Passive Offenders

If an amplifier is intended to be classified as high end, each component should be top quality. And although most false sounds occur in the transistors or tubes, the passive components could also be at fault because sometimes they, too, exhibit unwelcome behaviors. This also applies to capacitors. However, by selecting the best components and the appropriate circuit design, top-notch designers manage to avoid these pitfalls.

By
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Ideal components can only be found in textbooks. The reality is something far different. Many of them deviate from the physical models and not just the active and amplifying ones but also the passive components, which are actually considered unlikely to produce such problems. When it comes resistors, they are mostly harmless. At least the metal film types can be used without any problems. But with inductive components (e.g., transformers) it can be very different. Typical problems can involve series resistance, winding capacitance, eddy current losses, leakage inductance, and magnetic saturation and distortions of the core.

Normally, when deviating from the ideal capacitor, you only think of the series resistance and the inductance. However, the impedance drops inversely proportional to the frequency, it reaches a minimum with the resonance frequency and then increases again. This can be a problem in some applications. However, the effect is widely known and can be eliminated using the appropriate measures.

Capacitors

There are wound and front-contact capacitors. The wound capacitors consist of at least two electrically conductive foils and two insulating foils. Inevitably, the conductive layer will be the last one on the outside of the winding. The layers are connected by wires. The winding as well as the wire connections create inductances that may have an influence in the high-frequency range. When looking at the front-contact capacitors, you should imagine the layers as two combs slid inside each other. The teeth are the layers featuring insulation. The ridge of the comb forms the contacts. In this way, the inductive part of the capacitor is drastically reduced. Electrolytic capacitors made of aluminum are generally manufactured as wraps. In this case, the anode is connected several times to reduce the inductance and to increase the current load rating.

If you use capacitors in an amplifier, they can collect environmental interferences. Therefore, in tube technology, the capacitor's outer layer was originally marked in the schematics. If modern-day capacitors are wrapped, they will also have their outside layer marked, usually in the form of a thick line. If the capacitor is installed so that the outside layer points to the more noncritical side of a circuit, it is to be considered a detail improvement in device engineering. Therefore, the outside layer belongs to the preceding tube's anode since this is the point with the lower impedance and not vice-versa. If the capacitors have one grounded connection, this should be the outside layer. When using polarized electrolytic capacitors, the polarity needs to be observed. But with bipolar electrolytic capacitors, the mounting position does not matter.

During the heyday of tubes, there were still wound capacitors with three connectors. The ready capacitor was additionally equipped with an insulating shielding foil on the outside, which was connected to ground using the third connector. This shielded the capacitor and reduced the amplifier's interference voltage. Today, wound capacitors with three connectors are not available.

Bad Dielectrics Cause Harmonic Distortions

Some capacitors can also generate nonlinear distortions. Designers who are unaware of that could easily opt for the wrong capacitors (see **Photo 1**). And, the sonic result will not be optimal. However, by selecting the appropriate type and the matching circuit dimensions, the distortions can be kept low.

Although this has been the case for years, it is a timely topic as we attempt to make our devices as compact as possible. It also means that every component must be as small and light as possible. So, the capacitors produced today need to show high capacitances within small overall dimensions.

To achieve this, two things must be done in parallel. First, the insulating layer needs to be as thin as possible. Second, the dielectric constant must be increased to its limit. However, the associated extremely high electric field strengths in the material often lead to complications. hi-fi amplifiers with different capacitors, but otherwise identical components, may show different sound characteristics. Specific types are deemed to have "good" sound, whereas others sound "bad."

Electrolytic Capacitors

The dielectric of electrolytic capacitors is a few microns of thin oxide film on the positive electrode, which is called the anode. Its surface is roughened by etching, which increases it by the factor of about 100. To maintain the oxide film, these capacitors must only be operated with the correct polarity. Minor punctures heal through the chemical process. In case of a wrong polarity, the film is electrolytically dismantled and the electrolytic capacitor is destroyed. Most manufacturers play it safe, often saying that a wrong polarity of up to 0.8 V is not dangerous. Values of up to 1.5 V may occur for a duration of up to one second and should not be repeated.

Practical tests show that it doesn't seem to be that critical. However, with the wrong polarity, a

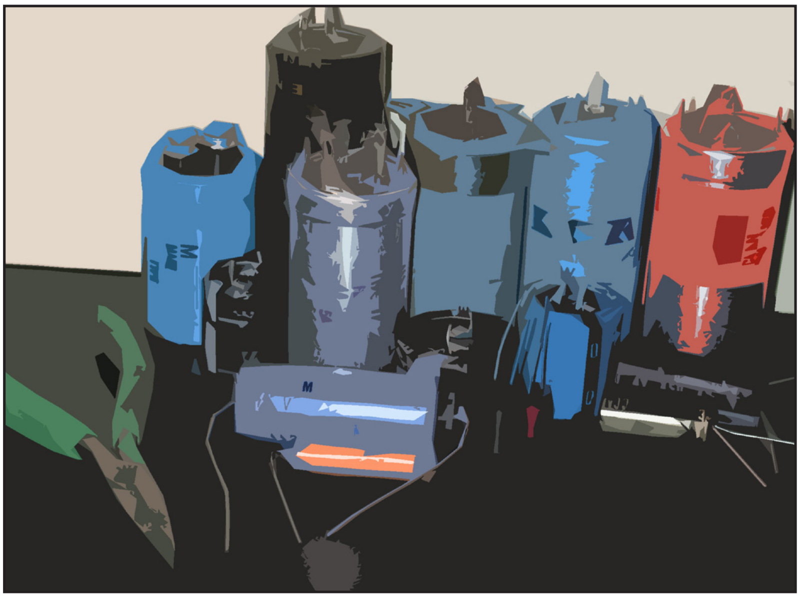

Photo 1: These are a few examples of bad capacitors.

DC current flows through the electrolytic capacitor. When electrolytic capacitors are connect with the wrong polarity, it is dangerous with higher voltages reaching up to 30 V and higher capacitances. In filter chains or when used as electrolytic coupling capacitors, there are current-limiting resistors. Depending on the capacitance and the voltage, a higher current results, which can make the resistor blow up. In case of weak or no current limiting, the electrolytic capacitor produces gas, swells, becomes hot, and can explode. With high capacitances and applications featuring higher voltages, especially for large cup-shaped electrolytic capacitors, overpressure disconnectors are used inside. Once the electrolytic capacitor generates gas and swells, a wire on the inside with a defined breaking point disconnects the power. This prevents the device from further damage or fire.

The bipolar electrolytic capacitors are secure against wrong polarity. Initially, these were opposing series connections made of two polarized ones placed inside a single housing. In more modern versions, both electrodes are equipped with an oxide

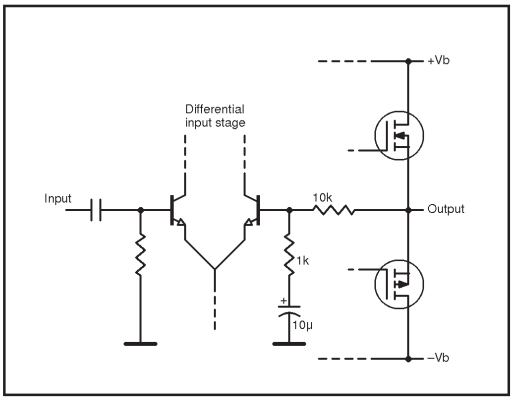

Figure 1: This circuit principle of a modern hi-fi power amplifier features a voltage divider in the negative feedback path. The electrolytic capacitor can generate distortions in the low-frequency range.

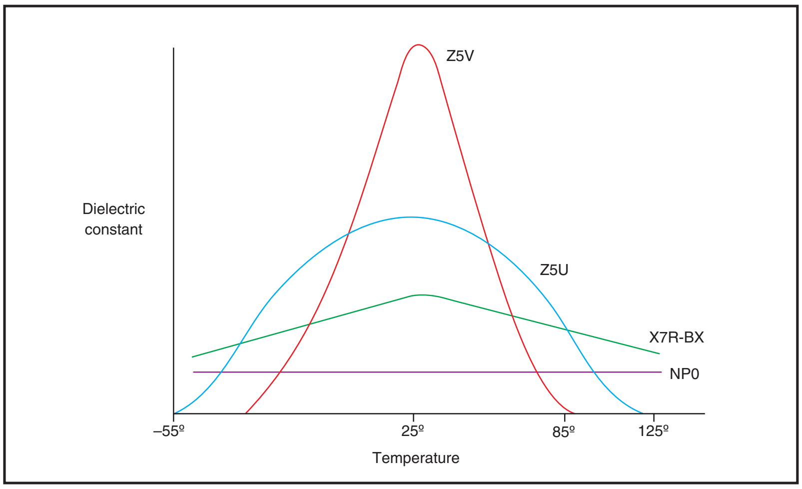

Figure 2: Temperature dependency on εr for different ceramic dielectrics. The maximum is at the Curie point. (Image courtesy of AVX Corp.)

film. The capacitance is half as high with the same overall dimensions. There are so-called "non-etched" electrolytic capacitors, which have electrodes that are not roughened. Having the same capacitance, they are significantly larger, but they have a lower series resistance, which is why they are used in high-quality crossover units and hi-fi loudspeakers.

Steve Bench, developer with Applied Digital Access (San Diego, CA) has found that the distortions are highest when the electrolytic capacitor is not biased with a DC voltage. Now, if a signal flows, it will be alternately polarized correctly and incorrectly. If the incorrectly polarized voltage is only connected for a short time, the capacitor should remain undamaged, but it falsifies the signal for the negative half-waves.

The effect is similar to bridging it using a bad diode—even harmonics appear. Many developers found the distortions to be lower if the electrolytic capacitor is continuously connected to the DC voltage of correct polarity, (i.e., the signal amplitudes are always lower than the DC voltage) so no wrong polarity on the curve will occur.

Paul J. Stamler of BEXT (San Diego, CA) recommends measuring the DC voltage at each electrolytic capacitor within the signal path and replacing those without DC voltage with bipolar ones. This makes it slightly better, but in Bench's opinion, this solution is still not good enough because some distortion remains. That is because even bipolar electrolytic capacitors work without bias voltage.

One typical application is the coupling of two subsequent amplifier stages. This layout represents a first-order high-pass filter. The lower cut-off frequency is calculated from the capacitance and the input resistance of the following stage. In this case, the lower the signal frequency (or the more the charge of electrolytic capacitor is revered), the greater the distortion. Far above the limit frequency, where charge reversal becomes negligible, they almost disappear. If you cannot avoid electrolytic capacitors, Douglas Self, author of the *Audio Amplifier Design Handbook*, recommends opting for a significantly higher capacitance than required by the signal bandwidth (e.g., by the factor 10), to reduce the charge reversal.

However, this may not work in all situations because the electrolytic capacitors are used as elements to determine the frequency response (e.g., in a low-cut filter for record play back) and therefore, as a high-pass filter. In this example, you should only use high-quality foil capacitors. Those also have a much narrower tolerance than electrolytic capacitors so the frequency response is no longer left to chance.

Tantalum and Niobium Are Forbidden

Those much younger capacitor types feature a much higher ratio between the capacitance and the overall dimensions than their aluminum siblings. That is because of the high dielectric constant εr of the isolator, for tantalum peroxide it is 27, for niobium oxide it is 41. There series resistance is lower, too. However, the distortion is much higher, easily reaching the percent range. Also, semiconductor effects in the dielectric play a role. Therefore, they should not be used in the signal path of high-quality audio circuits. Hi-fi experts say

Table 1: Several ceramic dielectrics are compared.

Class	Class 1	Class 2
Dielectric	Metal oxides and titanates	Titanates and zirconates (lead, calcium, and strontium)
εr	up to 200	approximately 200 to 10,000
C/Volume ratio	low	high
Temperature departure	linear	nonlinear
Linearity	moderate	bad
Losses	low	high
Insulation resolution	high	moderate
Aging	low	high

they ruin the sound. However, they perform well in blocking the supply voltage.

The Mystery of Dielectric Absorption

Even capacitor experts don't know the precise reason for distortion. Observations show that some dielectrics have some sort of "memory" for the electrical fields to which they have been exposed. When charging a capacitor, then short circuiting it for discharge and eliminating the short with a connected voltmeter, the voltage slowly increases again. This effect is called dielectric absorption (DA). It becomes stronger the higher the dielectric constant is—not only with electrolytic capacitors but also with non-polarized capacitors, only in a much weaker way. The voltage regenerated after the discharge is called the "recovery voltage." It is specified as a percentage of the preceding charging voltage. Some capacitors, especially electrolytic capacitors, can achieve values of more than 10%. For high-quality audio circuits, 1% is already unacceptably high.

When applying AC voltage, the DA avoids complete charging and discharging. Once the signal polarity is reversed, it generates a delayed current with the previous polarity. As a result, a hysteresis effect appears and increases with the frequency. With a hi-fi amplifier, the effect is a loss of accuracy, the playback seems imprecise, compressed and the dynamic range decreases, and the background noise increases.

According to John Curl, a high-end amplifier developer with Parasound, the impact of these effects widely depends on the shape of the curve of the signal: "Music is not a normal test signal, the curve is not necessarily symmetrical. The DA acts disturbing in particular with asymmetrical signals. The dielectric stores a part of the signal and releases it with delay. The capacitor weakens the peaks, so to say," Curl explained.

The standard MIL-C-19978D determines a test procedure for dielectric absorption, to which the capacitor manufacturers largely adhere. Connect the capacitor to the charging voltage for 5 minutes, discharge it for 5 seconds, let it rest with open connections for 1 minute, then measure the recovery voltage and specify as percentage of the charging voltage.

Assuming an equal capacitance and different dielectric strengths, the capacitor with the higher dielectric strength has the lower DA. That means that when an electrolytic capacitor is used, it is best to choose the one with the highest possible nominal voltage. Bipolar electrolytic capacitors have a lower DA than polarized ones. However, for most

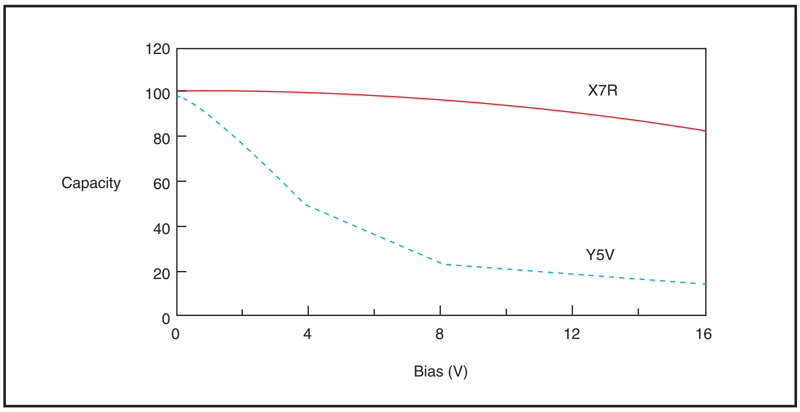

Figure 3: With Class 2 ceramic dielectrics, the capacitance can significantly drop under bias voltage. The "X7R" is moderately strong, but not suitable for high-end applications. The "Y5V" is very strong, but it is absolutely unusable. (Image courtesy of AVX Corp.)

applications the DA is still much too high. Electrolytic capacitors made from tantalum have a higher DA than the ones made of aluminum.

Hi-fi enthusiasts frequently praise the sound qualities of tube amplifiers, which are supposed to be so much better than those of transistor amplifiers. As can be seen upon closer examination, an essential part of this difference is not caused by the amplifying components at all, but by the coupling capacitors. Tube circuits have high supply

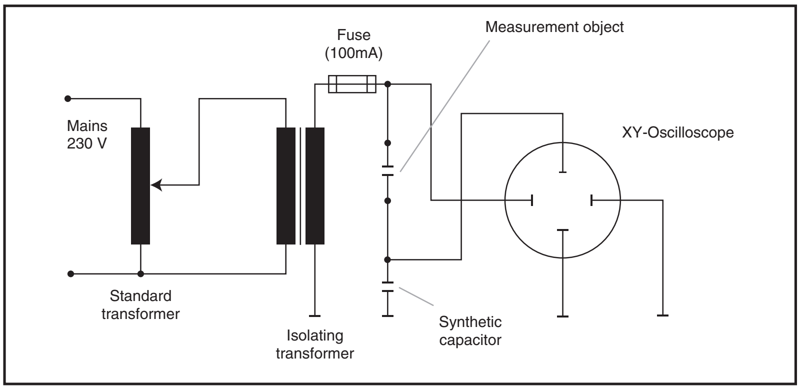

Figure 4: This is a simple measuring circuit for the hysteresis loop of ceramic capacitors. The integration capacitor must be much larger than the test object. The fuse is important in case of a breakdown.

About the Author

Helmuth Lemme studied physics (with an emphasis on solid-state physics and semiconductors). He then worked in the electronics industry for several years, and spent eight years as editor of the German magazine *Elektronik*. Helmuth is now a freelance journalist specializing in industrial electronics. His audio interests include electric guitars and their amplifiers. Helmuth is also the author of *Electric Guitar Sound Secrets and Technology* and he has written many articles on tube technology in *Elektor* special issues.

and signal voltages as well as high impedances. Therefore, relatively small capacitors with a high dielectric strength are used (e.g., types with plastic film). In transistor amplifiers, it is exactly the opposite. When the voltages and impedances are low, bigger capacitors are needed and electrolytic capacitors are used.

According to Curl, "A big part of the distortions is generated by bad capacitors. Once they are replaced by high-quality types with low DA, the sound is often audibly improved. Then, the difference between tubes and transistors are much smaller. Some residual distortion is still left for which there are other reasons."

The sound degradation caused by electrolytic capacitors is strongest wherever the signal levels are highest. In terms of audio, this is true in the power amplifier and the speaker crossover. The oldest ironless transistor power amplifiers worked with a single supply voltage. Between the output and the speaker, there was always a big electrolytic capacitor for DC voltage separation, typically about 2,200 µF. On one hand, its negative impact consists of the DA, which generates distortions in the low frequency range, and on the other, its negative impact consists of the series resistance, which is significantly high because of the high-signal currents, which reduces the attenuation factor. Bridging them with a high-quality plastic capacitor of several tens of microfarads can prove substantial improvement.

However, today, this kind of circuit is largely extinct. With modern power amplifiers having symmetrical supply voltages, the output capacitor is no longer needed, which is a significant improvement. There is still another weak point though—the negative feedback path. The input stage is designed as a differential amplifier.

The entire circuit shows similarities to an operational amplifier. The input signal is routed to the non-inverting input. The output signal being divided by a voltage divider is routed to the inverting input (see **Figure 1**). This one often features an electrolytic capacitor at its base point. In this way, the power amplifier has an amplification factor of (R1 + R2)/R2 for AC voltage, but only the factor 1 with DC voltage. Then, the output only features the offset voltage of the differential amplifier stage present at the input. And, the electrolytic capacitor is a normal, polarized one. Here, it is alternately polarized correctly and incorrectly, typically with several 100 mV, which it is able to withstand. However, this can make it generate harmonic distortions of up to 1 % which is unacceptably high for hi-fi applications.

With the typical dimensioning specified in **Figure 1**, the lower limit frequency (a 3 dB drop in gain) is 16 Hz. Assuming that the input voltage of the power amplifier is 1 V_{EFF} at 16 Hz, 0.7 V_{EFF} are measured at the electrolytic capacitor and correspondingly less in case of higher frequencies. In case of dull drum beats, distortions may occur

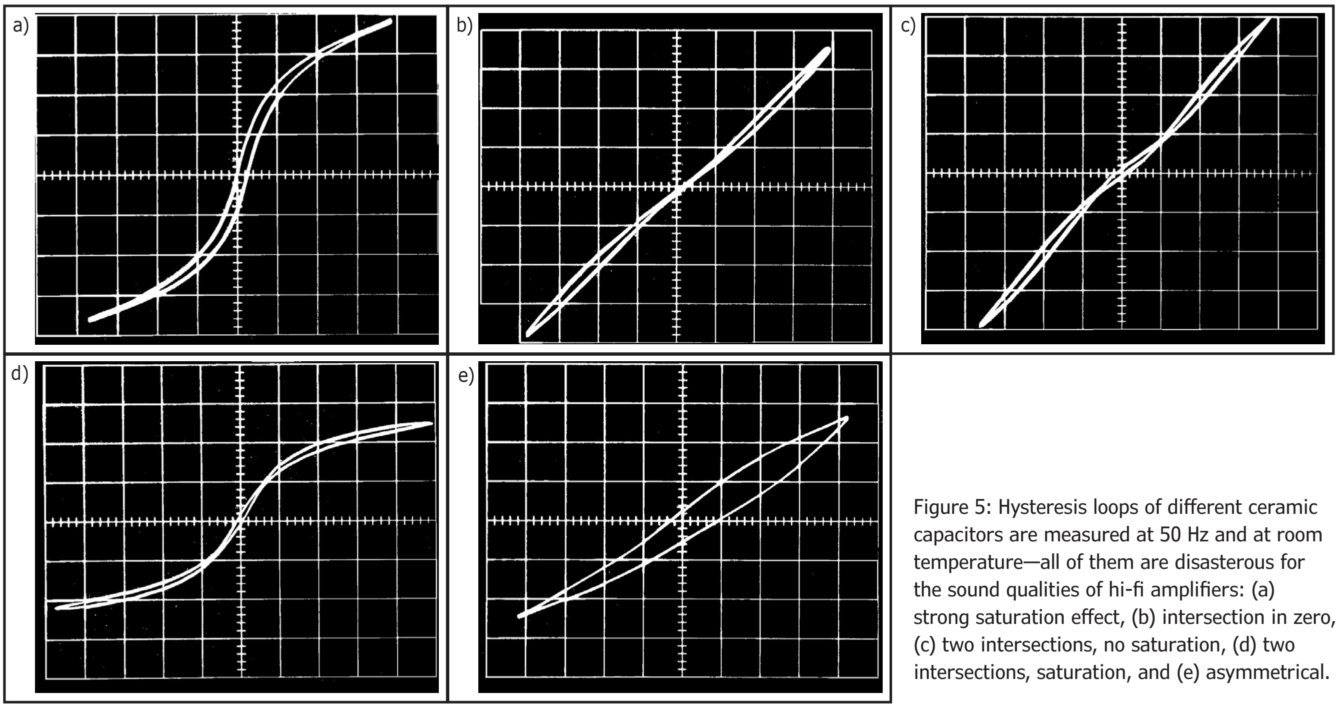

Figure 5: Hysteresis loops of different ceramic capacitors are measured at 50 Hz and at room temperature—all of them are disastrous for the sound qualities of hi-fi amplifiers: (a) strong saturation effect, (b) intersection in zero, (c) two intersections, no saturation, (d) two intersections, saturation, and (e) asymmetrical.

that can be perceived by fine ears. Here, a bipolar electrolytic capacitor is slightly better, but still not ideal.

It is more efficient to make the electrolytic capacitor much larger (e.g., 100 μF, as in this case only 1/10 of the AC voltage is present). However, it is best not to use any capacitor at all and eliminate the DC output voltage taking other measures. Using a suitable control circuit, that task can be accomplished except for a few millivolts, which are harmless to the speaker.

The speaker crossover units are another topic. In this case, electrolytic capacitors mounted prior to tweeters and mid-range drivers are bad, so are bipolar and unetched ones. Usually only the too high series resistance is the reason. In reality, however, the dielectric absorption should also be considered. Here, plastic capacitors are miles better, therefore, a replacement can significantly upgrade the cabinet. It seems to be less critical with capacitors that are connected in parallel to the woofer as in crossovers with a 12 dB/octave filter slope. Apart from that, the usual large tolerances of the electrolytic capacitors are negative. Sonic variations in speaker cabinets are really unwanted. Plastic capacitors can be manufactured in a much more precise way.

Ceramics: Evil of a Different Kind

To make the ratio between capacitance and overall dimensions of non-polarized capacitors as high as possible, one searches for insulating material with the highest possible dielectric constant. "Perovskite"-type ceramics feature very high values. The "forefather" of this group is barium titanate ($BaTiO_3$). However, this material has a disadvantage: it is ferroelectric. In this case, the electric field strength (E) and the dielectric displacement (D) are not linear as with the ideal capacitor, but they form a hysteresis loop similar to ferromagnetic materials.

After removing the outer field strength, some dielectric displacement is left, the direction of which can be reversed by an opposing electric field. Over the past several years, this effect is being used for manufacturing data memories. It is extremely temperature dependent. If the temperature exceeds the Curie temperature, it vanishes. Every ferromagnetic material loses its magnetic characteristics once the Curie temperature is exceeded. (Curie temperature is named after the chemist and physicist Marie Curie, 1867-1934).

The nonlinear correlation between E and D still remains. With growing field strength, the dielectric displacement cannot keep up, but it increases more slowly, similar to coils where the iron core, due to its nonlinear characteristic curve, reaches magnetic saturation with increasing current. Then, the dielectric constant $\varepsilon r = D/E$ no longer has a fixed value, instead it depends on the voltage. This effect is common with capacitance diodes, there it is specifically utilized. However, if you take a standard capacitor, this may not immediately realize it. As a result, signal distortions occur in the circuit. The higher the dielectric constant, the stronger the temperature dependency. εr is highest near the Curie temperature and lower the further it is away from it (see **Figure 2**).

Ceramic capacitors are available in a variety of designs. Originally, small tubes only had one layer and are very old. At that time, capacitances of up to approximately 0.1 μF could also be found. Modern versions are mostly built with multiple layers, allowing small overall dimensions. They are widely spread in surface-mount design. Ceramic dielectrics are roughly divided into two classes (see **Table 1**). The most interesting feature is the nonlinearity. The decrease of capacitance under bias voltage is closely linked. The Class 2 materials can cause extreme results (see **Figure 3**). With Class 1 material, the effect is weaker and it doesn't occur with electrolytic capacitors.

Therefore, the countless ceramic mixtures are tailored in a way that hysteresis and saturation effect remain as low as possible. However, a certain amount remains. **Figure 4** shows a simple measuring circuit with which the D/E curve can be represented using an oscilloscope.

Depending on the material, it takes very diverse forms. Some capacitors show a smooth "S" curve (see **Figure 5a**). Others feature entanglements (see **Figure 5b**, **Figure 5c**, and **Figure 5d**). There are even asymmetrical ones (see **Figure 5e**), when the same material is used. The form depends on the temperature and the measuring frequency. An ideal capacitor shows a perfectly straight line.

Class 1 ceramic capacitors should be treated with extreme caution. Class 2 capacitors should not be used at all in high-quality circuits because of their unpredictable behavior. The tone control part is the most vulnerable point as they are recharged to a much stronger level between amplifier stages. They are, at best, harmless for blocking supply voltages or in points where they are supposed to suppress parasitic oscillations or high-frequency irradiations.

There is another unpleasant characteristic that can occur with ceramic capacitors. They are often microphonic because many of these dielectrics are piezoelectric! Because of that, vibrations from the surroundings (e.g., coming from the speaker or the mains transformer) can enter the signal path. This definitely puts an end to hi-fi quality.

Resources

S. Bench, "The Sound of Capacitors," http://diyaudioprojects.com/mirror/members.aol.com/sbench102/caps.html.

J. Cain, "Comparison of Multilayer Ceramic and Tantalum Capacitors," AVX Corp., www.avx.com/docs/techinfo/mlc-tant.pdf.

J. Curl, "John Curl Interview," www.parasound.com/pdfs/JCinterview.pdf.

W. G. Jung, W. G. and R. Marsh, "Picking Capacitors," Audio magazine, February and March 1980,waltjung.org/PDFs/Picking_Capacitors_1.pdf.

M. Kahn, "Multilayer Ceramic Capacitors—Materials and Manufacture," AVX Corp., www.avx.com/docs/techinfo/mlcmat.pdf.

L. Olson, "Towards Perfection—Building a Better Capacitor, http://www.nutshellhifi.com/library/capacitor.html.

D. Self, "Distortion in Power Amplifiers," October 2001, www.douglas-self.com/ampins/dipa/dipa.htm.

P. J. Stamler, "Replacing Passive Components to Improve Sound Quality," www.bext.com/replace.htm.

K. A. Weber, "On Capacitor Dielectric Materials—A Chemist's View," www.audience-av.com/capacitors/a_chemistview.html.

Wikipedia, "Electrolytic Capacitor, https://en.wikipedia.org/wiki/Electrolytic_capacitor.

Wikipedia, "Aluminum Electrolytic Capacitor," https://en.wikipedia.org/wiki/Aluminum_electrolytic_capacitor.

Good Capacitors

According to Curl, it is best to keep the signal path completely free from capacitors and coils. However, that is hardly achievable. The ideal capacitor features a vacuum between the plates, which is not feasible. The second best has air, which is excellent from an electrical point of view, but with a ratio between volume and capacitance that is just as unfavorable as with the vacuum. Plastics with a low dielectric constant show relatively good characteristics. Even in this case, the dielectric absorption is not completely zero, but it is so small (a magnitude of 0.01 %) that it is no longer a problem.

Teflon has the best reputation, closely followed by polypropylene. Also polystyrene (Styroflex) and polycarbonate are still deemed to be quite good. Polyester (Mylar) gets the worst scores because of its DA of up to 1%. However, it is still significantly better than electrolytic capacitors and ceramics. Individual developers have different opinions on other, more rarely used dielectrics (e.g., glass, mica, and oil- or wax-soaked paper). Overall, they are considered inferior.

Final Analysis

Ceramic capacitors as well as tantalum- or niobium-based electrolytic capacitors should not be used in the signal path. Building high-quality amplifiers and metrologically precise circuits doesn't necessarily have to be prohibitively expensive. You only need the right know-how in the right places.