

Electrolytic Capacitor Non-Linearity

Cyril Bateman's series in *Electronics World* [3] included two articles on electrolytic capacitor distortion. It proved to be a complex subject, and many long-held assumptions (such as 'DC biasing always reduces distortion') were shown to be quite wrong. Distortion was in general a good deal higher than for non-electrolytic capacitors.

My view is that electrolytics should never, ever, under any circumstances, be used to set time-constants in audio. There should be a time-constant early in the signal path, based on a non-electrolytic capacitor, that determines the lower limit of the bandwidth, and all the electrolytic-based time-constants should be much longer so that the electrolytic capacitors can never have significant signal voltages across them and so never generate measurable distortion. There is of course also the point that electrolytics have large tolerances, and cannot be used to set accurate time-constants anyway.

However, even if you obey this rule, you can still get into deep trouble. Figure 2.14 shows a simple high-pass test circuit designed to represent an electrolytic capacitor in use for coupling or DC blocking. The load of $1\text{ k}\Omega$ is the sort of value that can easily be encountered if you are using low-impedance design principles. The calculated -3 dB roll-off point is 3.38 Hz , so the attenuation at 10 Hz , at the very bottom of the audio band, will be only 0.47 dB ; at 20 Hz it will be only 0.12 dB , which is surely a negligible loss. As far as frequency response goes, we are doing fine. But examine Figure 2.15, which shows the measured distortion of this arrangement. Even if we limit ourselves to a 10 Vrms level, the distortion at 50 Hz is 0.001% , already above that of a good op-amp. At 20 Hz it has risen to 0.01% , and by 10 Hz a most unwelcome 0.05% . The THD is increasing by a ratio of 4.8 times for each octave fall in frequency – in other words, increasing faster than a square law. The distortion residual is visually a mixture of second and third harmonic, and the levels proved surprisingly consistent for a large number of $47\text{ }\mu\text{F}$ 25 V capacitors of different ages and from different manufacturers.

Figure 2.15 also shows that the distortion rises rapidly with level; at 50 Hz going from an input of 10 to 15 Vrms almost doubles the THD reading. To underline the point, consider Figure 2.16, which shows the measured frequency response of the circuit with $47\text{ }\mu\text{F}$ and $1\text{ k}\Omega$; note the effect of the capacitor tolerance on the real versus calculated figures. The roll-off that

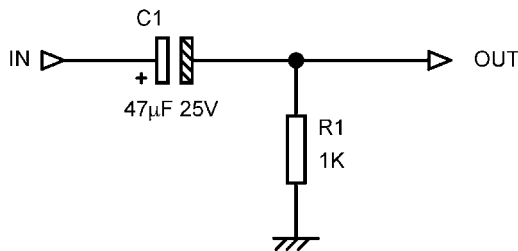


Figure 2.14: High-pass test circuit for examining electrolytic capacitor distortion

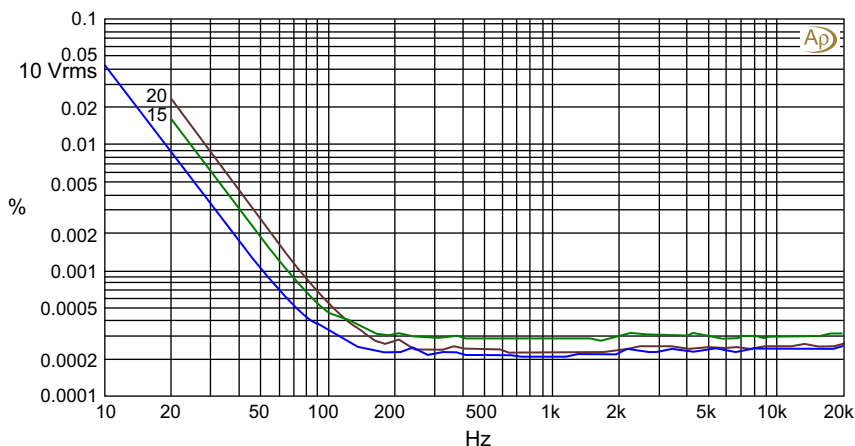


Figure 2.15: Electrolytic capacitor distortion from the circuit in Figure 2.13. Input level 10, 15, and 20 Vrms

does the damage, by allowing an AC voltage to exist across the capacitor, is very modest indeed, less than 0.2 dB at 20 Hz.

Having demonstrated how insidious this problem is, how do we fix it? As we have seen, changing capacitor manufacturer is no help. Using 47 μF capacitors of higher voltage does not work – tests showed there is very little difference in the amount of distortion generated. An exception was the sub-miniature style of electrolytic, which was markedly worse.

The answer is simple – just make the capacitor bigger in value. This reduces the voltage across it in the audio band, and since we have shown that the distortion is a strong function of the

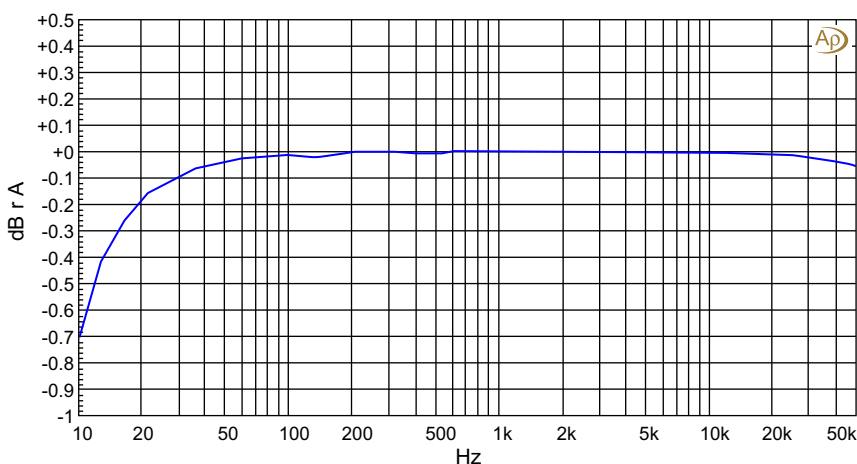


Figure 2.16: The measured roll-off of the high-pass test circuit for examining electrolytic capacitor distortion

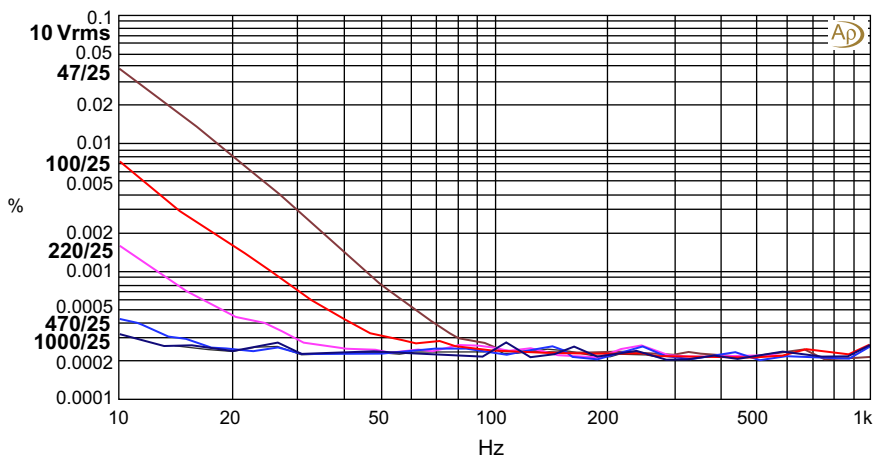


Figure 2.17: Reducing electrolytic capacitor distortion by increasing the capacitor value. Input 10 Vrms

voltage across the capacitor, the amount produced drops more than proportionally. The result is seen in Figure 2.17, for increasing capacitor values with a 10 Vrms input.

Replacing C1 with a 100 μF 25 V capacitor drops the distortion at 20 Hz from 0.0080% to 0.0017%, an improvement of 4.7 times; the voltage across the capacitor at 20 Hz has been reduced from 1.66 Vrms to 790 mVrms. A 220 μF 25 V capacitor reduces the voltage across itself to 360 mV, and gives another very welcome reduction to 0.0005% at 20 Hz, but it is necessary to go to 1000 μF 25 V to obtain the bottom trace, which is indistinguishable from the noise floor of the AP-2702 test system. The voltage across the capacitor at 20 Hz is now only 80 mV. From this data, it appears that the AC voltage across an electrolytic capacitor should be limited to below 80 mVrms if you want to avoid distortion. I would emphasize that these are ordinary 85°C rated electrolytic capacitors, and in no sense special or premium types.

This technique can be seen to be highly effective, but it naturally calls for larger and somewhat more expensive capacitors, and larger footprints on a PCB. This can be to some extent countered by using capacitors of lower voltage, which helps to bring back down the CV product and hence the capacitor volume. I tested 1000 μF 16 V and 1000 μF 6V3 capacitors, and both types gave exactly the same results as the 1000 μF 25 V part in Figure 2.17, with useful reductions in CV product and can size. This does of course assume that the capacitor is, as is usual, being used to block small voltages from op-amp offsets to prevent switch clicks and pot noises rather than for stopping a substantial DC voltage.

The use of large coupling capacitors in this way does require a little care, because we are introducing a long time-constant into the circuit. Most op-amp circuitry is pretty much free of big DC voltages, but if there are any, the settling time after switch-on may become undesirably long.