Understand Capacitor Soakage to Optimize Analog Systems

Dielectric absorption can cause subtle errors in analog applications such as those employing S/H circuits, integrating ADCs and active filters. But knowing how to measure this soakage and compensate for it helps you minimize its effects.

Veteran circuit designers often got a shocking introduction to dielectric absorption when supposedly discharged high-voltage oil-filled paper capacitors reached out and bit them. Indeed, the old oil-filled paper capacitors were notorious for what was once called soakage -- a capacitor's propensity to regain some charge after removal of a momentary short. Today, you won't find very many of these capacitors in use, but you will still encounter soakage. Do you know how to deal with it?

Nowadays, you're more likely to notice the effects of dielectric absorption in some more subtle way, perhaps in the performance of an integrator that can't be reset to zero or a sample/hold that refuses to work correctly. But whether you literally feel its effects or merely observe them in a circuit's behavior, dielectric absorption is an undesirable characteristic that every capacitor possesses to some degree. This characteristic is inherent in the dielectric material itself, although a poor manufacturing procedure or inferior foil electrodes can contribute to the problem.

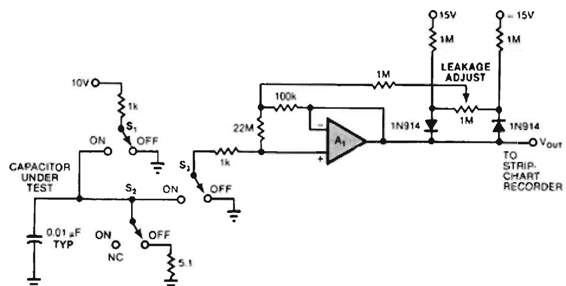

Fig 1 - A simple test fixture lets you evaluate dielectric absorption at low speeds. To use the one shown here, start with all switches off and throw S_1 and S_2 on for 1 min; throw S_1 and S_2 off and wait 6 sec, throwing S_3 on during the wait period. Next, turn S_2 on and watch V_{OUT} for 1 min. To compensate for leakage, leave all switches off for 1 min and then throw S_2 and S_3 on. Monitor V_{OUT} for 1 min and subtract this value from the V_{OUT} value obtained earlier. (View a larger version of the image.)

Indeed, soakage seems an apt term for dielectric absorption when you note what the capacitor seems to be doing. Consider a typical example: A capacitor charges to 10V for a long time T and then discharges through a small-value resistor for a short time t. If you remove the short circuit and monitor the capacitor terminals with a high-impedance voltmeter, you see the capacitor charge back to 0.1%, 1% or as much as 10% of the original voltage. For example, a 1-µF Mylar capacitor charged to 10V for 60 sec (T_{CHARGE}) and discharged for 6 sec ($T_{DISCHARGE}$) charges to 20 or 30 mV after 1 min (T_{HOLD}). Fig 1 shows a simple evaluation circuit for measuring this characteristic.

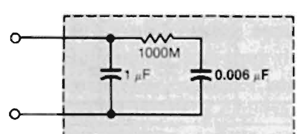

Fig 2 - To model the soakage characteristic of a 1-µF Mylar capacitor, consider a circuit that incorporates a 0.006-µF capacitor to represent the dielectric's charge-storage characteristics.

A capacitor exhibiting dielectric absorption acts as if during its long precharge time the dielectric material has soaked up some charge that remains in the dielectric during the brief discharge period. This charge then bleeds back out of the dielectric during the relaxation period and causes a voltage to appear at the capacitor terminals. Fig 2 depicts a simple model of this capacitor: When 10V is applied for 1 min, the 0.006-µF capacitor gets almost completely charged, but during a 6-sec discharge period it only partially discharges. Then, over the next minute, the charge flows back out of the 0.006-µF and charges the 1-µF capacitor to a couple of dozen millivolts. This example indicates that a longer discharging time reduces soakage error but that discharging for only a small fraction of that time results in a larger error. Illustrating this point, Fig 3 shows the results of conducting Fig 1's basic test sequence for 1-, 6- and 12-sec discharge times. Note that the capacitor tries to remember its old voltage, but the longer you hold it at its new voltage, the better it forgets -- in the Fig 3 case, soakage errors equal 31 mV at $t_{DISCHARGE}$=I sec, 20 mV at $t_{DISCHARGE}$=6 see and 14 mV at $t_{DISCHARGE}$=12 sec.

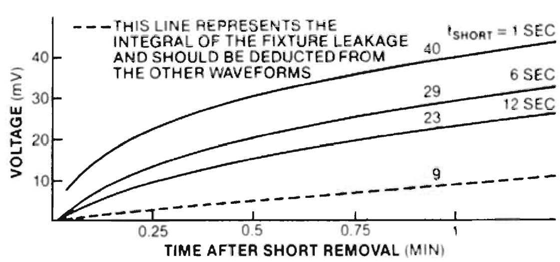

Fig 3 - Obtained using Fig 1's test circuit, these dielectric-absorption-measurement results for a 1-µF capacitor shown that longer $t_{DISCHARGE}$ times reduce soakage-caused errors.

High-speed tests predict S/H performance

You might now ask whether these low-speed tests have any bearing on a capacitor's suitability in fast millisecond or microsecond sample/hold applications. If you repeat the Fig 1 experiment for T_{CHARGE} = T_{HOLD} = 1000 µsec and $t_{DISCHARGE}$ = 100 µsec, you see very similar capacitor-voltage waveforms but with about 10-times-smaller amplitudes. In fact, for a constant T:t ratio, the resulting soakage error decreases only slightly in tests ranging in length from minutes to microseconds.

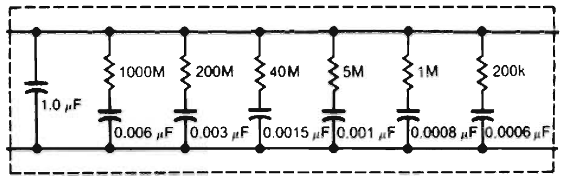

Fig 4 - More precise than Fig 2's equivalent circuit, a capacitor model employing several time constants proves valid for a wide range of charge and discharge times. This model approximates a Mylar capacitor.

Fig 4's circuit approximates this capacitor characteristic, which you can observe on actual capacitors by using Fig 5's test setup. Here, a sample/hold IC exercises the capacitor under test at various speeds and duty cycles, and a limiter amplifier facilitates close study of the small residual waveforms, without over-driving the oscilloscope when the capacitor is charged to full voltage.

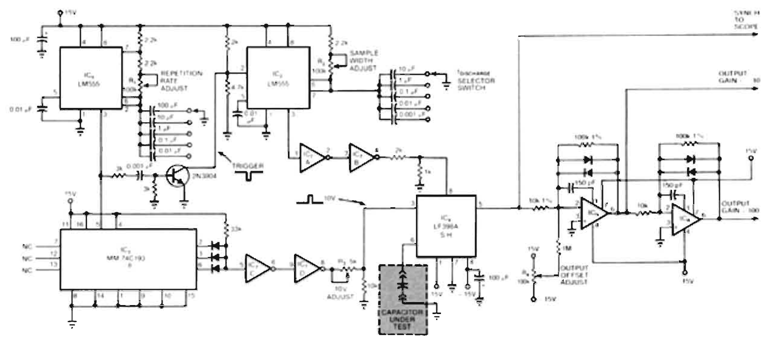
Fig 5 - Capable of automatically sequencing the dielectric-absorption tests, a circuit employing timers, a sample/hold and limiting stages allows you to make measurements for a wide range of T_{CHARGE}, T_{HOLD}, and $t_{DISCHARGE}$ values. Fig 7 shows the results obtained using the circuit shown here. (View a larger version of the image.)

Notes:

1. ALL DIODES = 1N914
2. IC5, IC6 = LM301A
3. IC7 = MM74C04
4. USE R4 OR -10 GAIN TO KEEP SCOPE WAVEFORM BELOW 200mV SO AS TO AVOID DISTORTION OR FALSE ATTENUATIONS

Such experiments illustrate that if you put a certain amount of charge into a less-than-ideal capacitor, you will get out a different amount of charge, depending on how long you wait. Thus, using low-soakage capacitors proves important in applications such as those involving high-resolution dual-slope integrating ADCs. And sure enough, many top-of-the-line digital voltmeters do use polypropylene (a low-soakage dielectric) devices for their main integrating capacitors.

But dielectric-absorption characteristics are most obviously detrimental in applications involving sample/holds. Manufacturers guarantee how fast these devices can charge a capacitor in their Sample mode and how much their circuits' leakage causes capacitor-voltage droop during the Hold mode, but they don't give any warning about how much the capacitor voltage changes because of soakage. This factor is especially important in a data-acquisition system, where some channels might handle small voltages while others operate near full scale. Even with a good dielectric, a sample/hold can hurt your accuracy, especially if the sample time is a small fraction of T_{HOLD}. For example, although a good polypropylene device can have only 1-mV hysteresis per 10V step if T/t=100 msec/10 msec, this figure increases to 6 mV if the T/t ratio equals 100 msec/0.5 msec. Because most sample/hold data sheets don't warn you of such factors, you should evaluate capacitors in a circuit such as Fig 5's, using time scaling suited to your application.

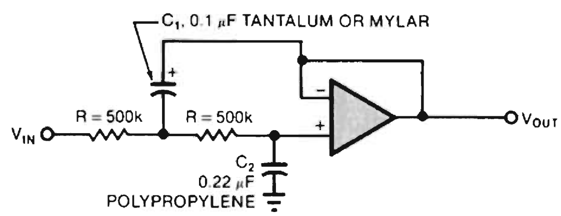

Fig 6 - Soakage can present problems when you're designing a fast-settling amplifier or filter. In the circuit shown here, for example, C_1 can be a Mylar or tantalum unit, but making C_2 a polypropylene device improves performance.

Other applications in which soakage can degrade performance are those involving fast-settling ac active filters or ac-coupled amplifiers. In Fig 6's circuit, C_1 can be a Mylar or tantalum unit because it always has 0V dc on it, but making C_2 polypropylene instead of Mylar noticeably improves settling. For example, settling to within -0.2 mV for a 10V step improves from 10 to 1.6 sec with the elimination of Mylar's dielectric absorption. Similarly, voltage-to-frequency converters benefit from low-soakage timing capacitors, which improve V/F linearity.

Some dielectrics are excellent at all speeds

Fortunately, good capacitors such as those employing polystyrene, polypropylene, NPO ceramic and Teflon dielectrics perform well at all speeds. Fig 7 shows the characteristics of capacitors using these dielectrics and others such as silver mica and Mylar. In general, polystyrene, polypropylene or NPO-ceramic capacitors furnish good performance, although polystyrene can't be used at temperatures greater than 80°C. And although NPO ceramic capacitors are expensive and hard to find in values much larger than 0.01 µF, they do achieve a low temperature coefficient (a spec not usually significant for a S/H but one that might prove advantageous for precision integrators or voltage-to-frequency converters). Teflon is rather expensive but definitely the best material to use when high performance is important. Furthermore, only Teflon and NPO ceramic capacitors suit use at 125°C.

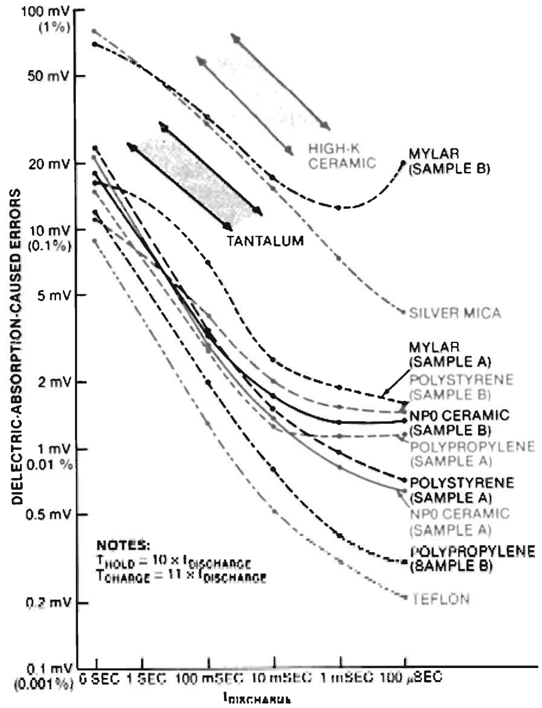

Fig 7 - Soakage-measurement results for a variety of capacitors illustrate the effects of $t_{DISCHARGE}$ values on dielectric-absorption-caused errors. Note the curves for two different samples of NP0 ceramic capacitors intersect.

If you look at Fig 7's dielectric-absorption values, you can see wide differences in performance for a given dielectric material. For example, polypropylene sample A is about as good as B at t=6 see, but B is four times better at high speeds. Similarly, NP0-ceramic sample A is slightly worse than NP0-ceramic sample B at low speeds, but A is definitely better at high speeds. And some Mylar capacitors (sample A) get better as speed increases from 1000 to 100 µsec, but others (sample B) get worse. So if you want consistently good performance from your capacitors, evaluate and specify them for the speed at which they'll be used in your application. Keep in mind that because most sample/holds are used at much faster speeds than those corresponding to the 1- or 5-min ratings usually given in data sheets, a published specification for dielectric absorption has limited value.

In addition, other dielectrics furnish various levels of performance:

- Because any long word that starts with poly seems to have good dielectric properties, how about polycarbonate or polysulfone? No -- they are about as bad as Mylar.
- Does an air or vacuum capacitor have low soakage? Well, it might, but many standard capacitors of this type are old designs with ceramic spacers, and they might give poor results because of the ceramic's hysteresis.
- If a ceramic capacitor is not an NP0 device, is it any good? Most of the conventional high-K ceramics are just terrible -- 20 to 1000 times worse than NP0 and even worse than tantalum.
- Is silicon dioxide suitable for small capacitances? Although Fig 5's test setup, used in preparing Fig 7's chart, only measures moderate capacitances (500 to 200,000 pF), silicon dioxide appears suitable for the small capacitors needed for fast S/Hs or deglitchers.

Cancellation circuit improves accuracy

A practical method of getting good performance with less-than-perfect capacitors is to use a soakage-cancellation circuit such as one of the form shown in Fig 8, in which a capacitor of the type modeled in Fig 4 serves as an integrator. (Only the first two soakage elements are shown.) The integrator's output is inverted with a scale factor of -0.1, and this voltage is then fed through one or more experimentally chosen RC networks to cancel the equivalent network inherent in the capacitor's dielectric material.

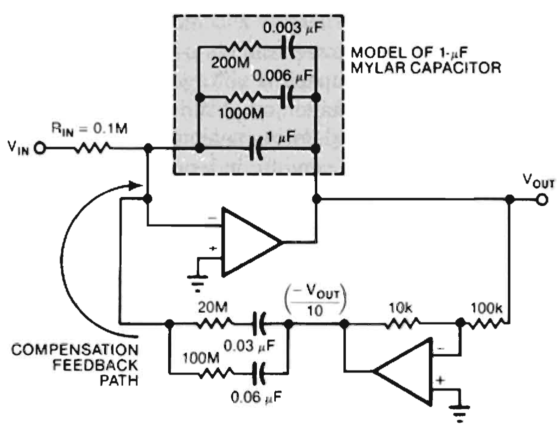

Fig 8 - You can compensate an integrator for dielectric absorption by feeding its inverted output back to the input through one or more experimentally chosen RC networks, which cancel the equivalent network inherent in the capacitor's dielectric material.

Fig 9 shows a practical sample/hold circuit with an easily trimmed compensator. This network provides about a 10-fold improvement for sample times in the 50- to 2000-µsec range (Fig 10). Although this compensation is subject to limitations at very fast or slow speeds, the number of RC sections and trimming pots employed can be extended.

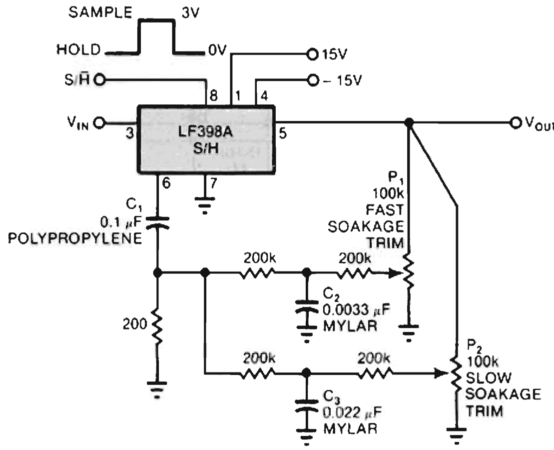

Fig 9 - Adding compensation circuitry to a sample/hold yields better-than-Teflon performance with a polypropylene capacitor. Using Teflon capacitors in such circuits can yield a 15- to 17-bit dynamic range.

Simple circuits similar to Fig 9's or Fig 8's have been used in production to let inexpensive polypropylene capacitors provide better-than-Teflon performance. In turn, using these compensator circuits with a good Teflon capacitor furnishes a dynamic range of 15 to 17 bits.

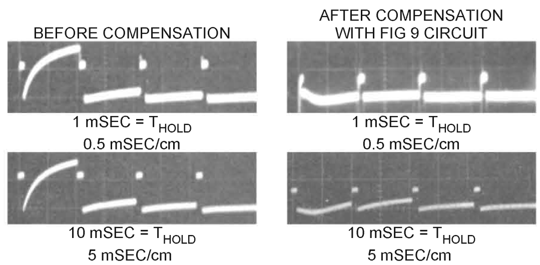

Fig 10 - Adding Fig 9's compensation network to a sample/hold circuit yields a 10-fold performance improvement for sample times of 50 to 2000 µsec; additional RC networks and trimming pots can extend the time range. The short pulses represent normal S/H jumps and occur during the sample time. The exponentially rising waveform during the hold time results from soakage. Note that soakage effects are still visible during the second hold period.

Notes:

1. Dielectric absorption errors with good polypropylene capacitor
2. All waveforms at 1mV/cm; T_{SAMPLE}/T_{HOLD} = 1/10

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RAP Update: *FIFTEEN years ago, back in 1982, when I wrote this, I had never seen any study of capacitors and their "soakage" -- nor of the kind of circuits you could use to shrug off the effects of soakage. Nobody ever talked about this, at high speed.*

To this day, I have not seen any other articles that covered either subject. So this is still about the prime source of info on how to evaluate capacitors for soakage, AND how to build good Sample-and-Hold circuits, so as to NOT get hurt by that soakage.