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Analogue circuit design for RF immunity

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Analogue circuit design for RF immunity

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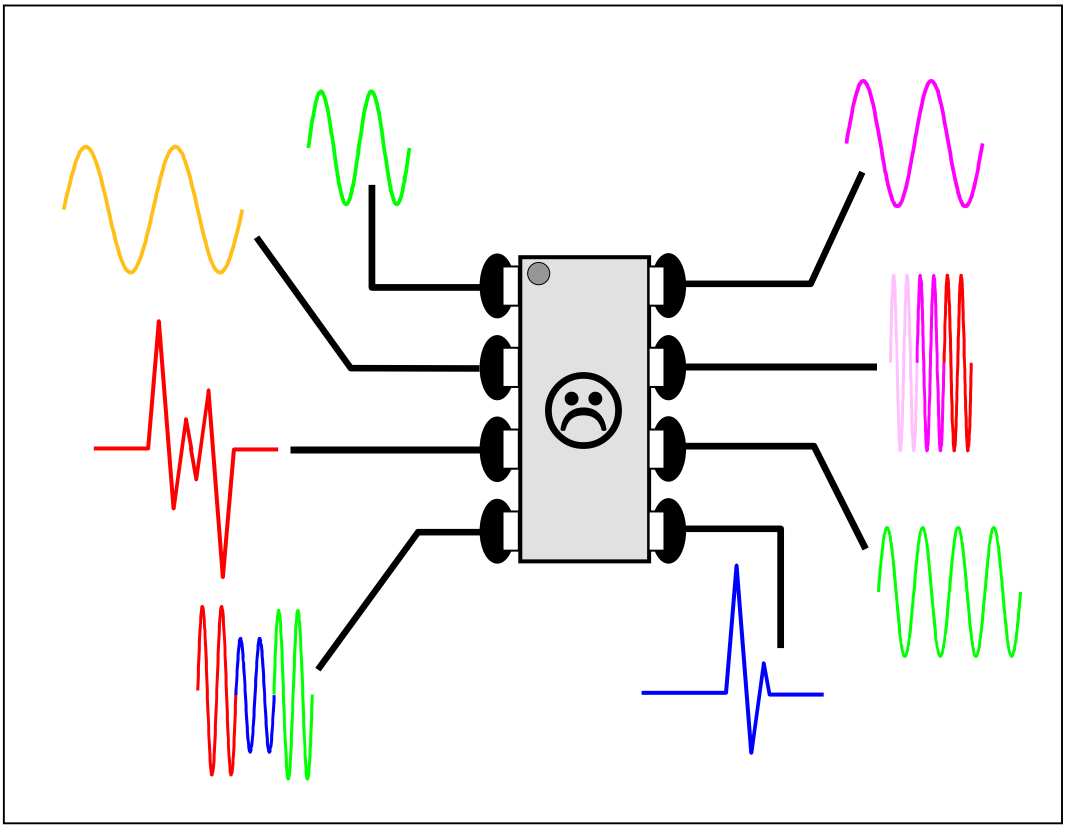
Why bother with immunity design for analogue?

The biggest problem for most analogue ICs is their susceptibility to demodulating and intermodulating radio frequency noises that are outside their linear frequency range of operation. Unfortunately there are no data sheet specifications which can act as a predictor of this problem. As a general rule, bipolar opamps are approximately 20dB less immune than BiFET types [1].

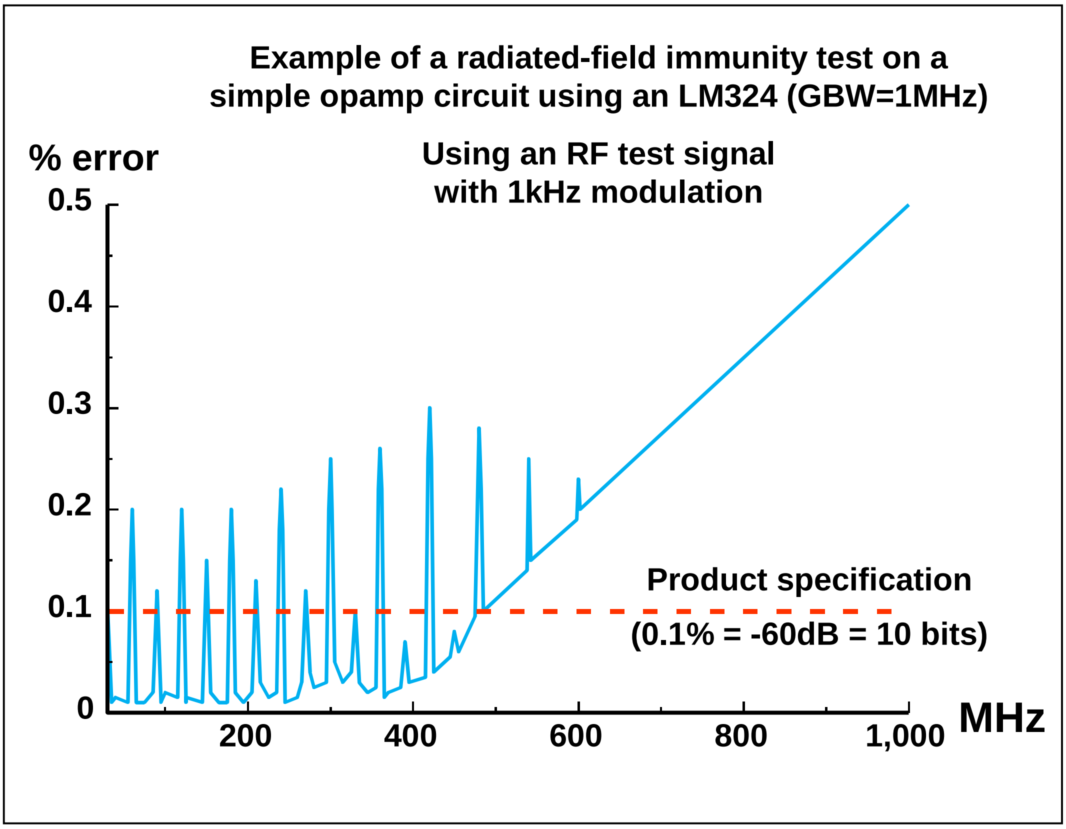
Some opamps are now available 'hardened' against RF noise, such as the LMV831 series, but even their circuits might still need to employ the good EMC design techniques described below. This article assumes the use of more traditional, 'normal' opamps.

Even very "slow" opamps are very sensitive to RF interference on *all* their pins, regardless of the feedback schemes employed, a situation shown graphically by figure 1.



All semiconductors demodulate and intermodulate RF due to the non-linear characteristics that make them useful as semiconductors. Demodulation and intermodulation are very common problems in analogue circuits, because they do not have the noise thresholds that well-designed digital circuits do.

Contrary to what some low-frequency analogue designers believe, even “slow” opamps will happily demodulate interference up to cellphone frequencies and beyond, as shown by the real product test results of Figure 2.



Note that despite the opamp having a GBW of just 1MHz, the output error was worse when exposed to RF fields at 1GHz, than it was at 500MHz. For more on this issue, read section 4.3.2 of [2].

Very many designers of analogue circuits discovered the above problems for the first time, to their great concern and at great cost to their employers, when RF radiated field testing from 150kHz to 1GHz, *using modulated fields,* became applicable to almost all CE marked electronic products sold in Europe in 2001. The basic test methods used by the compliance tests are IEC 61000-4-6 [3] (from 150kHz to 80MHz) and IEC 61000-4-3 [4] (from 80 to 1000MHz).

The types of products that suffered during that period included telephone handset and other audio products (especially very high-specification pro-audio products); video, and instrumentation (e.g. measurement and control of temperature, flow, weight, strain, etc., basically any instruments relying on transducers with millivolt outputs).

Preventing demodulation and intermodulation problems

Of course, for low-frequency analogue circuits it is often possible to fit filters and shields which remove all the RF so that no demodulation can occur. However, employing these techniques on their own often results in products that are larger, heavier, and more costly to manufacture than is necessary, making products uncompetitive.

Analogue circuits with a bandwidth of more than 20kHz can have a great deal of difficulty in finding affordable filters that will give good enough performance on the IEC 61000-4-6 immunity tests [5], which start at 150kHz, without affecting the functional bandwidth.

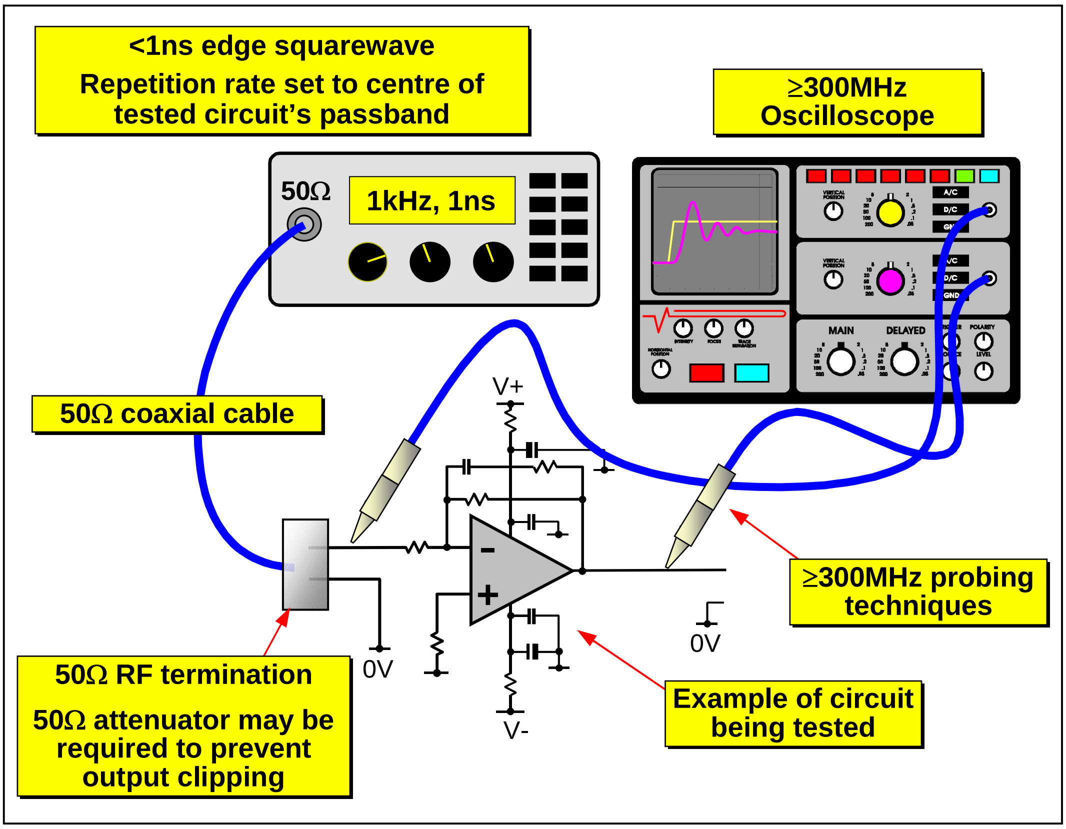
To help prevent demodulation and so reduce the cost of weight of filtering and shielding when exposed to one or more frequencies, and prevent intermodulation when exposed to two or more frequencies, analogue circuits need to remain as linear as possible up to the highest possible frequency.

And to prevent intermodulation problems when exposed to a single frequency, they need to remain as stable as possible. Stability is of course a desirable aim anyway, quite apart from EMC considerations, but it presents particular problems for feedback circuits.

Contrary to popular belief, the integrator connection of an opamp (an integrating capacitor from output to inverting input) is the least stable of all feedback configurations, and the most likely to result in RF demodulation problems, due to its poor phase margin at the highest frequencies, plus the existence of phase shifts and resonances at RF due to the inductance of the ICs' lead frames and bond wires and the capacitance of its input transistors. Using unity-gain-stable opamps can help *disguise* this problem in most cases, but is not a cure.

The stability and linearity of feedback circuits can be tested using ordinary test gear as shown by figure 3, by removing all the tested circuit's input and output filters and output loads and then injecting very fast-edged (<1ns risetime) square waves from a 50 ohm source into inputs (and possibly into outputs and power supplies, via small capacitors).

The 50 ohm source must be terminated in 50 ohms at the circuits input to maintain a good square waveform at that point. The test signal's amplitude should be set so that the output pk-pk voltage is about 30% maximum, to prevent clipping, and its fundamental frequency should be near the centre of the intended passband of the circuit.



The circuit's output is observed with a 300MHz (at least) oscilloscope and probes for its slew rate, overshoot and ringing (even for audio or instrument circuits). For higher-speed analogue circuits use an appropriately faster 'scope and take great care to use appropriate high-speed probing techniques.

Feedback circuits should be adjusted so that slew rates are maximised and overshoots are low (heights of more than 50% of the signal's nominal height indicate instability). Any long periods of ringing (say, longer than two cycles) or bursts of oscillation also indicate instability.

The idea is to make the circuit as fast and linear as possible – thereby extending the range of linear and stable operation to as high a frequency as possible. Passive RF filtering around the circuit will then take care of the rest.

Achieving good stability in feedback circuits usually requires that capacitive loads be buffered with a small resistance or choke which is outside the feedback loop.

A small amount of feedback capacitance, say around 4.7pF, is generally a good thing for stability, and integrator-type feedback circuits will almost always need a small-value resistor (often around 560 ohms) in series with each integrator feedback capacitor that is larger than about 10pF.

The PCB placement and routing can be an important factor too, and a 0V ground plane – not a "copper fill" but a real plane, see Chapter 4 of [6] – will generally be found to be essential.

Different batches of ICs can have very different stability performance, but it would be difficult to obtain examples of worst-case ICs to check their speed, linearity and stability, even where it was known which parameters were important.

However, it *is* easy to simulate IC tolerance extremes by cooling and heating a typical device under test over a wider range of temperatures than they would experience in normal operation, say: -30 to + 180°C and ensuring the circuit is as fast and stable as it is possible to achieve over the whole temperature range.

When a circuit is fast, linear, and stable over the full range of temperatures with a given manufacturer's typical device, it stands a good chance of being a useful circuit for volume manufacture.

Where second-sources are used for analogue ICs used in feedback circuits, repeat the above tests, using the full temperature range, with each manufacturer's typical devices and modify the circuit so that they all give acceptable results for speed, linearity and stability.

Some designers are more used to working in the frequency domain than the time domain, in which case the above method can be adapted to use a swept frequency input instead, with a spectrum analyser measuring the output. Take care not to overdrive the spectrum analyser's input.

Other analogue circuit techniques

Never try to filter or control RF bandwidth for EMC with active circuits – only use passive (preferably RC) filters outside of any feedback loops.

The integrator feedback method is only effective at frequencies where the opamp has considerably more open-loop gain than the closed-loop gain required by its circuit. It *cannot* control frequency response at higher frequencies.

Having achieved a fast, stable and linear circuit, all of its connections might need protecting by passive filters or other suppression methods (e.g. opto-isolators). Any digital circuits in the same product will cause noise on all internal interconnections, and all external connections will suffer from the external electromagnetic environment.

The filters associated with each IC should connect to its local 0V plane. Filter design can be combined with galvanic isolation (e.g. transformers, opto-isolators) to provide protection from DC to many GHz. Using balanced (differential) inputs and outputs can help reduce filter size while maintaining good rejection at lower frequencies.

Input or output filters are always needed where external cables are connected, but may not be necessary where opamps interconnect with other opamps by PCB traces over a dedicated 0V plane. Any wired interconnections inside unshielded enclosures might need filtering due to their antenna effect, as might wired interconnections inside shielded enclosures which also contain digital processing or switch-mode converters.

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Analogue ICs need high-quality RF decoupling of all their power supplies and voltage reference pins to their local 0V plane, just as do digital ICs. But analogue ICs often need low-frequency power supply decoupling too, because their power supply noise rejection ratio (PSRR) are usually increasingly poor for frequencies above 1kHz. RC or LC filtering of each analogue power rail at each opamp, comparator, or data converter, may be needed.

The corner frequency and slope of such power supply filters should compensate for the corner frequency and slope of device PSRR, to achieve the desired PSRR over the whole frequency range of interest.

Transmission line techniques are often only considered for high-speed analogue signals (e.g. RF signals), but they can be useful for improving the immunity of low-frequency signals, since correctly matched transmission lines of any length behave as very poor antennas and so do not pick up as much RF signal from the environment.

In general, avoid the use of very high-impedance inputs or outputs, as they are very sensitive to electric fields.

Because most of the emissions from products are caused by common-mode voltages and currents, and because most environmental electromagnetic threats (simulated by immunity testing) are common-mode: using balanced send and receive techniques in analogue circuits has many advantages for EMC, as well as for reducing crosstalk.

Balanced circuits drive antiphase (±) signals over two conductors, and does not use the 0V system for the return current path. Sometimes called differential signalling.

Comparators must always be designed to have hysteresis (positive feedback), to prevent false output transitions due to noise and interference, also to prevent oscillation near to the trip point. Don't use faster output-slewing comparators than are really necessary (i.e. keep their dV/dt low).

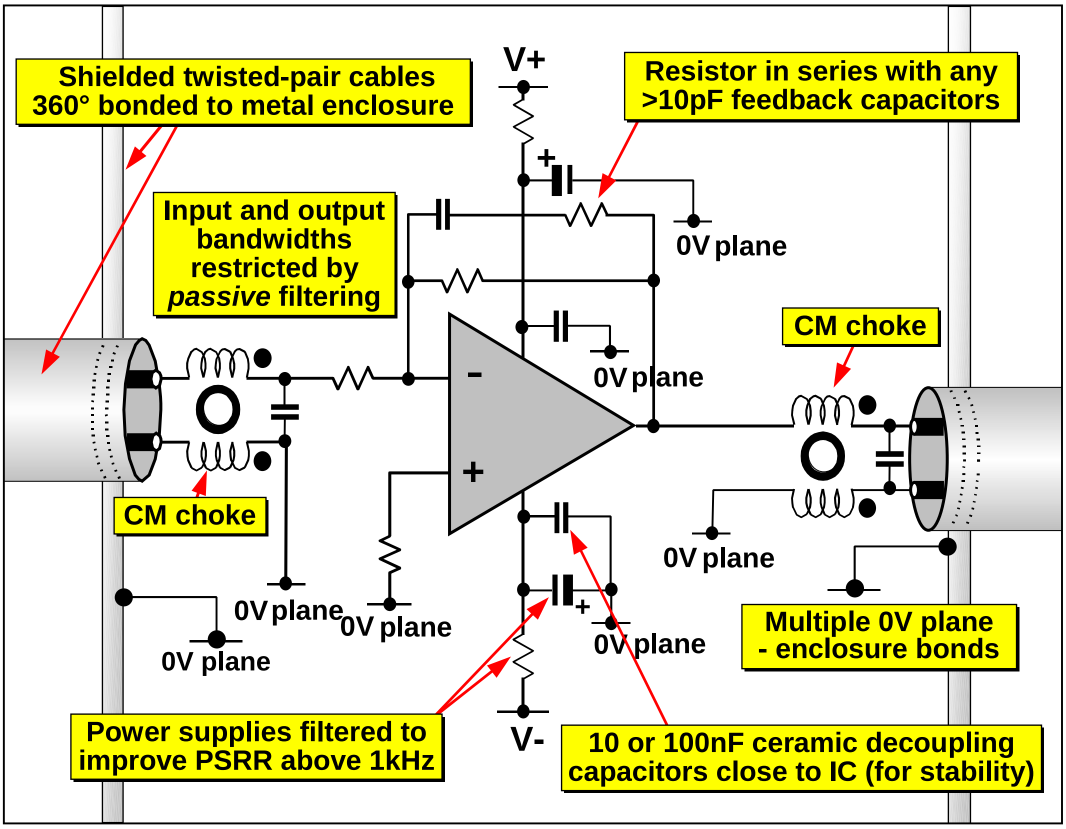

Figure 4 shows a simple opamp circuit (inverting amplifier) with some of the techniques described above applied. Even though the circuit uses single-ended signalling (i.e. uses 0V as the signal return) and is not balanced, common mode chokes will generally improve the EMC performance when used in the input and output filters.

Input or output filters are always needed where external cables are connected, but may not be necessary where opamps interconnect with other opamps by PCB traces over a dedicated 0V plane. Any wired interconnections inside unshielded enclosures may also need filtering, as might wired interconnections inside shielded enclosures which also contain digital processing or switch-mode converters.

Choosing analogue components

Specifications and standards for immunity testing of ICs are being developed, and in the future it may be possible to buy analogue ICs which have RF immunity specifications in their data sheets.

Some analogue ICs themselves are particularly susceptible to radiated fields. They may benefit from being shielded by their own little metal box soldered to the PCB ground plane (take care to provide adequate heat dissipation too).

It is recommended to test their immunity in their manufacturer's evaluation boards, using a single-turn loop probe and RF signal generator, so as to avoid choosing the wrong ICs early in a project. More detail on this technique will be found in section 4.4.1 of [2].

Different batches, second-sourced, or mask-shrunk analogue ICs can have significantly different EMC performance for both emissions and immunity. It is important to control these issues by design, testing, or purchasing to ensure continuing compliance in serial manufacture, Some batches of ICs with the same type numbers and manufacturers can have different EMC performance.

Large users can usually arrange with their suppliers to get advance warnings of mask-shrinks. This enables them to buy enough of the 'old' ICs to keep them in production while they find out how to deal with the changed EMC performance of the new mask-shrunk version.

If you know what silicon chips are used in the ICs in your products, I understand that it is often possible to discover their future mask-shrink programme from their manufacturers' websites, and plan accordingly.

It is possible to perform simple goods-in checks of IC EMC performance to see whether a new batch has different EMC performance, for whatever reason. This helps discover problems early on, and so save money.

Such simple checks can be based on the single-turn loop probe technique described above. Alternatively, sample-based EMC testing in serial manufacture is required to avoid shipping non-compliant or unreliable products, but it is much more costly to detect components with changed EMC performance this way than it is at goods-in.

Manufacturers of sensitive or high-speed analogue parts (and data converters) often publish EMC or signal-to-noise application notes for circuit design and/or PCB layout. Some of these can show that they have some understanding of, and care for, the real needs of their customers, and may help tip the balance when making a purchasing decision. But beware of application notes that encourage the use of bad EMC design techniques, such as single-point grounding (see 4.3 in [6]).

References

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[3] "*A Practical Guide for EN 61000-4-6, Testing and measurement techniques, Immunity to conducted disturbances induced by radio-frequency fields*", Keith Armstrong, Oct 2004, Version 2 Jan 2006, www.reo.co.uk/knowledgebase

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[5] IEC/EN61000-4-3, "*Testing and Measurement techniques-Radiated radio-frequency, Electromagnetic field immunity test*"

[6] "*EMC for Printed Circuit Boards – Basic and Advanced Design and Layout Techniques*", Keith Armstrong, February 2007, ISBN: 978-0-9555118-1-3 and 978-0-9555118-0-6, order via http://www.emcacademy.org/books.asp.

Keith Armstrong is a member of the EMC Industries Association, www.emcia.org.