Ask The Applications Engineer—14

by James Bryant (ADI Europe)
with Herman Gelbach (The Boeing Company)

HIGH-FREQUENCY SIGNAL-CONTAMINATION

Q. *I've heard that RF can make low-frequency circuits do strange things. What's that all about?*

A. I was once summoned to France because an Analog Devices Voltage-Frequency Converter (VFC), the AD654, suffered from "unacceptable variation of accuracy." I had measured the offending parts in my own laboratory and found them to be stable and within specification, but when I returned them to the customer with my test jig he was unable to reproduce my results. While considering a site visit to confirm my suspicions, I discovered that the restaurant "La Cognette" in the town where our customer was located had three stars in the *Guide Michelin,* and the chef was a "Maitre Cuisinier de France"—a title not lightly bestowed. The visit to the customer became doubly necessary. Herman, who was in England to look at data offsets in a Boeing wind tunnel test, offered to come and help—he said it was the interesting technical problem (but just before he offered I saw him earnestly consulting the *Guide Michelin)*.

To drive from the Analog Devices office in Newbury in the South of England to the centre of France involves six hours of driving, a six hour ferry crossing of the English Channel, and a change from the correct side to the right side of the road. Nevertheless, driving is better than flying, because one can take more test gear (and the portable ham-radio station as well—we are both hams).

As we approached the customer's works we passed an enormous short-wave transmitting antenna, and then another, and yet another. We began to guess what might be wrong, and when we entered the laboratory I was carrying a hand-portable two-metre ham transceiver (an HT or "handy-talky") in my jacket pocket.

The AD654 was indeed behaving unstably, as the customer had claimed. The VFC's output frequency varied by an equivalent offset of tens of mV over the space of a few minutes. I quietly reached into my pocket and pressed the transmit button of my HT. The output frequency jumped by an equivalent of 150 mV, thus demonstrating the problem to be high-frequency pickup. More-formal measurements a little later showed that the local transmitters (of the French Overseas Broadcast organization) produced high-frequency (HF) field strengths within our customer's works of tens or hundreds of mV/m.

Many problems of instability in precision measurement circuitry can be traced to high-frequency interference, but unless there is a loudspeaker in the system that might unexpectedly burst into hard rock music from the nearby radio station, it is common for engineers to overlook this source of inaccuracy and blame the manufacturer of the amplifiers or data converters.

Furthermore, this case was unusual in that it took a high-powered signal to affect the AD654, which is single-ended and also relatively insensitive to RF—it is much more common to see with a differential amplifier in-amp. Both inputs of these types of amplifier have high input impedances to common; they are therefore far more vulnerable and are affected by low-level RF, such as radiation from a personal computer (PC). [This phenomenon is detailed in the Analog Devices system-design seminar notes, available for sale as *System Application Guide* (1993).]

An important factor is that, in instrumentation amplifiers, common-mode rejection decreases with increasing frequency, starting to roll off at quite low frequencies—and distortion increases with frequency. Thus, not only are high-frequency common-mode signals not rejected; they are distorted, producing offsets. For some applications, where RF interference is a strong possibility, the AD830 difference amplifier has wideband common-mode rejection and is designed for line-receiver applications; it may be a useful substitute for an instrumentation amplifier.

Sensors are often connected to their signal-conditioning electronics by long cables. Radio engineers have a term for such long pieces of wire; they call them *antennas.* The long feeders from sensors to their electronics will behave in the same way and will serve as antennas, even if we do not wish them to do so. It does not matter if the sensor case is grounded—at high frequencies the reactances of the case and feeders will allow the system to behave as an antenna, and any high- frequency signals (E-field, M-field, or E-M-field) which it encounters will appear across any impedances. The most likely place for them to end up is at the amplifier input. Precision low-frequency amplifiers can rarely cope with large HF signals, and the result is error—commonly a varying offset error.

Q. *But this couldn't happen to me!*

A. Never believe it won't happen to you! An easy free lunch can always be obtained by persuading an innocent to bet on his or her circuit being free of such problems. Using a ham radio HT on the two-metre (144-148-MHz) band, one watt at a distance of one meter for one second will win you your free lunch almost every time. But a less-dramatic test can be equally convincing.

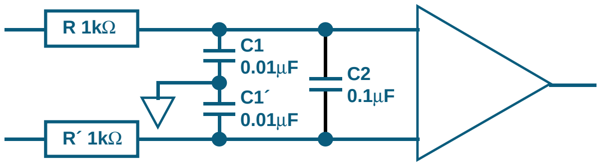
Disconnect the sensor and its leads. Short-circuit the amplifier input terminals to each other and to the amplifier circuit common (probably ground) with the shortest possible links and measure the amplifier output; observe its stability over a few minutes. Now remove the short-circuit, replace the sensor leads and place them in their normal operating environment. Disable the excitation and short-circuit the signal leads at the sensor end. Again measure the amplifier output, and its variation with time. Weep quietly.

It is often possible to see what is happening by using a high-frequency oscilloscope (or a spectrum analyzer, which is more sensitive but less easy to interpret) to measure the HF noise, both normal mode and common-mode, at the amplifier input; but normal mode measurements must be treated with some suspicion, because the oscilloscope itself—and its power- and probe leads—may themselves introduce signals and invalidate the measurement. The effect of the oscilloscope may be minimized by using a simple broadband transformer between the measurement point and the oscilloscope input, as shown in the figure; but such a transformer has fairly low impedance and will load the circuit being measured.

Common-mode signals can be observed quite easily by disabling any sensor excitation and connecting the oscilloscope ground to the ground at the board input and joining all the sensor leads together and to the oscilloscope input. All too often this signal will have an amplitude of several hundred millivolts and contain components from low frequencies to tens or hundreds of MHz.

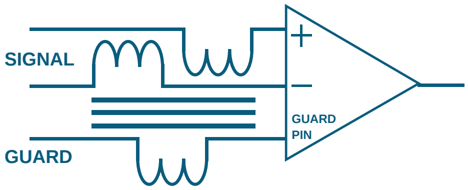
The world is full of HF noise sources: ham radio operators, police, people with portable phones, garage door openers, the sun, supernovas, switching power-supply and logic signals (e.g., PCs). Since we cannot eliminate HF noise in the environment, we must filter it out of low-frequency signals before they arrive at precision amplifiers.

The simplest type of protection can be used when the signal bandwidth is only a few Hz. A simple RC low-pass filter inserted ahead of an amplifier will afford both normal-mode and common-mode HF protection. A suitable circuit is shown in the figure. There are two important issues to be considered in the choice of components: the resistances R and R' (shown as 1 kΩ in the diagram, a value suitable for amplifier bias currents of a few nA or less) must be chosen so that they do not increase the offset appreciably as the amplifier bias current flows in them. The normal-mode time constant, $(R + R')C_2$, must be much larger than the common-mode time constants, RC_1 and $R'C_1'$, otherwise the common-mode time constants would have to be very carefully matched to avoid an imbalance that would convert the common-mode to a signal between the differential inputs.



If the signal bandwidth is wider, such simple filters will not be suitable because they remove the desired HF normal-mode signals as well as the unwanted HF common-mode signals. Large HF common-mode signals are very likely to suffer common-mode→normal mode conversion (as well as minor rectification, producing low-frequency errors) if they get to the amplifier, so it is necessary to use a filter which will reject HF common-mode signals but will pass DC and HF normal-mode signals.

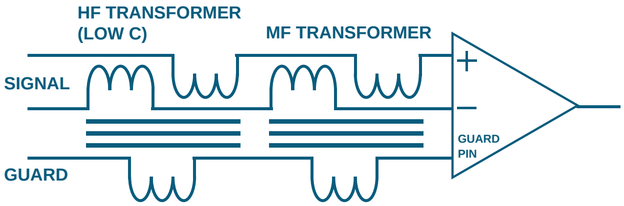
Such a filter is shown below. It was devised many years ago by Bill Gunning of Astrodata and is related to the "phantom circuit" used in long-distance telephone circuits. It uses a tightly coupled "trifilar" transformer having three windings in an accurate 1:1:1 ratio. An AC voltage across any winding will also be present on the others.



The guard line is connected to ground at the source end and at the other end to the amplifier's guard pin (or a comparable derived voltage), which represents what the amplifier "thinks" is common mode, via a capacitor. The high-frequency common-mode signal will appear (by definition) across the bottom winding, and will induce an equal common-mode voltage in the other two, subtracting the common-mode voltage in series with each line and effectively cancelling the HF common-mode signal at the amplifier inputs.

There are, of course, potential problems. A capacitor in series with the transformer is almost essential in the guard circuit to block DC and LF and prevent transformer core saturation by low-frequency currents in the guard circuit. The impedance looking into the amplifier guard terminal must be much lower than the impedance of the transformer windings; and at very high frequencies the capacitances of the transformer will allow signal leakage or may cause phase shift. These issues set incompatible constraints on the design of the transformer, if it must deal with a very wide range of common-mode frequencies.

In such a case double cancellation using two separate transformers as shown might be considered—the one nearer the amplifier having high inductance (and correspondingly high capacitance) and the other having good VHF efficiency.



Other approaches are also possible: the amplifier can be sited closer to the sensor and the long leads be replaced by leads (or optical fibre) carrying digital data, which is less vulnerable; more shielding is often (but not always) helpful; and sometimes (but rarely) it is possible to reduce the possibility of unexpected HF signals (even if you keep away the hams and police, there is always the possibility of the unexpected pizza delivery truck radioing to its base . . .)

The most important consideration, though, is awareness of the possibility of HF interference and readiness to tackle it. If designs are always made in the expectation of unwanted HF, chances are excellent that precautions will be adequate—it's when you don't expect it that the trouble starts.

Q. How did it work out with the French customer?

A. His problem was cured with two resistors, three capacitors and a piece of grounded copper foil. We went off to "La Cognette" to celebrate.

A Reader Notes

HIGH-FREQUENCY SIGNAL CONTAMINATION

by Leroy D. Cordill*

I found your article on high-frequency signal contamination ("Ask The Application Engineer—14," *Analog Dialogue* 27-2, 1993) interesting and would like to offer some additional comments.

EMI/EMC requirements are becoming more important to designers of industrial equipment as analog signal sensitivities are increased while more "RF generators" (higher-frequency digital circuits) are incorporated into the same equipment. Therefore, I would like to see a *good* application note relating to the issue of RF susceptibility produced by someone such as Analog Devices. By "good", I feel it should cover:

a. rules of thumb about the types of circuits where you will likely have trouble
b. some explanation of the phenomenon
c. general grounding/shielding approaches for equipment
d. "fix" type approaches to minimizing the effects when items from (c) can't be implemented
e. bench-level testing techniques.

(At least I'm not aware of any such application note in existence; maybe one exists and I haven't found it.) Based on my own experience, I offer the following comments on the above five areas:

Regarding (a), I generally see the problem with low-level input or preamp circuits involving a voltage gain of 50 V/V or more. In my case, the signals are usually from thermocouples, RTDs, pressure sensors, etc., and the required signal bandwidth is less than 100 Hz. And I'm trying to maintain signal integrity suitable for conversion by a 10-to-14-bit A/D converter.

For (b), my "model" of the effect is that the error gets created by rectification of the rf at the base-emitter junctions at the inputs of the op amp, and essentially becomes a large input offset voltage for the op amp. This introduces errors into dc-coupled circuits that cannot be corrected for by any usual low-pass filtering of the signal.

One observation I have made regarding this susceptibility problem is that it is primarily related to bipolar-type op amps (741, 5558, OP05, OP07, OP27, AD708, OP220, etc.) If I swap to a FET-input op amp (TL082, TL032, OP80, OP42, AD845) the error will largely disappear. (Due to other considerations, this is not usually a permanent solution, but helps to identify error sources during EMC testing.)

Also involved is the RF impedance at the two input nodes of the op amp. If (in a typical inverting configuration) the feedback path has a capacitor for low-pass filtering, it aggravates the problem as one input node of the op amp sees more of the RF than the other. If this is the situation, I'm not sure a wide-bandwidth op amp would help (regarding suggestions for using an AD830). Even without an intentional discrete capacitor in the feedback loop, PC-board layout makes it difficult to count on matched impedances at the two inputs.

Regarding (c), a good RF ground to the chassis is important for the signal common; but I find the shielding/grounding aspects of the equipment design relate more to the ESD requirements than RF (continuous-wave) susceptibility problems. I also try not to rely on these (shielding/grounding) to a great extent, since I find them very uncontrollable during the life of a piece of field-customizable equipment.

For (d), my best, most consistent prescription is placing a small capacitor directly across the input pins on bipolar op amps. I have used 100-1000 pF for this purpose in various circuits; it usually significantly reduces or eliminates the problem up to the level of interference that I plan for. I have found that with this in place on the critical parts of the circuit, the requirements for extreme care in grounding and shielding of cables are greatly reduced.

Regarding (e), I agree that a small walkie-talkie is useful, but primarily as a go/no-go test on the equipment when it is all assembled, in the enclosure, etc. However, for pc board or circuit-level work, I have two problems with the walkie-talkie technique: (1) you will get many unkind remarks from the guy on the next bench over if he's trying to breadboard a low-level circuit and is not ready for EMI testing yet; and (2) if you start attaching leads to various points in the circuit to determine where the problems are, and then apply RF in a radiated fashion, you have so many antennae, both to your circuit and to the various test gear, that you will have *no* idea what is happening.

I prefer to use an RF signal generator and apply the interference in a conducted fashion. This allows much better control of which items get RF applied to them. I don't use a lot of RF power, as I usually connect the output of the generator directly to some connector or cable supplying the low-level signal of interest, or in some cases the body of a sensor. A few hundred millivolts of RF signal is generally sufficient to identify problem circuits. I manually sweep from about 10 MHz to 100 MHz. While this is not a quantitative type of test, it is a very useful qualitative technique.

Some of the RF generators I have used for this are older model units—usually acquired at garage sales for $5 to $20 each:

RCA WV-50B
Advance Schools, Inc., Model IGB-102
Heathkit Model IG-102 (same as above)
Precise Model 630

I hope this may be useful, and, as I mentioned would like to see a good application note put together on this subject by someone who can add some additional information regarding performance implications of adding a capacitor on the op-amp inputs for various circuit configurations.

Thanks to Mr. Cordill for a useful contribution to the Dialogue, and for throwing down the gauntlet to our Application Engineers. They have accepted the challenge; so keep your eyes on the "Worth Reading" page in future issues. Having said that, we feel obliged to point out that the challenge is to get it together in one place; much of the material he suggests already exists in the Analog Devices literature (and elsewhere). For example, the System Applications Guide devotes pages 1-13 thru 1-55 to remote sensor application problems—including an exhaustive discussion of RFI rectification in high-accuracy circuits. Other good sources include the Applications Reference Manual, Chapter 3 and Bibliography of the Transducer Interfacing Handbook, and Part 5 and Bibliography of the Analog-Digital Conversion Handbook. ▶

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