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16. Analog Circuit Design

Analog circuit design involves a strange mix of intuition, experience, analysis, and luck. One of the nicest things about the job is that you feel very smart when you make something work very well.

A necessary condition for being a good analog designer is that you know about 57 important facts. If you know these 57 important facts, and know them well enough that they become part of your working intuition, you may become a good analog circuit designer.

Undoubtedly, there is an organized way to present these facts to the "interested student." The facts could be prioritized, or they could be alphabetized, or derived from first principles. The priority could be assigned, with the most important facts coming first on the list (for emphasis) or last on the list (for suspense). Some day, when I have a lot of time, I'm going to put the list in the right order.

It is difficult to present all the facts in such a way that will make sense to everyone. Sometimes I think that the only way to do this is by working examples over a twenty-year period. But we don't have time for that, and so as a poor alternative, I'm just going to write the facts down as they occur to me. There is a very good chance that you have run into most of these facts already. If so, just take heart that someone else has been tormented by the same problems.

Here's the list of things you should know:

0. If you even look at another engineer's approach to solving an analog circuit design problem before you solve the problem yourself, you greatly reduce the chance that you will do something creative.

1. Capacitors and resistors have parasitic inductance. A good rule of thumb is 4nH for a leaded component, and about 0.4nH for a surface-mount chip component. This means that a 100pF leaded capacitor will have a self-resonance at 250MHz. This can be just great, if you are using the part to bypass a 250MHz signal, but might be a nuisance otherwise.

2. If you don't want a transistor with a high bandwidth to oscillate in a circuit, place lossy components in at least two out of its three leads. A 33Ω resistor in the base and collector leads will usually do the trick without degrading performance. Ferrite beads in the leads work well to fix the same problem.

3. If you are probing a circuit with a dc voltmeter and the readings are not making any sense (for example, if there is a large offset at the input to an op amp, but the output is not pinned) suspect that something is oscillating.

4. Op amps will often oscillate when driving capacitive loads. A good way to think about this problem is that the low-pass filter formed by the output resistance of the op amp together with the capacitance of the load is adding enough phase shift (taken together with the phase shift through the op amp) that your negative feedback has become positive feedback.

5. The base-emitter voltage (V_{be}) of a small signal transistor is about 0.65V and drops by about 2mV/°C. Yes, the V_{be} goes down as the temperature goes up.

6. The Johnson noise of a resistor is about $0.13\text{nV}/\sqrt{\text{Hz}}\sqrt{\Omega}$. So, multiply 0.13nV by the square root of the resistance value (in Ohms) to find the noise in a 1Hz bandwidth. Then multiply by the square root of your bandwidth (in Hertz) to find the total noise voltage. This is the rms noise voltage: you can expect about 5–6 times the rms value in a peak-to-peak measurement.

Example: a 1kΩ resistor has about $4.1\text{nV}/\sqrt{\text{Hz}}$, or about 41m Vrms in a 100MHz bandwidth, which would look like about 0.2mV peak-to-peak on a 100MHz 'scope. Note that the Johnson noise voltage goes up with the square root of the resistance.

7. The Johnson noise current of a resistor is equal to the Johnson noise voltage divided by the resistance. (Thanks to Professor Ohm.) Note that the Johnson noise current goes down as the resistance goes up.

8. The impedance looking into the emitter of a transistor at room temperature is 26Ω divided by the emitter current in mA.

9. All amplifiers are differential, i.e., they are referenced to a "ground" somewhere. Single-ended designs just ignore that fact, and pretend (sometimes to a good approximation) that the signal ground is the same as the ground that is used for the feedback network or for the non-inverting input to the op amp.

10. A typical metal film resistor has a temperature coefficient of about 100 ppm/°C. Tempcos about 10× better are available at reasonable cost, but you will pay a lot for tempcos around a few ppm.

11. The input noise voltage of a very quiet op amp is $1\text{nV}/\sqrt{\text{Hz}}$. But there are a lot of op amps around with $20\text{nV}/\sqrt{\text{Hz}}$ of input noise.

Also, watch out for input noise current: multiply the input noise current by the source impedance of the networks connected to the op amp's inputs to determine which noise source is most important, and select your op amps accordingly. Generally speaking, op amps with bipolar front-ends have lower voltage noise and higher current noise than op amps with FET front-ends.

12. Be aware that using an LC circuit as a power supply filter can actually multiply the power supply noise at the resonant frequency of the filter. A choke is an inductor with a very low Q to avoid just this problem.

13. Use comparators for comparing, and op amps for amplifying, and don't even think about mixing the two.

14. Ceramic capacitors with any dielectric other than NPO should be used only for bypass applications. For example, Z5U dielectrics exhibit a capacitance change of 50% between 25°C and 80°C, and X7R dielectrics change their capacity by about 1%/V between 0 and 5V. Imagine the distortion!

15. An N-channel enhancement-mode FET is a part that needs a positive voltage on the gate relative to the source to conduct from drain to source.

16. Small-signal JFETs are often characterized by extremely low gate currents, and so work very well as low-leakage diodes (connect the drain and source together). Use them in log current-to-voltage converters and for low-leakage input protection.

17. If you want to low-pass filter a signal, use a Bessel (or phase linear) filter for the least overshoot in the time domain, and use a Cauer (or elliptic) filter for the fastest rolloff in the frequency domain. The rise time for a Bessel-filtered signal will be .35 divided by the 3dB bandwidth of the filter. Good 'scope front-ends behave like Bessel filters, and so a 350MHz 'scope will exhibit a 1.0ns rise time for an infinitely fast input step.

18. A decibel (dB) is always 10 times the log of the ratio of two powers. Period. Sometimes the power is proportional to the square of the voltage or current. In these cases you may want to use a formula with a twenty in it, but I didn't want to confuse anybody here.

19. At low frequencies, the current in the collector of a transistor is in phase with the current applied to the base. At high frequencies, the collector current lags by 90°. You will not understand any high-frequency oscillator circuits until you appreciate this simple fact.

20. The most common glass-epoxy PCB material (FR-4) has a dielectric constant of about 4.3. To build a trace with a characteristic impedance of 100Ω, use a trace width of about 0.4 times the thickness of the FR-4 with a ground plane on the other side. To make a 50Ω trace, you will need a trace width about 2.0 times the thickness of the FR-4.

21. If you need a programmable dynamic current source, find out about operational transconductance amplifiers. NSC makes a nice one called the LM13600. Most of the problem is figuring out when you need a programmable dynamic current source.

22. An 5V relay coil can be driven very nicely by a CMOS output with an emitter follower. Usually 5V relays have a "must make" specification of 3.5V, so this configuration will save power and does not require any flyback components.

23. A typical thermocouple potential is 30μV/°C. If you care about a few hundred microvolts in a circuit, you will need to take care: route all your signals differentially, along the same path, and avoid temperature gradients. DPDT latching relays work well for multiplexing signals in these applications as they do not heat up, thus avoiding large temperature gradients, which could generate offsets even when the signals are routed differentially.

24. You *should* be bothered by a design which looks messy, cluttered, or indirect. This uncomfortable feeling is one of the few indications you have to know that there is a better way.

25. If you have not already done so, buy 100 pieces of each 5%, ¼W carbon film resistor value and arrange them in some nice slide-out plastic drawers. When you are feeling extravagant, do the same for the 1% metal film types.

26. Avoid drawing any current from the wiper of a potentiometer. The resistance of the wiper contact will cause problems (local heating, noise, offsets, etc.) if you do.

27. Most digital phase detectors have a deadband, i.e., the analog output does not change over a small range near where the two inputs are coincident. This often-ignored fact has helped to create some very noisy PLLs.

28. The phase noise of a phase-locked VCO will be at least 6dB worse than the phase noise of the divided reference for each octave between the comparison frequency and the VCO output frequency. Hint: avoid low-comparison frequencies.

29. For very low distortion, the drains (or collectors, as the case may be) of a differential amplifier's front-end should be bootstrapped to the source (or emitter) so that the voltages on the part are not modulated by the input signal.

30. If your design uses a $3 op amp, and if you are going to be making a thousand of them, realize that you have just spent $3000. Are you smart enough to figure out how to use a $.30 op amp instead? If you think you are, then the return on your time is pretty good.

31. Often, the Q of an LC tank circuit is dominated by losses in the inductor, which are modeled by a series resistance, R. The Q of such a part is given by $Q = \omega L/R$.

At the resonant frequency, $f = 1/2\pi\sqrt{LC}$, the reactance of the L and C cancel each other. At this frequency, the impedance of a series LC circuit is just R, and the impedance across a parallel LC tank is Q^2R.

32. Leakage currents get a factor of 2 worse for every 10°C increase in temperature.

33. When the inputs to most JFET op amps exceed the common-mode range for the part, the output may reverse polarity. This artifact will haunt the designers of these parts for the rest of their lives, as it should. In the meantime, you need to be very careful when designing circuits with these parts; a benign-looking unity follower inside a feedback loop can cause the loop to lock up forever if the common-mode input to the op amps is exceeded.

34. Understand the difference between "make-before-break" and "break-before-make" when you specify switches.

35. Three-terminal voltage regulators in TO220 packages are wonderful parts and you should use a lot of them. They are cheap, rugged, thermally protected, and very versatile. Besides their recommended use as voltage regulators, they may be used in heater circuits, battery chargers, or virtually any place where you would like a protected power transistor.

36. If you need to make a really fast edge, like under 100pS, use a step recovery diode. To generate a fast edge, you start by passing a current in the forward direction, then quickly (in under a few nanoseconds) reverse the current through the diode. Like most diodes, the SRD will conduct current in the reverse direction for a time called the reverse recovery time, and then it will stop conducting very abruptly (a "step" recovery). The transition time can be as short as 35pS, and this will be the rise time of the current step into your load.

Well, there you have it. These are the first 37 of the 57 facts you must know to become an analog circuit designer. I have either misplaced, forgotten, or have yet to learn the 20 missing items. If you find any, would you let me know? Happy hunting!