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A MATTER OF BALANCE: line-receiver CMR in real-world environments

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BY JOSHUA ISRAELSOHN • CONTRIBUTING TECHNICAL EDITOR

Common interconnect methods satisfy bandwidth, impedance, noise-immunity, attenuation, and signal-run-length requirements for a broad range of applications with surprisingly few topologies. Among the more robust is the balanced line, which finds use in such disparate applications as industrial process control, medical sensing, professional audio, and high-speed digital communications, among others. The balanced line is particularly useful for long feeds in applications that require a high degree of noise immunity.

IN A PERFECT WORLD ...

Though balanced signal-processing structures do exist, most moderate-bandwidth applications do well implementing functions with single-ended structures and reserve balanced signal paths for longer interconnects. In such cases, interface circuits must convert single-ended signals to balanced differential outputs and provide sufficient signal current to drive the load impedance. On the other end of the rope, a line receiver must capture the differential signal and reject the common-mode component while converting the balanced signal back to single-ended (**Figure 1**).

Transformers offer a simple means of conversion between balanced and single-ended signal feeds and additionally provide galvanic isolation between the signal source and its load that can easily extend to several hundred volts and, with care, to beyond 1 kV. Most installations, however, demand a common-mode range of only a few volts, and the additional cost, weight, and size of the transformers are often undesirable.

An electronic alternative uses line-driver and line-receiver ICs to replace either or both transformers. The drivers simply provide a pair of antiphase outputs, often with local sense feedback (**Figure 2**). On the receiver side, however, replicating the transformer's high degree of symmetry is a challenge. Historically, the most successful circuit approaches have used a difference amplifier and exploited analog-IC manufacturers' ability to fabricate and precisely trim matching resistors (**Figure 3**).

By superposition, the difference amplifier's output is the sum of two terms: $V_O=V_{OA}+V_{OB}$. Kirchoff's

AT A GLANCE

- Electrically balanced signal feeds are subject to a variety of imbalancing influences that result in asymmetrical source impedances.
- Traditional balanced line receivers use difference amplifiers to recover the differential-mode and suppress the common-mode signal components.
- Source-impedance asymmetries reduce CMR (common-mode-response) performance in difference amplifiers and allow common-to-differential-mode conversion.
- An input bootstrapping method improves a receiver's CMR performance in the presence of a source-impedance asymmetry.

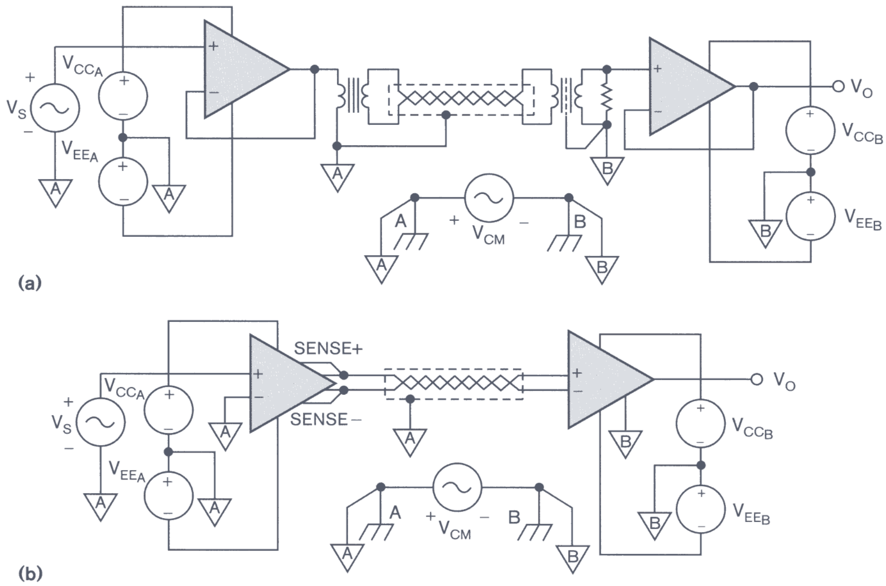


Figure 1 It's hard to beat transformer-coupled balanced feeds (a) for CMR performance and standoff voltage, but electrically balanced drivers and IC-balanced receivers (b) provide often-compelling economies.

Current Law applied to the inverting input requires that

$$\frac{V_{OA}}{R_2}+\frac{V_{CM}-\frac{V_D}{2}}{R_{SA}+R_1}=0,$$

from which one of the output terms directly derives:

$$V_{OA}=\left(\frac{V_D}{2}-V_{CM}\right)\left(\frac{R_2}{R_{SA}+R_1}\right).$$

The solution for the second term assumes that the amplifier is operating in its linear range, which forces the two inputs to equal potentials.

$$V_{OB}\left(\frac{R_{SA}+R_1}{R_{SA}+R_1+R_2}\right)=$$
$$\left(V_{CM}+\frac{V_D}{2}\right)\left(\frac{R_4}{R_{SB}+R_3+R_4}\right).$$

Isolating the output term yields

$$V_{OB}=\left(V_{CM}+\frac{V_D}{2}\right)$$
$$\left(\frac{R_{SA}+R_1+R_2}{R_{SB}+R_3+R_4}\right)\left(\frac{R_4}{R_{SA}+R_1}\right)$$

and a good reason to say nice things about whomever first pointed out the value of symmetrical structures:

If you let $R_{SB}=R_{SA}$, $R_3=R_1$, and $R_4=R_2$, the last expression collapses into

$$V_{OB}=\left(V_{CM}+\frac{V_D}{2}\right)\left(\frac{R_2}{R_{SA}+R_1}\right).$$

Adding the two terms confirms that, if properly balanced, this topology responds only to the differential-mode input and rejects the common-mode term.

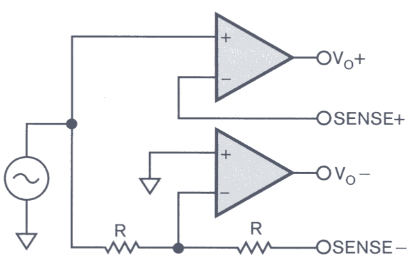


Figure 2 A simplified schematic of a unity-gain, electrically balanced driver includes local sense feedback, which can compensate for protection circuits.

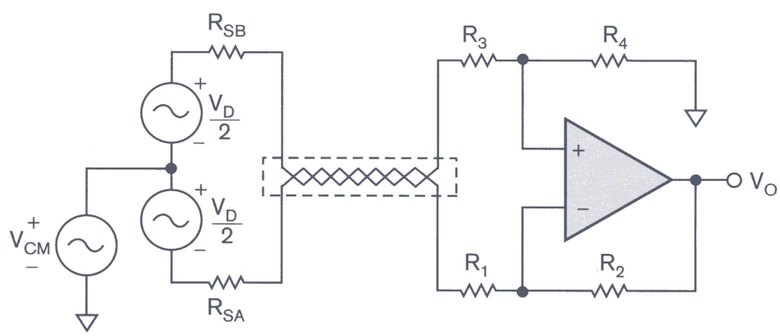


Figure 3 A balanced receiver, based on a difference-amplifier topology, rejects common-mode signals but passes differential-mode inputs. The CMR, however, depends on precisely trimmed resistors, R_1 to R_4, and a symmetrical source impedance.

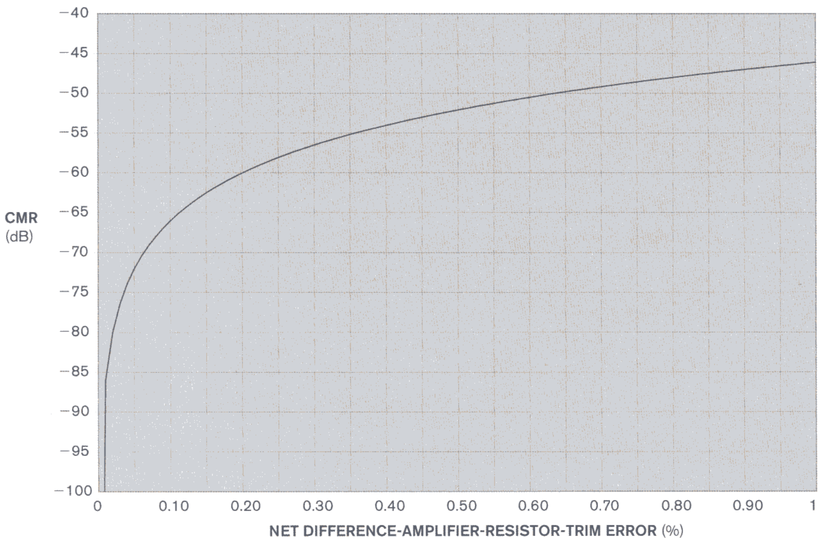


Figure 4 The balanced receiver's CMR performance degrades with resistor mismatches in the difference amplifier.

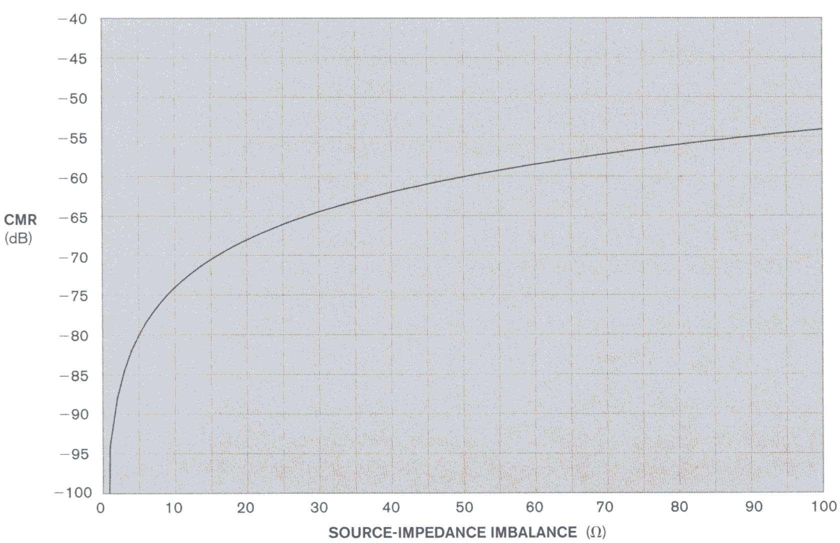


Figure 5 Asymmetries in the source impedance are indistinguishable from difference-amplifier-resistor mistrims. This curve models the CMR of a difference amplifier constructed with perfectly trimmed, 25-kΩ resistors and a signal source with 100Ω output impedance in each leg. An additional resistance in one leg rapidly degrades the CMR performance.

$$V_O = V_{OA} + V_{OB}$$
$$= \left(V_{CM} + \frac{V_D}{2} - V_{CM} + \frac{V_D}{2}\right)\left(\frac{R_2}{R_{SA}+R_1}\right)$$
$$= V_D\left(\frac{R_2}{R_{SA}+R_1}\right).$$

In practice, balanced-line-receiver manufacturers trim the on-chip resistors sufficiently well that the resultant ICs commonly provide minimum CMR (common-mode-response) specifications on the order of −70 dB or better at low frequencies (**Figure 4**, **references 1** and **2**). The sensitivity to the trim accuracy explains why, even with careful component matching, discrete balanced receivers tend toward comparatively marginal CMR performance.

IN THE REAL WORLD ...

Compared with typical source impedances, the difference amplifier's input resistors are reasonably large. Values in the few tens of kilohms are common, whereas source resistances usually fall in the area of a couple of hundred ohms. The source terms add to the difference amplifier's input resistances; the amplifier cannot distinguish between them. So, to the differential signal, the source impedance represents a minuscule gain error typically much smaller than 0.1 dB. To the common-mode signal, the source impedance has no effect as long as it is balanced across the two source legs. A source-impedance imbalance, however, is indistinguishable from a mistrim of the input resistors, the effect of which is readily calculable (**Figure 5**).

Impedance imbalances can arise in a variety of ways. Small asymmetries, on the order of a few ohms, can derive from component tolerances in the signal source's output-protection circuits. Connector-contact resistance can contribute several ohms more, particularly in temporary installations typical in sound-reinforcement systems for concerts, dramatic performances, lectures, meetings, and conferences; sound-capture facilities for on-location film, television, and sound recording; and signal-routing facilities in production studios and postproduction suites. Even with well-maintained, permanently installed equipment, a net imbalance of 5 or 10Ω is not out of the question—a condition that can degrade the CMR of an ideal receiver to −80 and −74 dB, respectively.

Connecting a piece of equipment with unbalanced outputs to a balanced input creates a source-impedance imbalance equal to the source's output impedance—often in the neighborhood of 100Ω. In this case, the CMR of an otherwise-perfect receiver degrades to −54 dB. Combining the two error sources—finite-trim accuracies and nonzero source imbalances—results in the CMR performance typical of many balanced-signal feeds (**Figure 6**).

These values hold for low-frequency common-mode signals. Performance degrades further at higher frequencies with decreasing loop gain and the increasing influence of reactive imbalances within the interface circuit. This oft-ignored behavior should be of concern with the growing prevalence of switch-mode power supplies and construction techniques that pose challenges to ground-management designs—conditions that can invite broad-spectrum common-mode signals.

The most obvious method of desensitizing the receiver to a source-impedance asymmetry is to increase the difference amplifier's resistor values. This approach increases common-mode input impedance, which makes the source error proportionately smaller. Unfortunately, this approach simultaneously increases the differential-mode input impedance, which increases noise and dc offsets due to the amplifier's bias offset current (**references 3** and **4**).

WHITLOCK'S BOOTSTRAPS

The CMR of balanced receivers in the presence of source-impedance asymmetries has long been a simple fact of the interface topology. The traditional cost of resolving the issue has been that of a transformer-coupled interface. Ironically, perhaps, it was an expert in transformer design, Jensen Transformer President Bill Whitlock, who suggested a plausible solution for IC receivers (**references 5** and **6**). Whitlock's method buffers the incoming balanced signal, derives the common-mode level, and uses that signal to bootstrap the input resistors. The bootstrap path is ac-coupled, so the amplifier's input bias currents have a low-impedance return path. But the arrangement tracks the ac component of the common-mode signal, forcing the same ac potential to appear on both ends of the input resistors. The result is a substantial increase in the apparent common-mode input impedance and a reduced sensitivity to source-impedance asymmetries.

That Corp recently announced a family of IC receivers that implement Whitlock's bootstrap. The product announcement promised unusually high CMR even in the presence of asymmetrical source impedances. To compare the devices with other receivers, I checked the data sheets from the two leading suppliers of IC-balanced receivers, Analog Devices and Texas Instruments. Unfortunately, these data sheets don't characterize CMR performance with asymmetrical sources. They also do not reveal the input-circuit topology in any detail beyond the simplified schematics that accompany most ICs, so you cannot guess if they address the issue in some

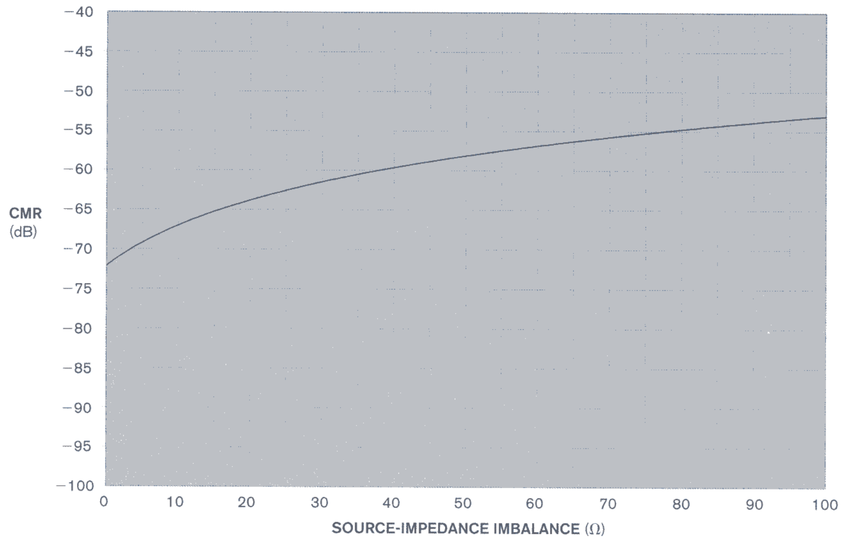
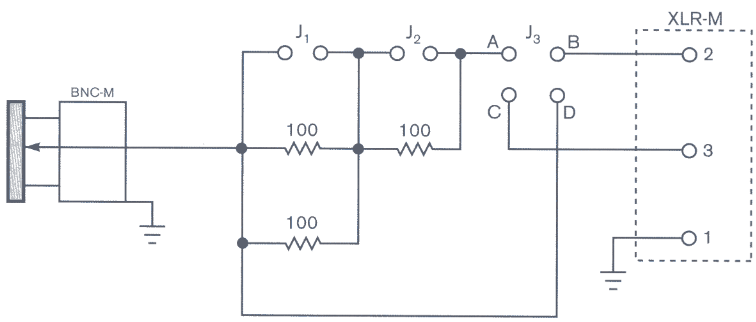


Figure 6 In practice, a combination of the residual error in the resistor trims and the source-impedance asymmetry limits an IC-balanced receiver's CMR performance. Here, the effect of a 0.05% error in R_1 (25 kΩ nominal) combines with a variable imbalance added to a source with 100Ω in each leg.



J_1	J_2	IMBALANCE (Ω)
SHORTED	SHORTED	0
OPEN	SHORTED	50
SHORTED	OPEN	100
OPEN	OPEN	150

J_3 A-C	J_3 B-D	IMBALANCE ON LOW PIN
J_3 A-B	J_3 C-D	IMBALANCE ON HIGH PIN

Figure 7 A simple fixture derives a common-mode test signal from the Audio Precision SYS-2722's analog generator. Jumpers J_1 and J_2 provide the means of injecting a source-impedance asymmetry of 0, 50, 100, or 150Ω. Jumper J_3 selects the output leg to which the fixture adds the asymmetry.

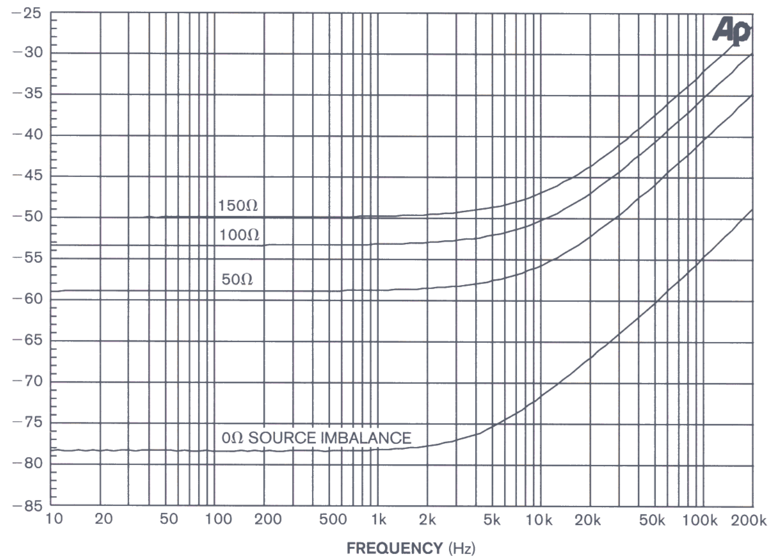


Figure 8 The Analog Devices SSM-2141's CMR performance agrees with a theoretical difference amplifier with matching error within about 0.02%.

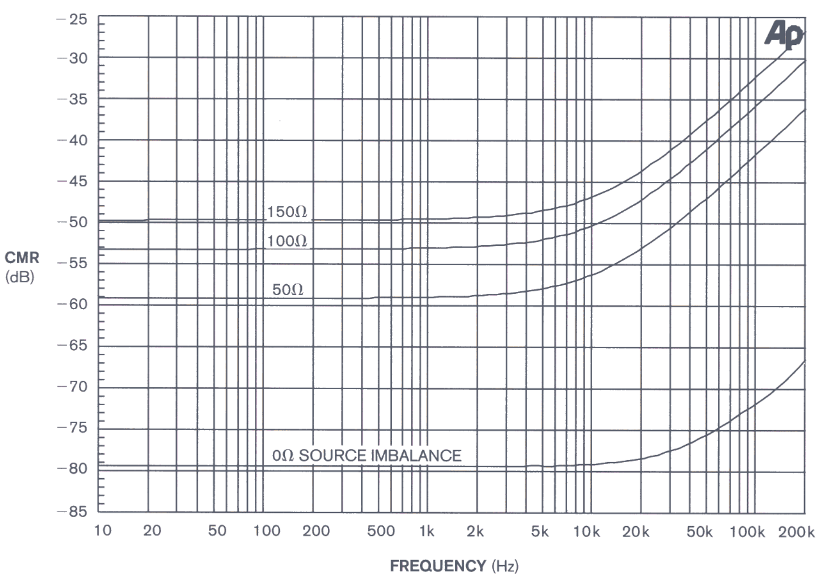


Figure 9 Like the SSM-2141, the Texas Instruments INA-134's CMR performance agrees with a theoretical difference amplifier with matching error within about 0.02%.

other way. The unanswered question then is: How much better—if at all—could the CMR of the bootstrapped receiver be than those of the long-standing industry leaders?

TO THE BENCH!

A trivially simple fixture provides a CMR test signal from the Audio Precision SYS-2722 that serves as the core of *EDN*'s BenchPress test facility (**Figure 7**). Jumpers set the CMR source-impedance asymmetry to 0, 50, 100, or 150Ω. The three manufacturers provided samples of unity-gain balanced receivers—the Analog Devices SSM-2141, the Texas Instruments INA-134, and That Corp's That-1200. The SSM-2141 and the INA-134 share identical pinouts; the That-1200 differs in that a coupling capacitor for the bootstrap circuit uses the traditional pinout's unused and output-sense pins.

As is apparent from the CMR curves, the SSM-2141 (**Figure 8**) and INA-134 (**Figure 9**) provide similar common-mode performance. Low-frequency CMR with no source imbalance is on the order of −80 dB at low frequency, suggesting net resistor-matching errors on the order of 0.02%. Try doing that with a handful of discretes! A 50Ω source imbalance knocks about 20 dB off that figure, and another 10 dB comes off as the imbalance increases to 150Ω. Indeed, the CMR curves for the two devices are nearly congruent except in the fully balanced case in which the SSM-2141's CMR starts to decay at about 1 kHz, whereas the INA-134 holds on up to about 10 kHz. With 50- or 60-Hz power lines as the dominant common-mode concern, both devices turn in good performance with balanced sources and follow the theoretical curve for well-matched difference amplifiers driven by imbalanced source impedance (**figures 5** and **6**).

The That-1200 sample apparently has *incrementally* better resistor-matching errors than the SSM-2141 or INA-134 samples, which translates into a small improvement in CMR performance at low frequency with a well-balanced source (**Figure 10**). Based on the low-frequency CMR results, it appears that the samples *EDN* tested had net residual trim errors of about 0.015%. This figure does not give the 1200 a significant competitive claim over the traditional designs. It does show, however, in striking contrast to the other two receivers, the 1200's CMR performance with an asymmetrical source impedance: an 18-dB improvement at low frequency with a 50Ω imbalance, extending to a 25-dB improvement at 150Ω.

The bootstrap seems to work very well through the third harmonic of the line frequency. Beyond that point, the benefits start to degrade. The bootstrapped topology appears to provide at least incremental benefit throughout the audio spectrum, however. The CMR degrades, as you would expect, at a rate of 20 dB

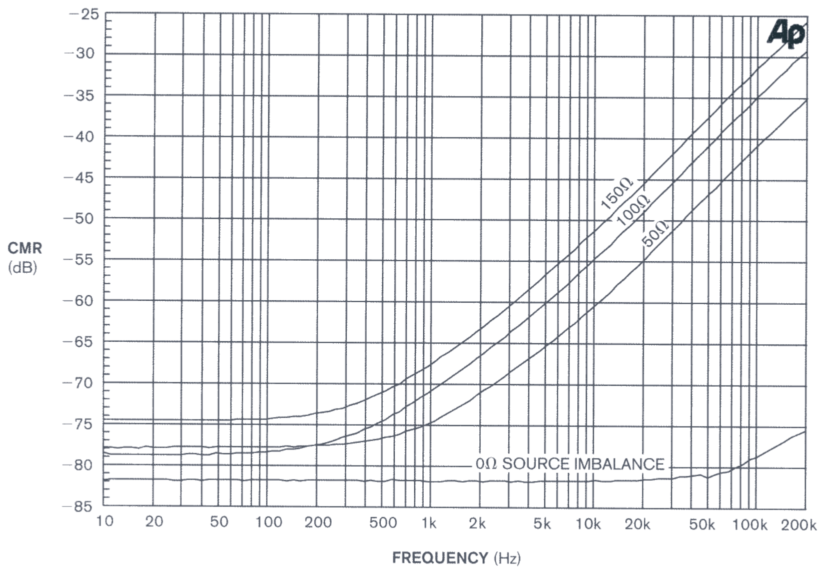


Figure 10 That Corp's That-1200, which implements Bill Whitlock's bootstrapped input structure, improves the balanced receiver's CMR performance in the presence of source-impedance asymmetries. The benefit begins to taper off at about the third harmonic of the power-line frequency.

per decade at high frequencies (**figures 8 through 10**). Take care to minimize the high-frequency common-mode components deriving from switching supplies, EMI, or other sources: Slight asymmetries can convert these common-mode signal components to differential mode. Should that happen, only the antialiasing filter ahead of a digitizer prevents them from aliasing back into the audio band. **EDN**

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