Capacitor Distortion Mechanisms

An Overview

A resistor is a resistor, a coil is a plain ol' inductance, and a capacitor is a capacitor - or so you thought. Alas, life isn't quite so trivial...

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Non-ideal properties of real components

Real resistors, capacitors and inductances can be non-ideal in various ways.

First there are the *linear* non-idealities that can be described by linear *"parasitic elements"*, the number of which varies with the degree of detail required. Usually the higher the frequencies involved, the more complex the model becomes. For example, a capacitor is typically modelled with a series inductance to account for the inductance of the connection wires, a parallel resistance to describe leakage currents and a series resistance (equivalent series resistance, ESR) which effectively limits the lowest obtainable impedance. With these three parasitic elements the absolute-impedance-over-frequency plot of a typical electrolytic capacitor can be modelled quite well already - first impedance drops with 6 dB per decade like it should, then it reaches kind of a broad valley (series resistance in action), until finally it rises again with 6 dB per decade (inductance at work). See the Jung / Marsh article for examples.

However, it doesn't stop there. As if it weren't enough that *active* elements show *nonlinearities*, passive elements also do that! For example, carbon film resistors are known to change their resistance slightly depending on voltage applied - or just take a classic incandescent lightbulb with a tungsten filament, which when cold will have a much lower resistance than when hot. It gets really bad when looking at inductors and transformers, with the issues of core saturation, hysteresis and - when looking at ferrite cores – frequency-dependent losses / Q. Now since you are reading this page, you can probably guess that capacitors also have a bunch of nonlinear effects up their sleeve – we'll get to know them soon.

Capacitors: Linear considerations

When choosing capacitors for a given application, one normally looks at their linear properties first – it would, for example, be of little value to use an ordinary electrolytic cap to get rid of supply voltage ripple in the MHz range, since due to its high series inductance the poor thing would not only not work very well, but may also heat up and dry out prematurely. If nonetheless high capacitance requirements and high frequencies come together, a proven trick has been using multiple capacitors in parallel, for example two or even three different ones with descending capacities (typically factors of a little more than 1:100, depending on the combined impedance characteristics – one does not want resonance peaks), where generally the smaller caps are closer to the device that might be sapping power with such a high frequency (up to final supply bypass caps being only millimeters away from supply pins in things like DACs). Other important parameters include things like temperature stability and losses (ESR, dissipation factor etc.).

Nonlinear effects in capacitors

In some applications, however, nonlinear effects may become disturbing. Effects and underlying mechanisms that may appear are:

1. *Polarity.* Of course a polar capacitor (any kind of electrolytic) is inherently nonlinear. These are typically modelled as a nonpolar capacitor with an imperfect diode in parallel. Therefore these make for a pretty decent short when significantly reverse biased – if this happens, the results may be *phunni* indeed, up to outright explosion (tantalums are pretty nasty in that regard, it's the magnesium in their electrodes that tends to ignite).
2. Change of relative permittivity (relative dielectric constant, ϵ_r or K) with electric field strength – $\epsilon_r = \epsilon_r(E)$. This reflects linearly in capacitance, so effectively $C = C(U)$. It is obvious that given the same external voltage, thinner dielectric layers found in capacitors with lower voltage ratings will worsen the effect (same voltage drop in less distance means higher fieldstrength).
3. *Piezoelectric effect.* If dielectric layers contract or expand with applied voltage (an effect used for piezo buzzers), this will directly affect

capacitance - again, *C = C(U)*. This is mainly found in high-K ceramic capacitors, as these contain barium titanate which is very piezoelectric - for the very high capacitance types, you may find that they've lost 80% of their capacitance at rated voltage (ouch). This effect is actually used to build ceramic resonators which are employed as IF filters and discriminators.

4. *Dielectric absorption* (DA) or "capacitor soakage". Take a charged capacitor, then quickly dischange it, then wait for a while - and the voltage measured at its terminals will not be zero. That's DA in a nutshell. This kind of hysteresis or "memory" may generate funny distortion as well as keep analog computing circuitry from working correctly. As you may remember, hysteresis is typical for ferromagnetic materials and may therefore be an issue when working with things like output transformers. DA can be described with an infinite number of parallel R-C networks, which one might consider a linear model, but I guess the infinite number is the problem.

1. *Leakage current varying* with applied voltage - mainly an issue of electrolytics. Significant leakage current in itself seems to be problematic in some applications, e.g. coupling capacitors. If it happens to flow through the volume pot in an audio amplifier, you may get a lot of scratching when adjusting the volume even if the pot itself is fine.
2. *Degradation of leakage current and other parameters* if left without bias voltage (or with a very low one, compared to their maximum rating) for a long time - an effect unique to Al electrolytics.
3. *Degradation of ESR and capacity* due to the capacitor physically drying out - another effect unique to Al electrolytics.

The worst offenders are easily named - it's high-K ceramics, tantalum and electrolytic capacitors, all of them types using dielectrics with high relative permittivity. The best performers include caps using polystyrene, PTFE (a.k.a. Teflon®), air/vacuum (of course) and also NP0 ceramics, where ϵ_r is much lower. (That's relatively speaking - the dielectric in NP0 ceramics in fact has a permittivity higher than that in electrolytics, but compared to other ceramics this still is very low.)

Pecularities sorted by capacitor type

Electrolytic and tantalum

Traditional *electrolytic capacitors* are polar electrochemical devices not totally unlike batteries. Therefore it should not be surprising that they behave in a similar way sometimes – just consider the fact that they work better at higher temperature, unlike just about any other electronic part. If you leave one alone for a longer time span, you can also expect to measure a voltage of a few tens or hundreds of mV across its terminals that results from the degradation of the Al oxide (Al_2O_3) layer that makes up the dielectric. This voltage (which turns out to be a positive bias voltage) then counteracts further degradation, slowing down aging considerably – a fairly neat mechanism. (If that didn't suffice and leakage currents and voltage endurance are way off after a long time of storage, there still is the option of rebuilding the oxide layer by "forming".)
Unfortunately most capacitors that are already installed somewhere see relatively low impedances and therefore have no chance sustaining this rather elusive and easily impressed voltage (a load in the megohm range like a digital multimeter is sufficient to drain it). Their only chance for long-term stability is a good bit of bias voltage during operation, together with a chance to plug leaks in the oxide layer without extreme currents starting to flow (i.e. moderate impedances). A nice thick oxide layer (excess voltage rating) also helps.
Of course a cap that's in use is in much greater danger of drying out (since that is accelerated by high temperatures and power dissipation in the cap), which in turn increases ESR and decreases capacity (usually more the former than the latter).
Electrolytics can apparently take some reverse bias (up to 1..1.5 V due to a thin oxide layer on the other side of the Al foil) but not for longterm use.

Without biasing, there will be quite some hysteresis (not surprisingly, since they're pretty bad in terms of DA, but leakage currents also show a similar effect). Reportedly types with higher rated voltages do better in terms of distortion when used as coupling caps (they usually have a lower DF, and their thicker oxide layer means that they'll survive longer unbiased time spans without becoming leaky – you don't want your precious signal currents to be used for stuffing holes in Al_2O_3 layers). The findings of *Jung* suggest the distortion generation mechanism to be related to current through or at least signal voltage drop across the capacitor.

Tantalum electrolytics do not like reverse biasing at all, and while they do not require as much biasing for longterm stability, they do need quite a bit to keep hysteresis down. They are known to sound pretty weird without any. When tantalums fail (which happens once in a while), they usually short out.

Ceramic

Ceramic capacitors vary widely in performance - for audio and other critical purposes, one is best advised to use "Class 1" types (NP0/C0G, unfortunately those have the lowest relative permittivity and thus capacitance, being most common below 1 nF), while X7R as a medium capacitance high-K type still is useful for some power supply applications, but the rest of them is only suitable for replacing small electrolytics at lower ESR (alternatively "specialty polymer" electrolytics also exist). High-K ceramics can be very microphonic (piezoelectric effect) and usually aren't exciting in terms of other properties either. DA in Z5U seems to be even higher than tantalum (i.e. pretty bad), Y5V only a little less bad, X7R so-so, NP0/C0G very good if a little variable.

Film

Film capacitors can be very good performers, but the common polyester types (which are not all created equal) are a pretty mixed bag in terms of DA; yet, for films they are quite compact and available in relatively large capacities. Polypropylene and Teflon (PTFE) caps usually do very well as far as DA is concerned, as well as the now-uncommon styrene ones which used to be popular for RF applications. Metallized film caps are quite a bit smaller than their "normal" colleagues, plus they have self-healing capabilities for applications that need this, but their other properties in general seem to be a little worse. Some film caps (polyester?) have been noted to generate distortion when used with DC bias; I'm not sure how much DC it would take but I thought it might be worth mentioning.

For other types check out the links below.

Fun stuff

Here's an LTSpice file for DA simulation for your entertainment.

Further reading

Please note: This page is intended as an overview of what I've found on this topic while cruising the interweb. It is not comprehensive by any means - one could write books on capacitors. Check out the very helpful literature given below.

Highly recommended links

- Picking Capacitors - Walt Jung & Dick Marsh (1980)

- The "Sound" of Capacitors (note that the hysteresis seen covers both "real" hysteresis caused by DA and bog standard leakage currents)
- Op Amp Applications Handbook, Chapter 7 Hardware and Housekeeping Techniques
- CapSite 2007 - Introduction to Capacitors (what some folks call an "introduction"...)
- Understanding Capacitor Soakage - Bob Pease (1982)
- What's all this soakage stuff anyhow? - Bob Pease (1998)
- np0 dielectric absorption - Google Groups
- Electrochemistry Encyclopedia --- Electrolytic capacitors:
- Some more on electrolytics and their chemistry
- AVX Technical Information > Ceramic Capacitors

Specific measurements

- [PDF] Do Passive Components Degrade Audio Quality in Your Portable Device? (Maxim appnote für "capless" amplifiers, w/ highpass THD measurements but w/o biasing)
- Tech Tutorial: Choose the correct capacitors for reliable automotive applications (has some temperature and voltage coefficient plots)
- Capacitor Voltage change (looks at capacitance and DF vs. bias)
- Capacitance and Dissipation Factor Measurement of Chip Multilayer Ceramic Capacitors (Murata, Cat.No. C10E)
- What's All This Capacitor Leakage Stuff, Anyhow? - Bob Pease (2007) (my, these polypros really have low leakage)

Related interesting material

- Strategies to Repair or Replace Old Electrolytic Capacitors (practical text dealing with reforming etc.)
- Resistor Types - Does It Matter? (a little on resistors)
- Cable Distortion and Dielectric Biasing Debunked

How not to use capacitors

Want to see a little collection of design mishaps when using capacitors? Here you go.

RF on electrolytics

My #1 fav can be found in the Sony ICF-SW7600 shortwave receiver (as well as the ICF-2001D/2010, ICF-SW55 and ICF-SW77 models), more precisely in the DC/DC converter that is needed to generate +15V from +3V for varicap tuning. This basically is an oscillator with a small transformer and rectifier. On the primary side they use a 22µ 6.3V electrolytic capacitor with no bypass cap to stabilize the voltage, along with a choke at the input to keep RF from creeping back into +3V. Now the whole thing works at a frequency of 1.85 MHz. How well do you think does the poor lonely electrolytic cope with that? Not very, and not for very long. An ordinary electrolytic capacitor has a pretty high ESR at that sort of frequency and will get heated up pretty badly due to ripple current, eventually drying out prematurely. And so this one does. It doesn't help that longevity of the relatively early surface mount electrolytics used in this and other Sony devices from about 1985 into the early '90s is pretty lousy in general; it looks like they can't take as much ripple current as would have been normal for others of the same capacity and voltage rating (in short, junk).

Unbiased normal electrolytic as coupling cap

A classic that may go unnoticed for years, but eventually means that the cap needs replacement by e.g. a suitable film type or even something as simple as a resistor. This was actually quite common after the transition from (usually discrete) single-ended amplification circuits (which run between B+ supply and ground and typically have an output DC offset of half supply voltage) to opamp based ones that ran with symmetric +/- supplies. Following a "better safe than sorry" approach, one would typically place these around muting circuitry and on outputs (since who knows what the user might connect there), and sometimes between stages just to get rid of some DC offset (implementing your opamps correctly is the smarter solution).

Actually low-leakage types seem to hold up quite well even there (which makes sense since leakage current is needed for Al_2O_3 layer regeneration, and if that doesn't degrade as quickly, the same will apply to the whole cap; similarly, "normal" caps with higher voltage ratings and thus thicker dielectric layer can be expected to last longer as well). The normal 10µ 16V ones in my Kenwood KT-80 obviously did not after 25 years - bridging them improved sound noticeably. (Yes, replacing them with some resistors like 47 ohm would have been safer for the muting IC, but the headphone amp connected there is AC coupled anyway and this was the easiest way of getting rid of them.)

Reverse-biased electrolytic as coupling cap

A typical case of "oops". I found this in the Kenwood KT-1100 - someone must have slept there. Now thankfully the DC offset is just -0.8 V or so, which an electrolytic can still take, but correct this is not. Kenwoods of the early/mid '80s also had pretty sloppy opamp implementations, which makes it all that more interesting that the KT-1100 sounds as good as it does. (OK, later models that tended to be stuffed with even more opamps typically aren't as good-sounding, but that can be fixed, if with some effort.)

Tantalums in audio stages

Tantalum electrolytics were the "new hot sh!t" of the 1970s. They were also used for audio, of course - all the worse since nowadays we know that they have a lot of DA, need lots of bias to work well and when unbiased are truly dreadful. Early ones also seem to have their share of reliability problems especially when operated close to rated voltage. I guess they were dropped pretty quickly in this application (along with run-of-the-mill ceramics) after the Jung/Marsh article appeared in 1980...

Thriftiness with electrolytics

It has been shown that if we're talking about coupling caps and such (and not those in the power supply), electrolytics are better chosen with at least ten times the minimum required capacity (as a rule of thumb). Why then the coupling caps in the output stages of tuners like Kenwood's KT-900 or KT-9X are not only unbiased, but also pretty small (just 2.2µF) is a mystery and can only be explained with a tight budget. The latter model even has two in series, for -3 dB at 12 Hz for a 10kOhm load (one would want it to be something like 2.. 3 Hz or less), plus the opamps in the output stage didn't even get any bypass caps for supply. OK, a Grundig T 7000 is yet worse, with .47µ (if biased), but that was a budget tuner and intended for use with higher input impedances after all (plus its simple output stage sucks anyway).

Source: http://www.co-bw.com/Audio_Capacitor_Distrotion_Mechanisms.htm