerable detail.

THE NEW CIRCUIT

The new circuit uses a technique known as "bootstrapping" to raise the ac common-mode input impedance of the receiver to over 10 MΩ at audio frequencies. Figure 4 shows the basic 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. 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 and bandwidth of amplifier G. Impedances greater than 10 MΩ across the audio spectrum can be achieved.

Another widely used balanced input circuit is called an instrumentation amplifier. Figure 5 shows a standard instrumentation amplifier with its input bias resistors bootstrapped. Note that its common-mode gain, from inputs to outputs of A1 and A2, is unity

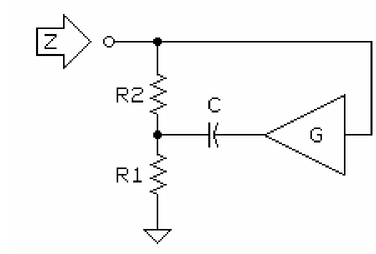

Figure 4: Boostrapped Resistor

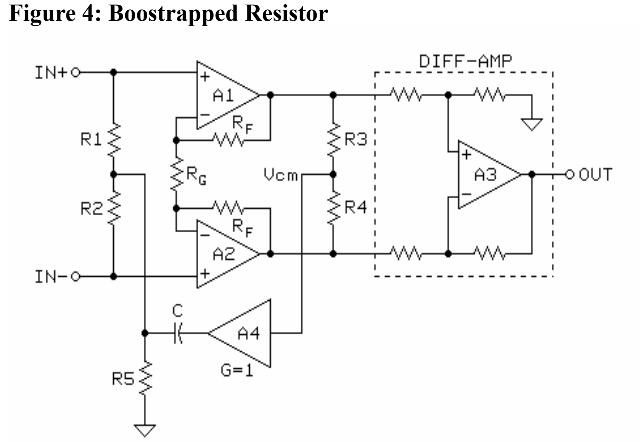

Figure 5: New Circuit Boostraps R1 and R2

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. 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.

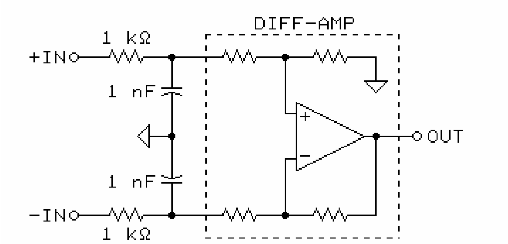

Figure 6: Conventional RFI Suppression

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 Figure 6. 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. The new circuit eases this tradeoff.

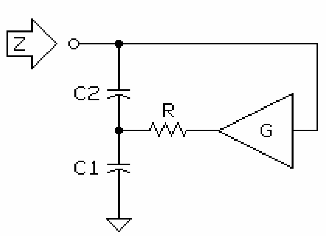

Figure 7: Boostrapped Capacitor

Figure 7 shows how bootstrapping can make these effective value of these capacitors small within the audio band yet become full value at RF frequencies. By forcing the lower end of C2 to the same ac voltage as the upper, 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 = 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.

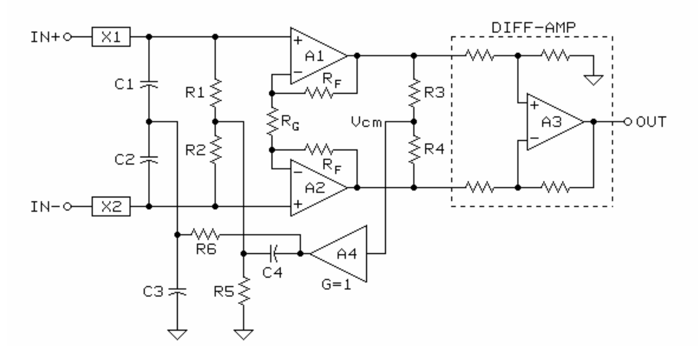

Figure 8: New Circuit with Bootstrapped RFI Suppression

Figure 8 shows a complete input stage with bootstrapping of input resistors R1/R2 and RF filter capacitors C1/C2. Series filter elements X1 and X2 can be resistors or inductors, which provide additional RFI suppression. A previous paper by Whitlock describes these circuits in much greater detail. [2]

THE NEW INTEGRATED CIRCUIT

The InGenius® circuit, covered by US Patent 5,568,561, is exclusively licensed to THAT Corporation. The silicon implementation differs from the discrete solution in many respects. Since 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. But the integration of certain components creates new challenges.

The process used by THAT Corporation for this device is 40-volt Complementary Bipolar Dielectric Isolation (DI) with Thin Film (TF). The DI process has several advantages. First, high performance, PNP and NPN transistors can be made on the same piece of silicon without sacrificing the performance of either one. Thus, fully complementary designs are possible. Second, each device in THAT's DI process is placed in a tub that is 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.

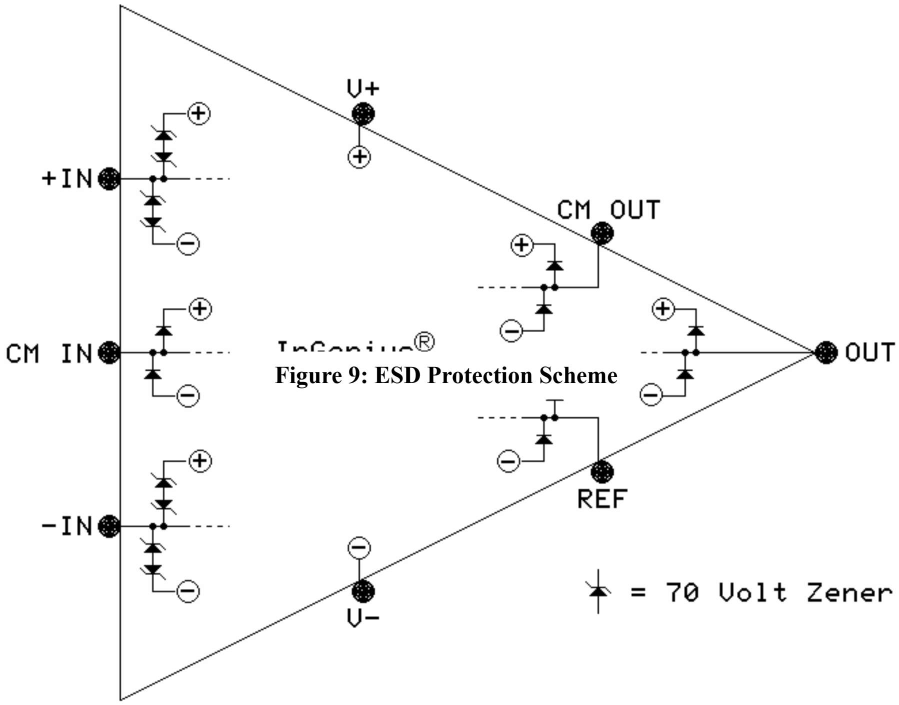

Figure 9: ESD Protection Scheme

It minimizes stray capacitance to the substrate (usually connected to the negative rail), therefore wider bandwidths can be achieved with a simpler 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 10 V/us.

The op-amp design topology used is a folded cascode with PNP front end, chosen for better noise performance. 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 awarded a few years ago. 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 have relatively high distortion and poor matching. The solution is to use thin film (TF) resistors. The family of thin film resistors include compounds such as, Nichrome (NiCr), Tantalum Nitride (TaNi) and Sichrome (SiCr). Each compound is suitable for a certain range of resistor values. In InGenius, SiCr thin film is used due to its stability over time and temperature and 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 of resistors. The integrated environment makes it possible to achieve matching that would be practically impossible in a discrete implementation. Typical resistor matching in the InGenius® IC is 0.005%, which delivers about 90 dB of CMRR. In absolute numbers, this means the typical resistor and metal error across all resistors is no greater than 0.35 Ω! Discrete implementations with such performance are very difficult to achieve and would be extremely expensive. Based on accelerated life tests, THAT expects the CMRR performance will hold up to no worse than 70dB over the life of the part. In the case of the 6 dB line receiver version, this means maintaining 0.047% matching of all resistors.

In order to get the extreme resistor matching of the SiCr film, laser trimming is required. Laser trimming is generally very costly, especially when high performance is necessary. There are two main methods of laser trimming thin film resistors: link cut and linear cut. The link cut requires that resistors of known value to be completely removed (cut) from the circuit in order to achieve the required value. It is very fast, but the granularity of trim is rather coarse, so high performance (in the form of tight matching) is difficult to achieve. Linear trimming gradually cuts into the resistor body until the right value is reached. This is a slower process, but delivers extremely accurate results when a properly designed resistor is used. InGenius® uses a linear laser cut that is optimized to balance the cost of the trim against the resulting matching. This is done using two speeds for the laser cut. The higher speed is used to coarse trim the thin film and when a certain threshold is reached the laser switches to a slower and more accurate cutting mode.

Real-world environments for input and output stages require ESD protection. Putting it on the chip, especially for an IC that can accept input voltages higher than the supply rails, posed interesting challenges. The conventional solution is to connect reverse-biased protection diodes from all pins to the power pins. In the InGenius® IC, this works for all pins except the input pins. Due to the configuration of the resistor input pad, the input pins can swing to voltages higher than the power supply rails. Connecting protection diodes between these pins and the supply rails would turn the diodes on when the peak input voltage exceeds the supply rail by about 600 mV. A conventional solution might connect back-to-back diodes in series between the input pins and the power supply lines. There would always be a reverse biased diode between the inputs and protection lines. The input pins could then rise above or fall below the power rails by the amount of reverse breakdown voltage in the diodes. Unfortunately, THAT's DI process offered only two standard diodes: one with about 8 volts reverse breakdown, and a second with 120 volts or higher. The breakdown voltage of the first is too low and the second is too high. To solve this problem, THAT decided to design a new diode having more suitable breakdown behavior for this purpose. THAT's designers developed a lateral protection diode structure that lowered the breakdown voltage without changing the diffusion and implant sequences required for the rest of the IC devices. This also avoided triggering a lengthy process qualification cycle. Thus, using the same layers but modified layout, the new protection diodes have typical breakdown voltage of about 70 volts.

CONCLUSION

Traditional active line receivers are widely used because they are far cheaper, smaller, and lighter than a quality transformer. But, as balanced line receivers in real-world audio systems, transformers consistently outperform conventional active counterparts for reasons that need to be widely understood and appreciated. The most important advantage of a transformer stems from its inherently high common-mode input impedances.

The new circuit embodied in the InGenius® IC exhibits the high common-mode input impedances previously associated only with transformers, giving it noise-rejection performance that rivals the finest transformers. It is so tolerant of source impedance unbalances that it provides excellent results even when driven by completely unbalanced consumer-type sources. The IC also lends itself to very effective and novel RFI suppression circuitry. Its internal op- amps have wide bandwidth and high slew rate. The result is good sound.

REFERENCES

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

[2] Bill Whitlock, *A New Balanced Audio Input Circuit for Maximum Common-mode Rejection in Real-world Environments,* AES 101st Convention Preprint 4372, 1996.