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AUDIO OUT

By Jake Rothman

Using Capacitors for HiFi, Part 1

Having read the editor's article "All About Capacitors" in the December 2024 issue, I thought a bit more detail could be added about their audio aspects, which differ from other areas of electronics. That took me down quite a rabbit-hole, as you shall discover!

Because high-quality audio is a relatively small area of the industry, audio engineers have had to develop their own specific capacitor knowledge base. This is almost passed down in the form of folklore. Consequently, there is a huge amount of "audiofoolery", rip-offs and falsehoods out there.

It's a bad idea to ask about capacitors on audio forums. They tend to be populated by musicians and DIY HiFi buffs who will put subtle artefacts and their own biases before rational engineering. It's quite likely you will find there somebody who suggests re-capping your whole system with mil-spec Teflon capacitors.

Quotes such as "I had my whole mixer recapped by Quantum Dielectric Energy Systems.com and it sounds wonderful and it only cost me $2000" are common. Often, so-called upgraded PCBs have mechanical problems. A classic error is hanging an 80mm-long axial polypropylene capacitor on the pads designed for a 2.5mm-pitch electrolytic.

However, within this mass of falsehoods are some important truths and circuit techniques. Capacitor sonics are a subtle second-order effect. Capacitor distortion was once a contentious issue; traditional objective engineers like Peter Baxandall and Douglas Self didn't think it was significant enough to quantify.

It was only when Douglas Self, with his Blameless amplifier, got the total harmonic distortion (THD) level down to 0.001% that the capacitor-induced tip-ups in distortion at the low and high frequency ends were noticed and investigated

Engineers such as Ben Duncan and Graham Nalty in the 1980s (who've written for PE) also noticed capacitor effects, but the necessary instrumentation, such as the Radford Low Distortion Oscillator (LDO), wasn't readily available.

Capacitor non-linearity

The main concern for audio engineers is avoiding non-linearity, which manifests itself as harmonic distortion. This does occur with capacitors, but they are very low down on the list of contributors. Loudspeakers are the worst offenders, with semiconductors and circuit design next.

Once there are enough active devices with plenty of negative feedback (NFB) in a good design, the total harmonic distortion due to these can drop below 0.001% (sometimes approaching even 0.0001%, which is just 1ppm!). This is the point where capacitor distortion can easily dominate that part of the circuit.

This is because capacitors are usually not within the negative feedback loop, so are not linearised. Even if they are, because an amplifier's open-loop gain is finite, the effects of their non-linearities on signals can't always be fully cancelled.

The subjective effects of capacitors are also overstated, especially since the distortion produced tends to be benign second and third harmonics, as opposed to distortion from op-amps and other high NFB amplifiers, which generate a spray of dissonant higher order harmonics.

I get annoyed when I test an expensive piece of audio equipment exhibiting distortion in the region of, say, 0.05% or more and finding expensive high-linearity capacitors fitted. What's the point, besides marketing? They would have been better off spending that money on something else!

Dielectric absorption (DA)

Known as DA or 'soakage', this effect is a slow release of charge as dielectric molecules return to their original random alignment after initially discharging a capacitor. This is why a capacitor that has been discharged can charge itself up a bit again later. In audio work, this can cause a small amount of very low-frequency shift that is subjectively unnoticeable, in my opinion.

In electrolytic capacitors, the DA can be as much a 3%, whereas for plastic-film types, it is much lower. It can be hidden in electrolytics due to leakage. The rectification, storage and

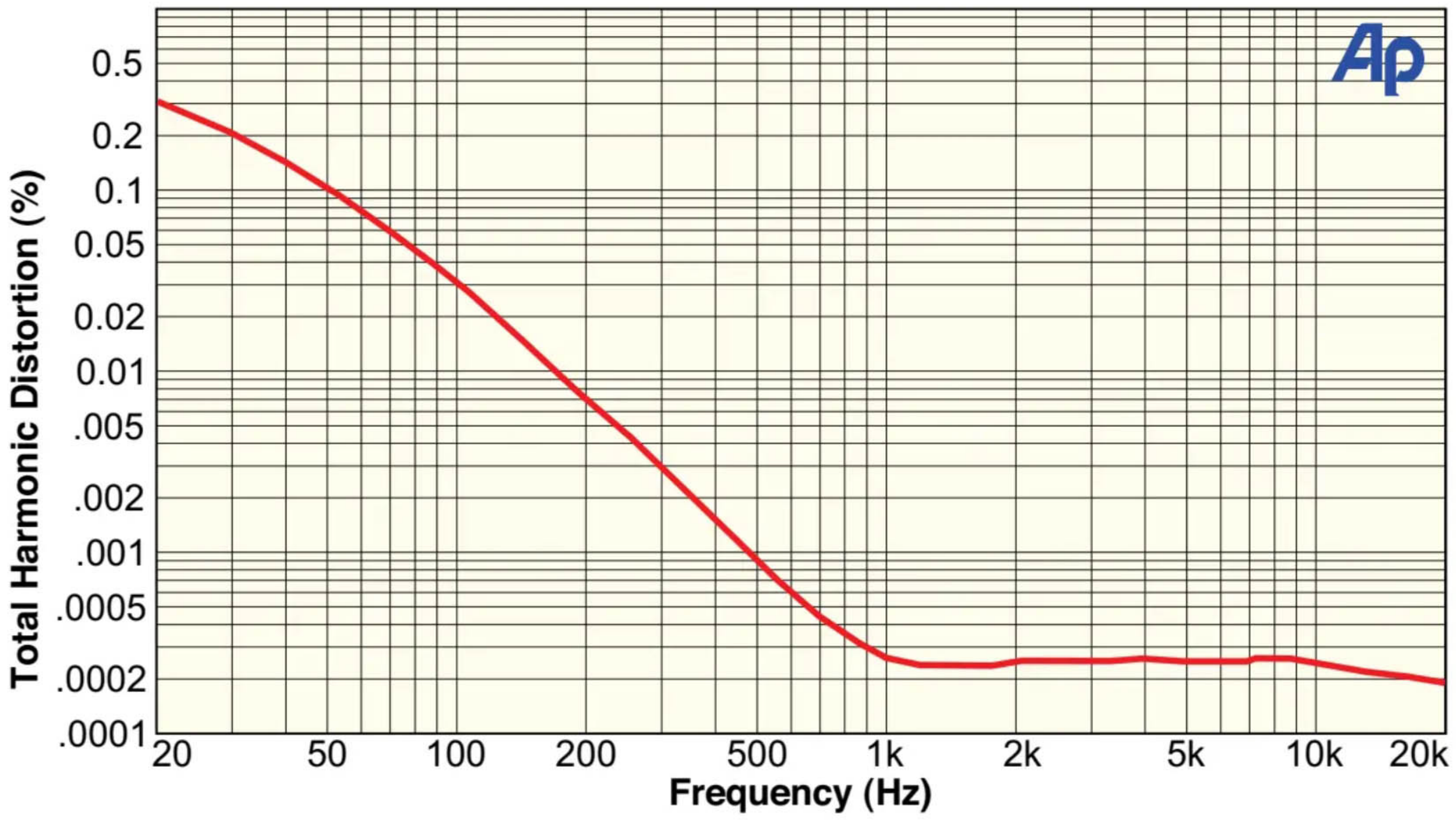


Fig.1: bad capacitor distortion: the typical rapid rise below 1kHz from a 4.7μF 10V cheap tantalum bead. This was 1V RMS into 600Ω load; the -3dB point is 56Hz.

Fig.2: a component linearity tester at Charcroft's capacitor and resistor plant in Wales. It screens for bad contacts, which cause distortion.

cone-drift effects in loudspeakers are much worse.

No distortion harmonics are generated from DA since it's a linear effect. On transient signals, there may be a small absorption of energy and a release in the form of a tail. It is this that makes some engineers such as Jung and Marsh believe audible distortion must occur. Maybe it could lead to bias modulation and a possible variation in THD.

It is a real concern with sample-and-hold circuits, though, as used in ADCs and analogue synthesisers. DA is bad in paper, mica, glass and Mylar/polyester capacitors. Non-polar dielectrics, such as polystyrene, polypropylene and Teflon/PTFE don't exhibit it.

A usable model for a polyester capacitor is 1µF in parallel with two series RC networks: 6nF/1GΩ and 3nF/200kΩ. I have read some suggestions that DA is bad for asymmetrical signals in audio, but I can't see how it can add additional frequency components/distortion.

Bass effects

The distortion from capacitors is similar to that from magnetic sources, such as balancing transformers. It's said that the distortion from magnetic tape and transformers is subjectively enhancing, and yet the similar capacitor distortion is bad, even though the capacitor distortion is an order of magnitude less.

Fig.1 shows a bad case of capacitor distortion caused by a cheap tantalum bead. This sort of problem was common in amplifiers from the 1970s, but hidden by other distortions.

In my opinion, all distortion is bad for HiFi and studio monitoring, because it leads to intermodulation and a consequent lack of clarity and muddle. However, for individual sounds within a mix, such distortion can be enhancing.

An occasional problem all passive components can suffer from is bad internal contacts. These can be identified as the 30kHz third harmonic of 10kHz by the equipment shown in Fig.2. Most manufacturers don't screen for this, so the odd rogue capacitor can be found that has bad distortion across the whole frequency range. Luckily, these are rare.

"Capacitosis"

Despite all the evidence that capacitor distortions are a subtle second-order effect, capacitor foibles have achieved a notoriety out of all proportion to their reality in the audio community, which is a strange marriage of art and technology.

I have a theory that it's psychological, that people are influenced by what they see, rather than what they hear or measure. I've christened this phenomenon "capacitosis". Maybe it's because capacitors are the most visually diverse and colourful of all electronic components. A mixed bag of surplus capacitors from the late 1970s looked like a bag of sweets!

Fig.3: colourful Phillips/ Mullard C280 capacitors in... a Colorsound Powerboost pedal.

Fig.4: the NAD 3030 amplifier – a classic, discrete and well-designed HiFi amp.

They certainly provided an initial attraction for me as a child; I remember collecting and arranging them. The Mullard C280 series "liquorice all-sorts" (or "tropical fish" in the USA) capacitors were my favourite (Fig.3). They are the only capacitor where you can read the value at any angle two metres away!

The area of subjective capacitor analysis is very similar to wine tasting. I suspect that extremely objective, cost-driven engineers would go to a wine tasting with a pH meter.

I have suffered from "capacitosis" myself. This happened with a NAD 3030 amplifier (Figs.4 & 5). I put £30 worth of new pretty 'audiophile' capacitors into one channel and left the other as was.

Upon listening, I was convinced the modified channel was the best and then found I was accidentally listening to the other side, with the original 5p Chinese grey electrolytics, green Mylar films and brown ceramic discs.

When I sold the unit, I hoped the recipient would notice and say something like, "I think it sounds better on the left side or something". They never did. However, the NAD circuit did use the capacitors according to the basic audio engineering capacitor rules, ensuring the distortion was minimised. Those rules are:

1) Bigger is better

This is a rare case of bigger is almost always better, both physically and in capacitance. The linearity of a given type of capacitor depends on the voltage stress applied across the dielectric in terms of voltage per metre. Large physical size is the reason a 250V polyester capacitor produces five times less distortion than a 50V component of the same capacitance.

That is not to say you can't get good performance with tiny capacitors – you can, but you have to be more careful to choose the right types and use them appropriately (more on choosing the type later).

A big old-fashioned capacitor will have less distortion than its micro-sized surface-mount equivalent. This is why designers always ensure (with coupling capacitors) that there is very little voltage drop at low frequencies by making the capacitance very high. Typically, one makes the -3dB point 2Hz, or 10 times less than the lowest required frequency.

One problem with this approach is that the large capacitance values take a long time for their DC level to stabilise, causing long settling times when powering up and thumps on switch-off. This is why 2Hz is the sweet spot; any higher and you risk introducing distortion; any lower, and the settling time becomes noticeable.

2) Low dielectric constant caps

The dielectric constant, K, is the amount that the dielectric multiplies the capacitance compared to a vacuum

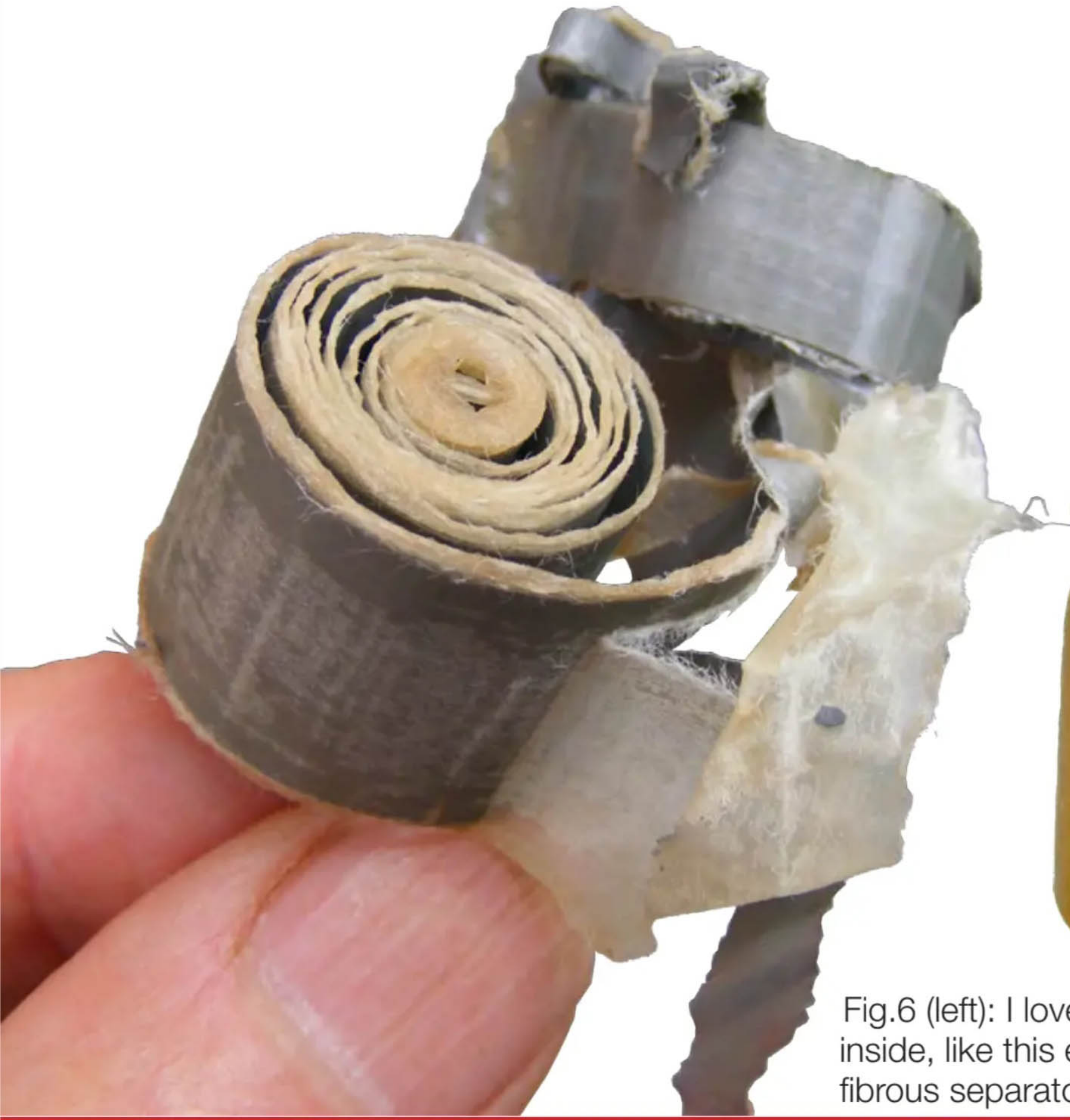


Fig.6 (left): I love demolishing things to see what's inside, like this electrolytic capacitor! Notice the coarse, fibrous separator paper.

Fig.7: tough side-cutters work well to open most components. The aluminium can then be unwound, away from the rubber bung.

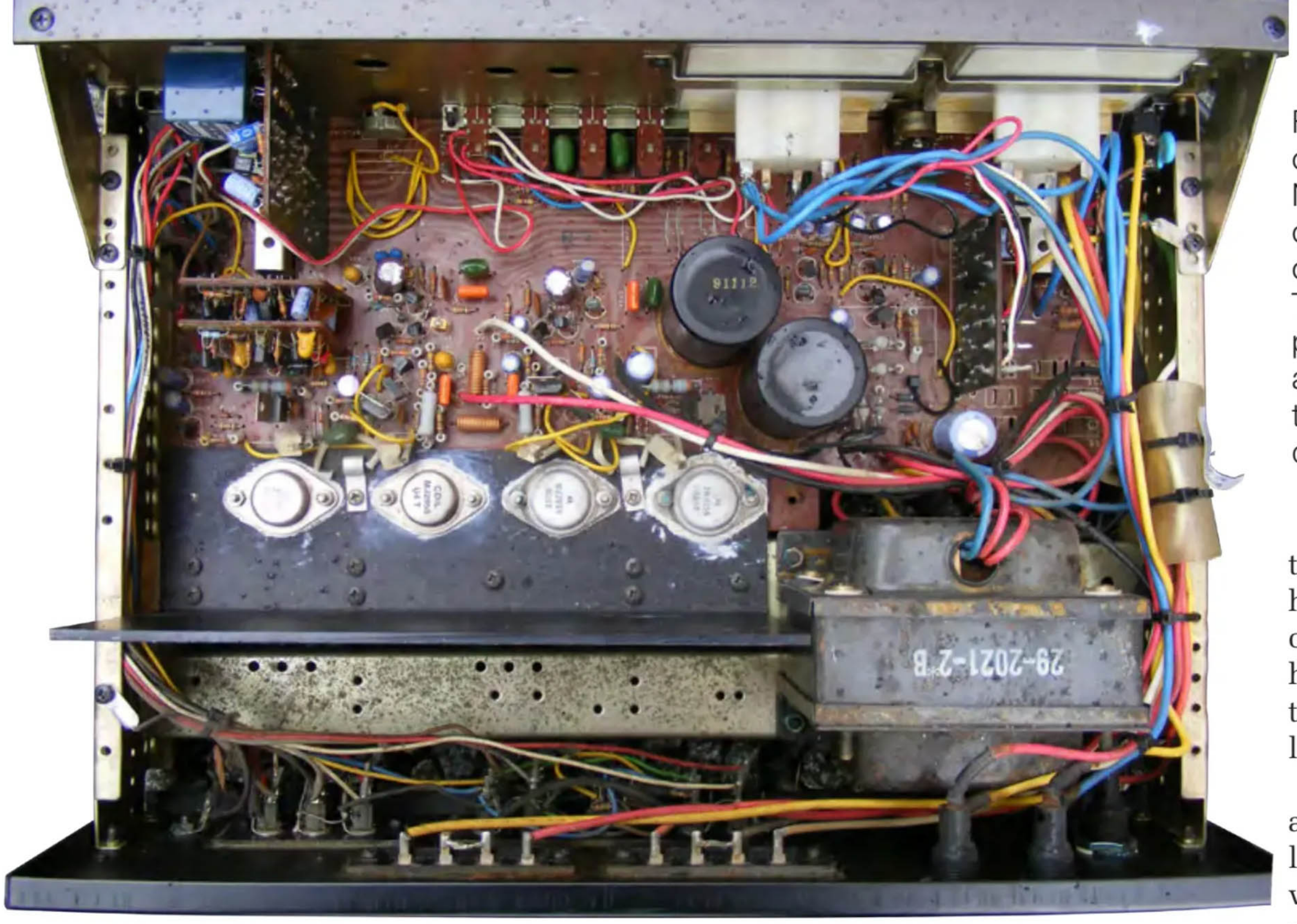


Fig.5: I swapped in expensive capacitors on one channel of this NAD 3030 amp and left the other original. I and a 27-year-old listener couldn't hear any audible difference. The design proved a high-voltage polymer electrolytic in the power amp bootstrap circuit was safe, and tantalum types in certain positions did not increase distortion.

in its place. The higher the K value, the worse the audio performance. As K increases, the smaller the capacitor is for a given capacitance. A case of bigger is better again.

Low dielectric constant (K=2-3) dielectrics, such as polystyrene and polypropylene, involve non-polar molecules. That is, the molecule has a uniform electric charge. Non-polar plastic films also have a negative temperature coefficient (tempco) that cancels out with the positive tempco of metal film resistors when they are combined (eg, in low-pass or high-pass filters).

Most other plastic films used in capacitors, such as polyester, have polar molecules, with a charged end. This causes them to become aligned with the applied electric field, resulting in higher distortion.

Fig.8: special Black Gate electrolytic capacitors for audio use by Rubycon. They are so expensive that I always reuse them if their ESR is okay.

3) Use electrolytics properly

Only use electrolytics (aluminium or tantalum) when high capacitance values are required and don't use them for audio filtering (eg, avoid using them in low-pass or high-pass filters). They are generally only used for AC coupling or supply bypassing/filtering in HiFi designs.

Any capacitor up to about 2.2μF can be replaced with a plastic film type. Wima makes a very small outline polyester series, MKS 2, which will outperform any electrolytic for distortion. The MKS2B051001N00JS in 10μF/50V is only 11mm wide and 16mm high with a 5mm lead pitch. However, it costs £3.50.

Using an electrolytic or tantalum of 470nF or even 1uF is silly, except in SMT, where tantalum capacitors will give lower distortion than X7R ceramics (SMD plastic film caps are available if a little expensive).

Small radial electrolytic capacitors are also less reliable than larger case sizes because the surface area and resulting electrolyte evaporation is proportionally higher. Fig.6 shows an unwound electrolytic, while Fig.7 shows how to open them up.

Electrolytic capacitors have a high dielectric constant, in the region of eight for aluminium oxide, 28 for tantalum oxide and 41 for niobium oxide. These are not particularly high, but the capacitance-to-size ratio is also greatly increased by surface area multiplication from foil etching and, in the case of tantalums, sintering, where tantalum powder is compressed into a porous sponge.

These K values are quite low compared to high-K ceramics, which can be as high as 1200, but the electrolytic oxides are also very thin and have high voltage stress. This explains the relatively high distortion (non-linearity).

Bipolar or non-polarised wet aluminium electrolytics always give lower distortion than the polarised variety, even when used with a polarising voltage.

This is because the naturally oxidised cathode/negative foil (which breaks down at around 1.5V, causing extra distortion in normal polarised capacitors) is formed to the same voltage of the anode foil, so it can take the same voltage in either direction.

Some of the high-quality 'audio' electrolytics such as the Black Gate (Fig.8) are asymmetric bipolars, in that the cathode foil is formed to an intermediate (eg, 6V) rating, which gives the best characteristics of both types.

4) Be careful with tantalum caps

Solid tantalum type capacitors produce up to 10 times more distortion than wet aluminium electrolytics because of the higher K and the solid manganese dioxide, which has a non-linear resistance. So this has to be taken into account in the circuit design.

For a given CV product, eg, 100μF × 10V = 1000C, they cost six times more than wet aluminium. However, they don't dry out and, if used for low currents, such as coupling rather than decoupling, they last for decades, whereas wet electrolytics are often the first components to fail.

The leakage is 10 times lower for tantalum, and they don't need to stabilise and reform at power-on after long periods of disuse. This gives much lower clicks and thumps, and equipment can be used immediately.

Tantalum pentoxide is a more stable material than aluminium oxide and, once formed, does not degrade. Therefore, they can live without a polarising voltage and be stored for decades.

Tantalum capacitors are an important part of the sound character of the famous Neve modules. Fig.9 shows some excellent metal-cased tantalum types that Neve used.

Some engineers, like Rod Elliott (https://sound-au.com), disapprove of tantalums, having experienced a lot of shorts with tantalum beads. However, military and aviation engineers love them.

I suspect the antipathy comes from having to fix a lot of circuits where they have been incorrectly used. When tantalum capacitors fail, they go short circuit, unlike wet aluminium type capacitors, which slowly go open-circuit. Also, the bead type can catch fire dramatically because the manganese oxide solid electrolyte acts like an oxidising agent.

Unlike wet electrolytics, which suffer no effect from being run at full-rated voltage, the reliability of tantalums increases with a reduction in voltage. Derating, running at no more than 70% of rated voltage, is good, conservative design.

It's best to limit the surge current with solid tantalum capacitors to 1A, especially if running them at their full voltage rating. For example, if you have a tantalum bead across the output of a 15V regulator, it should 'see' a series resistance of 15Ω. This is rather a lot, and would reduce its decoupling ability. Hence my advice not to put tantalums across power rails.

Many designers did, however, because National Semiconductor used to recommend tantalum capacitors across the outputs of their regulators. Their ESR of around 0.7Ω to 2Ω is ideal for damping the inductive output of linear regulators.

One way round the surge problem is to configure the regulator for soft starting. Another trick is to use a series decoupling resistor in the power rail. That seems rather old-fashioned today, because it reduces the regulation.

It is now possible to get surge-tested tantalum capacitors, such as the Kemet T495 series, which require no derating or current limiting.

It's difficult to get high-CV products in solid tantalum. The biggest I use is the 1000µF 10V AVX F721 for mic preamp gain control blockers (Fig.10). For SMT, they are the better choice than wet aluminium, since they are not stressed by the baking involved. Also, they seem to solder onto the board better, being shaped like resistors.

I like tantalum capacitors; used correctly, they increase reliability and reduce clicks… at a price.

5) Avoid most ceramics

Don't use high-K (X7R, Y5V, Y5U, Z5U) ceramic capacitors for coupling (or filtering). They distort much more than tantalum types. Although excellent for power rail decoupling, high-K ceramics self-modulate their capacitance with applied voltage, causing very high distortion, even if just used for coupling.

SMT electronics usually use high-K ceramics, which has led to SMT assemblies getting a bad name with regards to audio quality. However, if you can choose an NP0/C0G capacitor, it will generally perform very well. They can be quite expensive and large for a given capacitance and voltage rating combination, although they still can be cheaper than plastic film in many cases.

For higher capacitances, especially in coupling roles, you can replace them with tantalum capacitors. For 100nF and similar values, they come in similarly sized cases.

High-K ceramics can also act as piezoelectric transducers and can pick up or emit music with very strange results. The construction of piezo tweeters is basically a lead titanate disc 'ceramic capacitor' bonded to a small paper cone.

Real differences

Generally, capacitor effects don't show up in double-blind listening trials or ABX tests. Where I have heard definite differences are in the most highly stressed audio application, the tweeter section of loudspeaker passive crossovers (Fig.11).

Just the equivalent series resistance (ESR) rating of the capacitor can make a difference. The 0.3–1.0Ω ESR of a bipolar electrolytic used in cheaper systems will make a significant difference in a 4Ω loudspeaker system, compared to the 0.01Ω ESR of a plastic film capacitor. This could mean a 25% reduction in signal level, so everybody would hear if the electrolytics were upgraded.

When I designed crossovers, I included this ESR in the circuit. When people upgraded my circuits with plastic-film capacitors, it tonally unbalanced the sound. I told them to put series resistors in to fix it.

Interestingly, special bipolar electrolytics using plain rather than etched foil are specially made for crossovers and are called low-loss, often marked LL, as shown in Fig.12. The inductor distortion in passive crossovers is much worse than the capacitors, especially if a ferrite or iron core it used (air-cored inductors are preferred for this reason, but are rather bulky).

Fig.9: this Neve output module uses five tantalum bead capacitors, including one metal-cased type. I have a huge stock of RAF surplus tantalums that I use and sell to Neve and Naim module builders.

Fig.10: tantalum capacitors don't get to very high values. This AVX F721 is rated at 1000µF and 10V, which is about the practical limit.

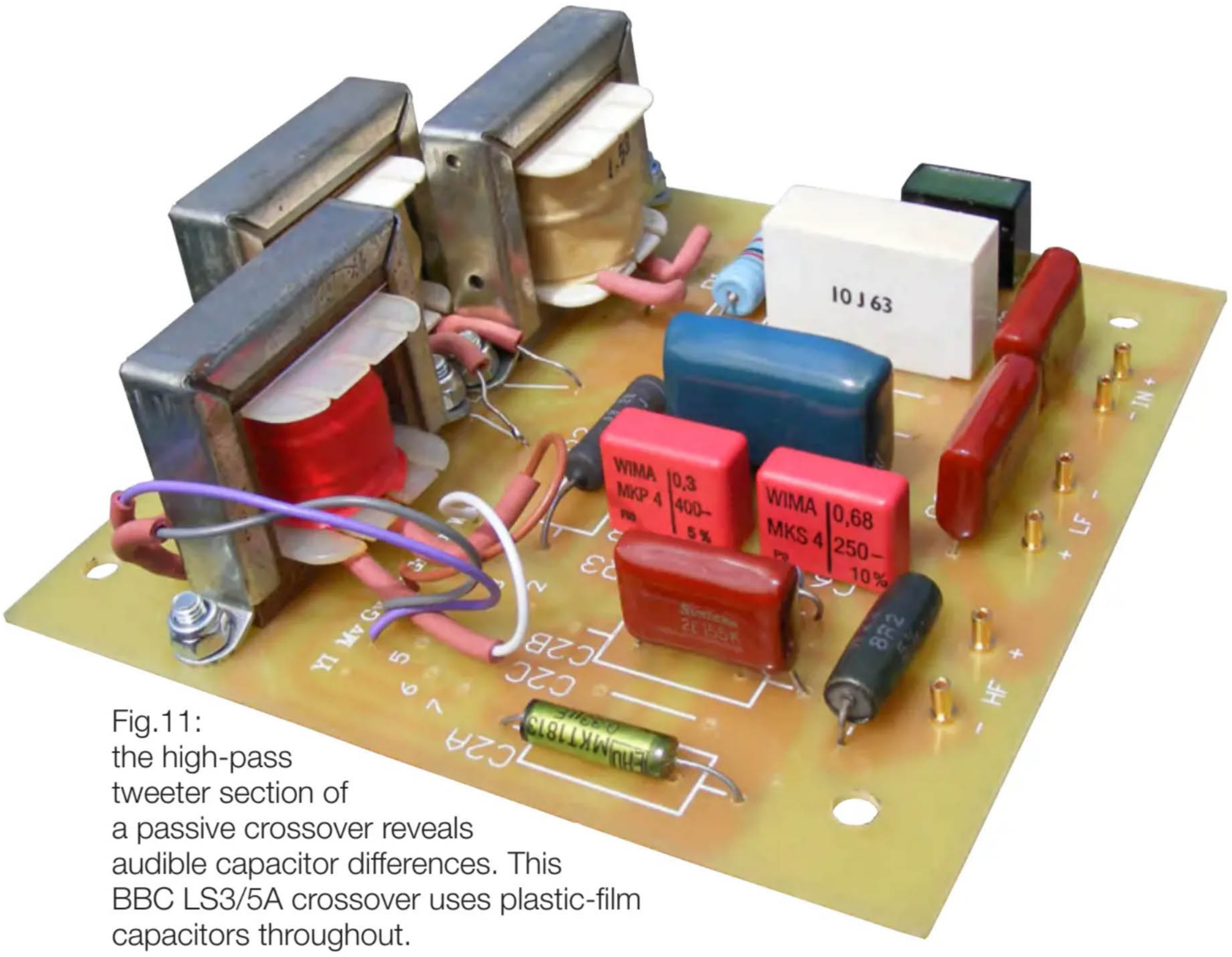


Fig.11: the high-pass tweeter section of a passive crossover reveals audible capacitor differences. This BBC LS3/5A crossover uses plastic-film capacitors throughout.

The only good capacitor is ~~a dead~~ no capacitor

This is a more extreme philosophy popular among some American and Japanese designers, almost ‘capacitophobic’, where all coupling capacitors are eliminated and the whole circuit is DC-coupled end-to-end. This technique gives flat distortion performance to DC, but the system may destroy itself and an expensive pair of speakers if a DC offset develops and there is no DC fault protection circuitry present.

There is no need for audio to go down to DC; doing so invites a whole load of extra problems, such as switch clicks, scratchy pots and thumps. AC-coupling also isolates one stage from another, generally confining faults to one stage.

The need for low bias current/offset voltage audio op amps (generally single-sourced JFET input types) and DC servo circuits increases silicon costs by around five times compared to using audio bipolar devices, such as the venerable (and excellent) NE5532. This chip was designed for AC-coupled audio, so its DC performance is poor.

Silicon Chip has designed numerous amps and preamps with capacitor coupling that have THD+N levels down to 0.0004% and below, with very little distortion rise at either end of the frequency spectrum, and without using any exotic or overly expensive parts. So total avoidance of any capacitors in a HiFi circuit seems unwarranted.

Group delay

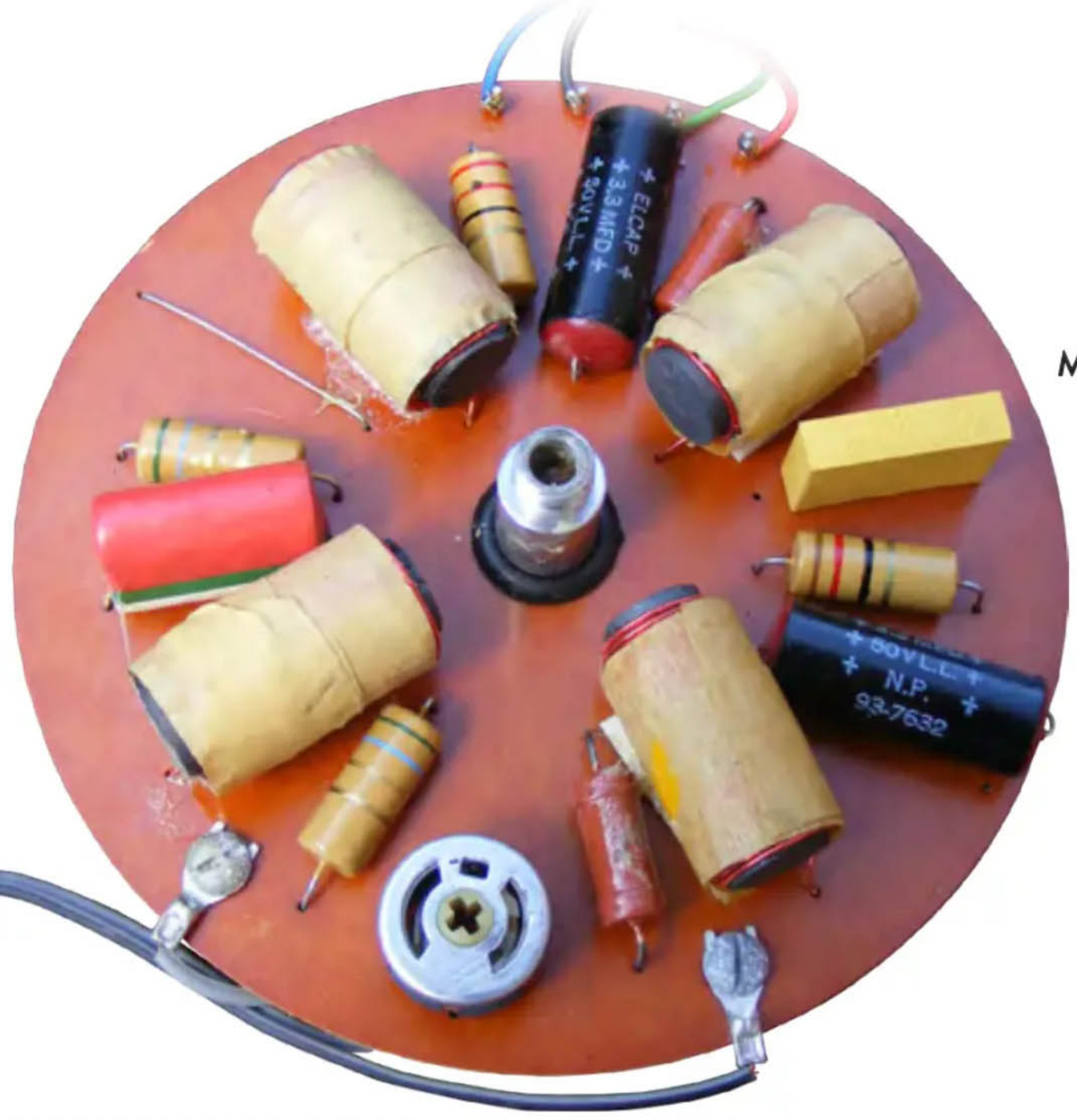
As well as acting as high-pass filters and giving rise to bass loss, coupling capacitors also have an associated phase shift. The rapid change in phase can cause a disconnect between the bass fundamental and associated transients.

How rapid the phase change is can be represented as group delay. This delay becomes noticeable on kick drums, where the ‘thump’ may seem to come late, after the ‘click’. It counter-intuitively gives a bass boost effect to male voices, making them sound ‘chesty’. This effect begins to occur at a 10 times higher frequency than the cut-off frequency.

Laurie Fincham, KEF’s principal engineer, became aware of this effect when developing the loudspeaker CUBE bass equalisers. He built two systems, one with coupling capacitors and one without, and gave a comparative demonstration at an Audio Engineering Society meeting in London.

The circuit shown in Figs.13(a) & (b) gives an example. It is impossible to remove all phase shifts and high-pass filtering from the reproduction chain. The microphone and sealed-box

Fig.12: sometimes, low-loss bipolar electrolytics like 3.3μF Callins Elcaps are used in crossovers, such as this one from a JR149.



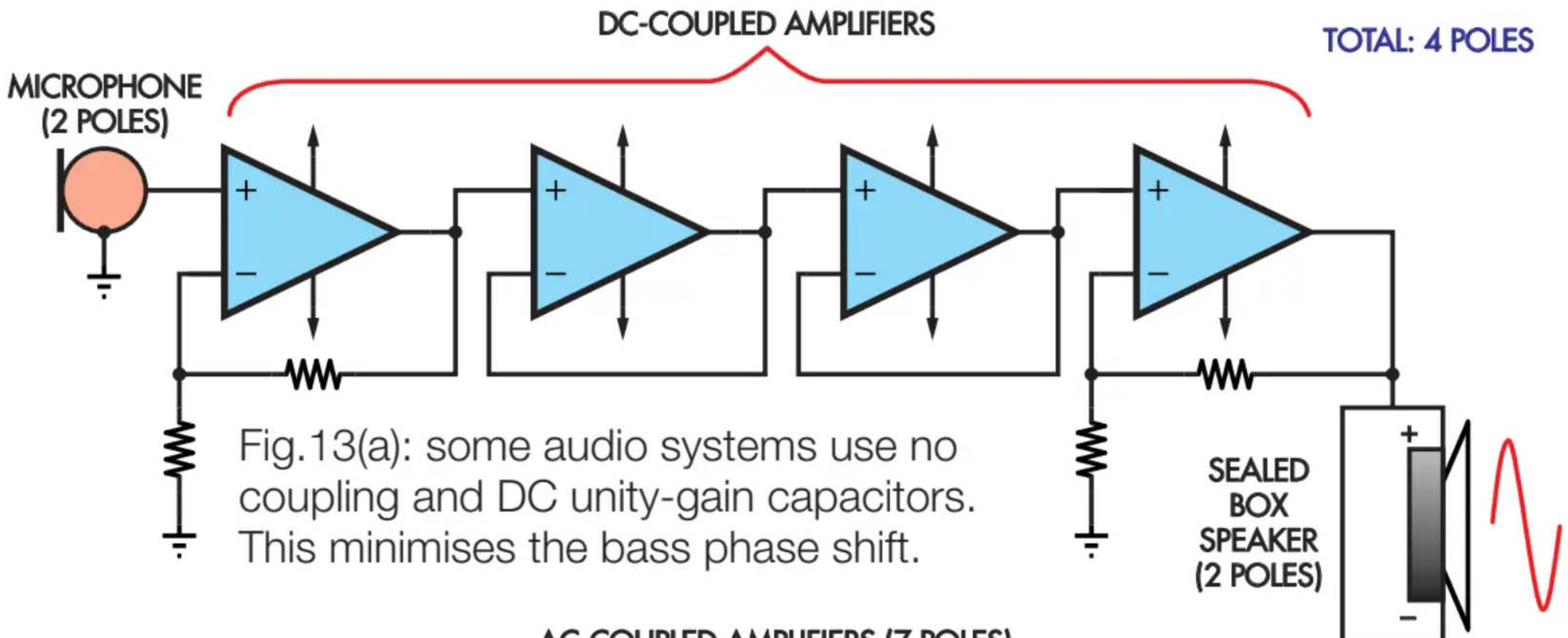


Fig.13(a): some audio systems use no coupling and DC unity-gain capacitors. This minimises the bass phase shift.

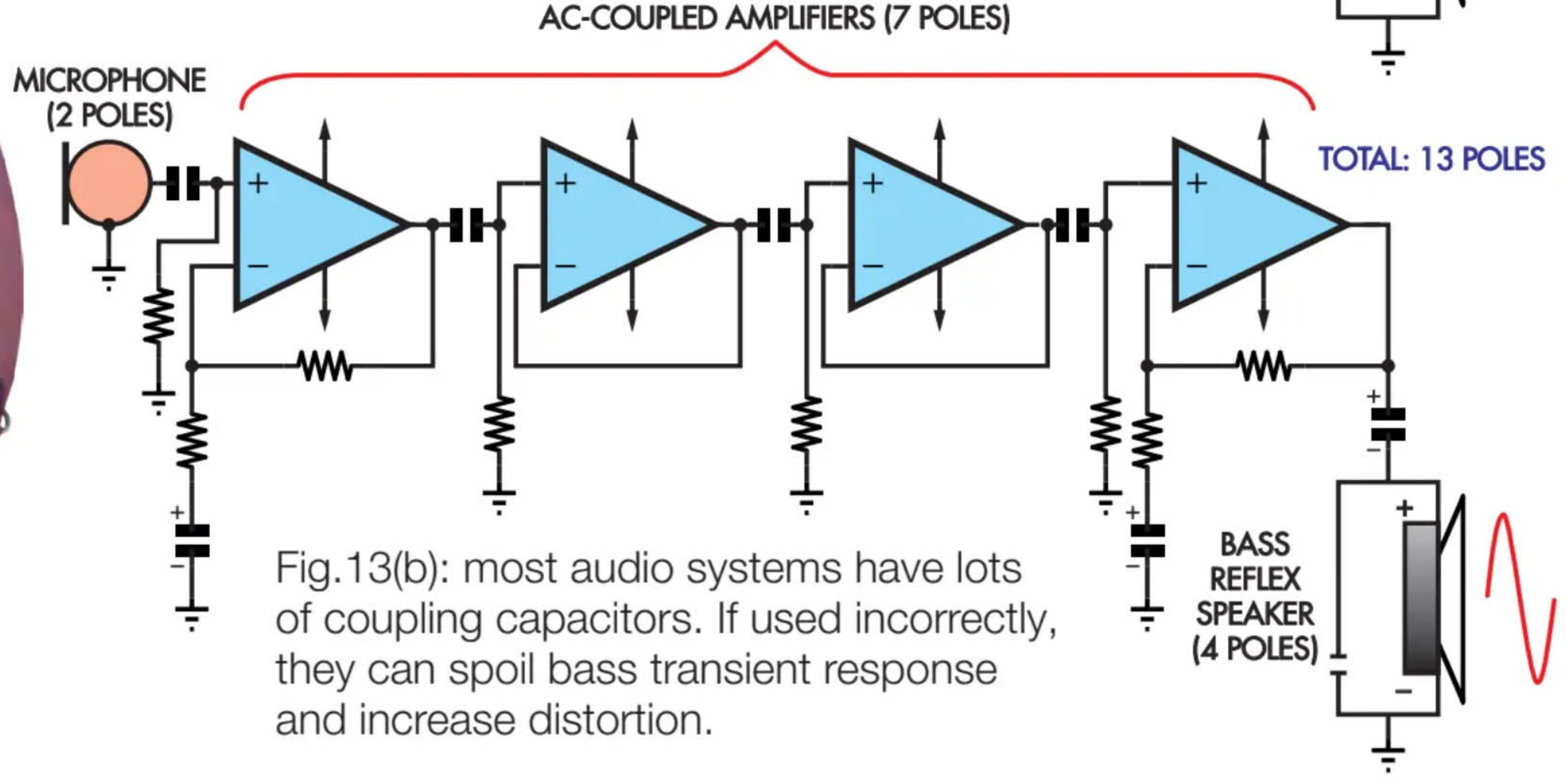


Fig.13(b): most audio systems have lots of coupling capacitors. If used incorrectly, they can spoil bass transient response and increase distortion.

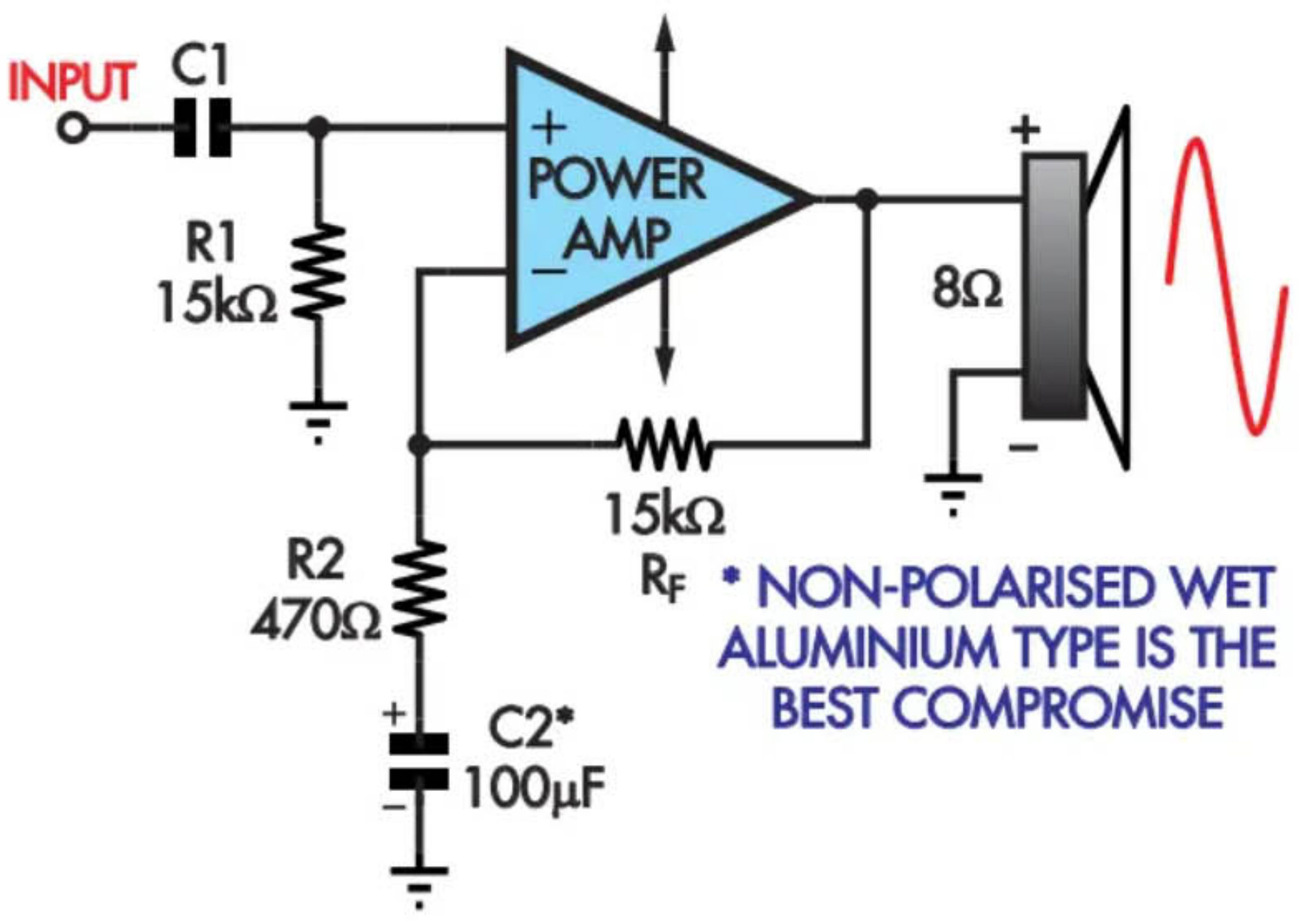


Fig.14: capacitor C2, drops the DC gain to unity. A bipolar electrolytic, like Nichicon's UVP1E101MPD (100µF 25V), gives low distortion at low cost.

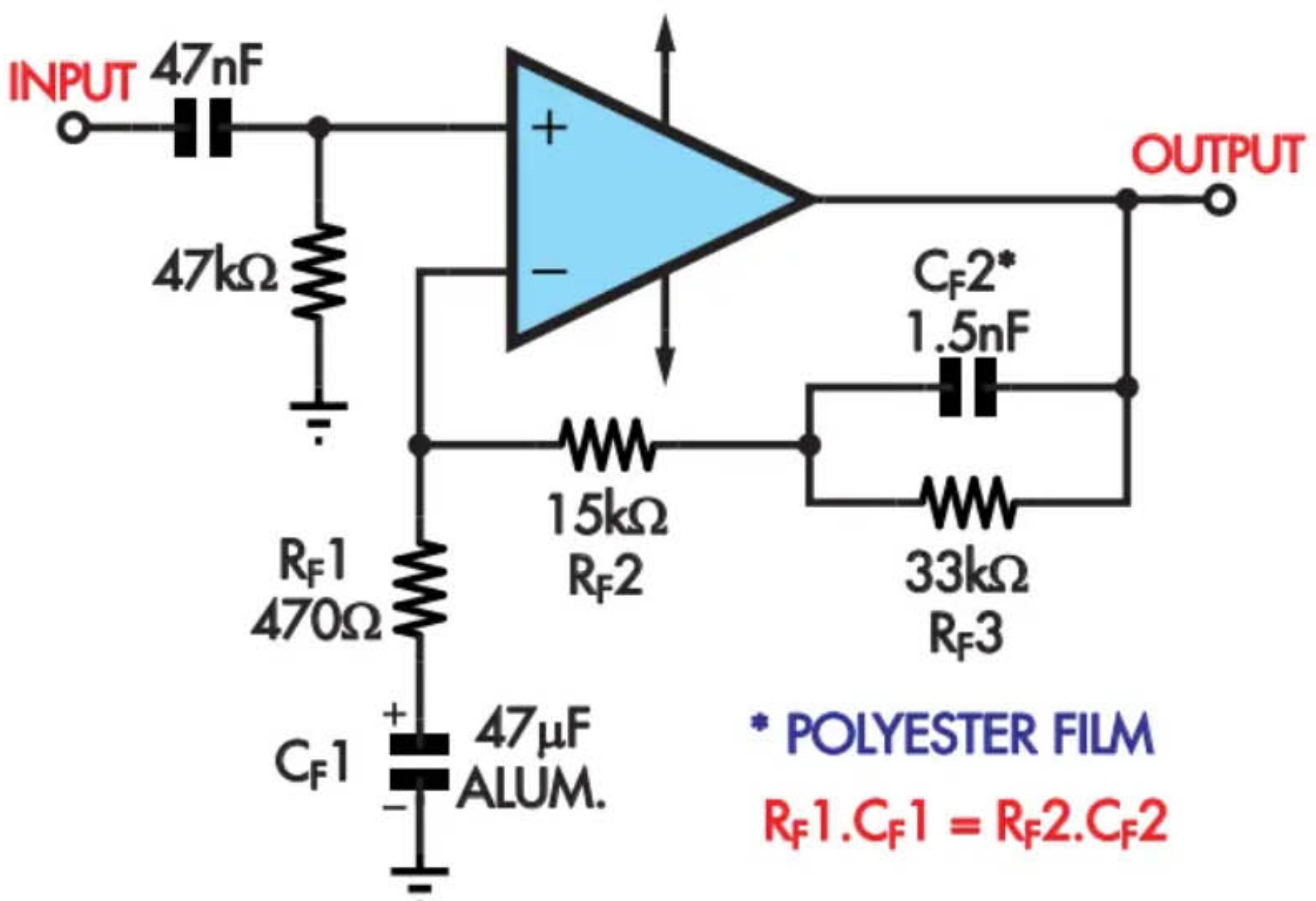


Fig.15: this shows the Cherry low-frequency compensation scheme, which minimises the signal's phase shift at low frequencies like 20Hz.

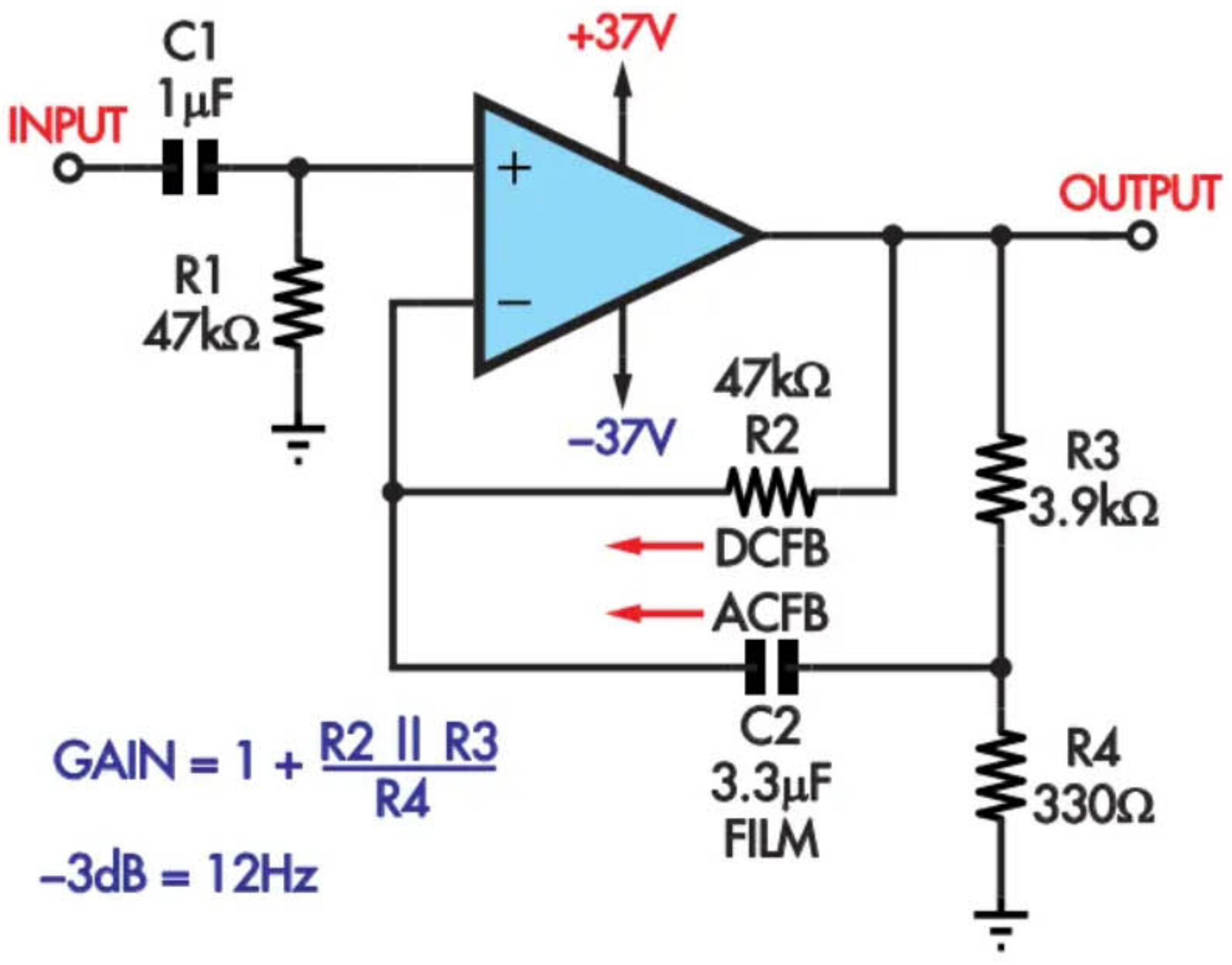


Fig.16: one way of avoiding an electrolytic capacitor in a feedback network.

speaker will have inherent high-pass filtering of second order.

However, it is possible, with a complementary bass boost to a sealed box speaker, to give a flat response down to 5Hz, where the whole system will roll off with a fourth-order slope and minimal phase shift.

Contrast this with a normal reproduction chain, with an additional seven coupling capacitors and reflex speaker, shown in Fig.13(b). Now the total roll-off is 13th order. Add in a modern sixth-order roll-off equalised reflex active loudspeaker system and the total roll-off is of the 15th order.

This leads to a large phase shift, approaching 1350º, and a consequent huge group delay, resulting in a 'warm' and 'boomy' sound. We're now accustomed to it; it is typified by Sonos speakers, Bose Wave radios, Genelec monitors and American podcasters. Most people love the effect, but it is also completely inaccurate, so the 'capacitophobic' people may be onto something.

I was surprised to read a letter raising all of this by the late mixer designer Barry Porter in HiFi News and Record Review magazine, September 1987. He also said he used non-polarised electrolytics for coupling. It seems he was ignored, like many people ahead of their time.

Edward Cherry

The lower-arm feedback capacitor used to reduce DC gain to unity in non-inverting amplifiers, such as most audio power amps shown in Fig.14 (C2 here), is critical. After all, the linearity of a feedback system can only be as good as its feedback network.

Australian power amplifier designer Edward Cherry investigated the linearity of electrolytic capacitors back in the 1970s and found them to be much better than originally believed. He also noticed that tantalum beads, which were in fashion at the time, were worse.

He used to compensate for the LF phase shift in his power amps, such as in his *ETI* May 1983 design, using the circuit shown in Fig.15. The network C_F2, R_F3 in series with the feedback resistor R_F2 reduces the negative feedback (NFB) in the region across the same range of frequencies that the attenuation of the lower feedback arm due to capacitor C_F1 boosts it.

This allows the main feedback capacitor (C_F1) to be just 47µF. Without the added compensation network, it would need to be 1000µF. He demonstrated this using a 20Hz square wave, giving the same minimal square-wave tilt for the big capacitor and his circuit with the lower value.

The voltage attenuation of the feedback network makes it possible to use lower-voltage capacitors than expected. I have seen 6.3V used with no ill effect. Due to NFB action, the maximum signal voltage across the capacitor is the same as the input voltage, typically 775mV RMS maximum.

If the amplifier latches up to one of the power rails, the feedback resistor limits the current through the capacitor to a safe value and leakage currents stop the voltage building up.

If you want to be extra safe, place 3.3V back-to-back zener diodes across C2 in Fig.14, since occasionally the charge does build up and destroy the capacitor if the amplifier is offset for some time. I have seen this with polymer electrolytics.

An alternative circuit that can be used to reduce the size of the feedback capacitor is shown in Fig.16. This allows a polyester capacitor to be used rather than electrolytic.

Both of these circuits involve the use of a high-value feedback resistor, which passes the DC bias current to the input transistor long-tailed pair. This will increase the offset voltage.

Biasing

Polarised capacitors give lower distortion with DC bias, especially solid tantalum types. Not much is required; 3–5V is usually enough.

I tested the effects of bias by connecting

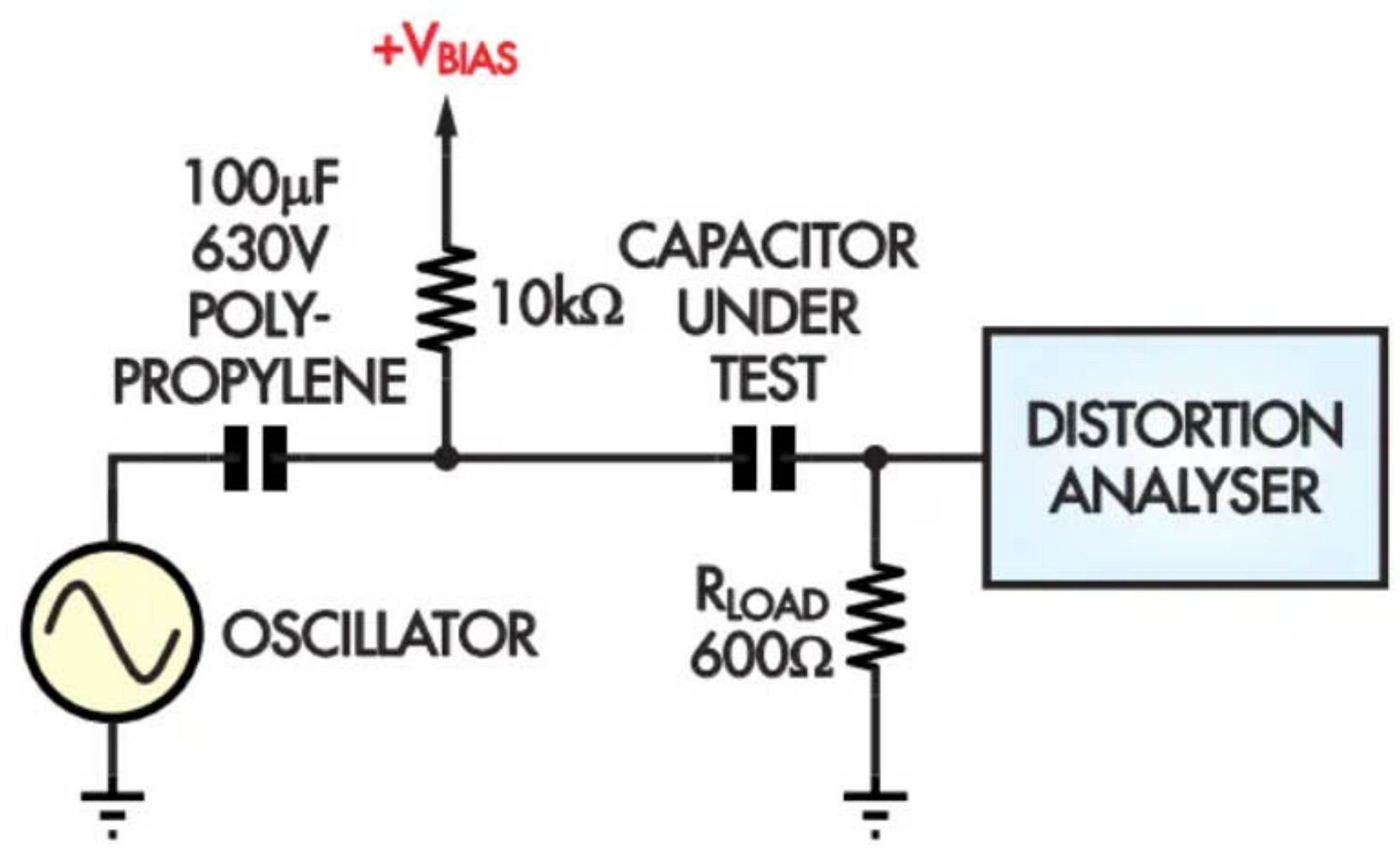


Fig.17: I used a 100µF 630V PP capacitor as a reference and for bias blocking. Its distortion was below the resolution of the AP analyser.

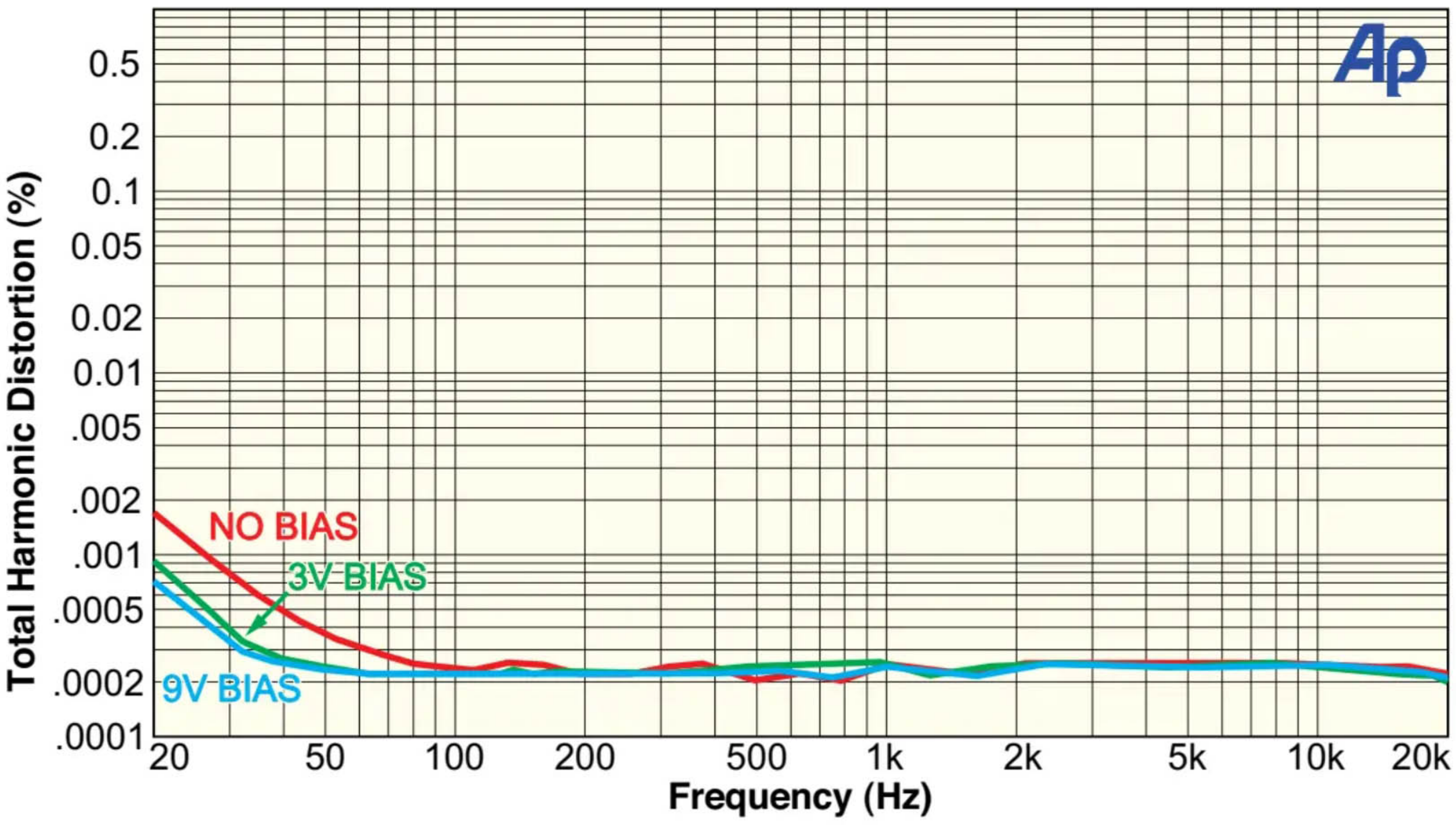


Fig.18: solid tantalum bead capacitor distortion curves, 1V RMS into 600Ω with a 100µF 10V Kemet type. No bias THD = 0.0018%, 3V = 0.0009%, 9V = 0.0007%.

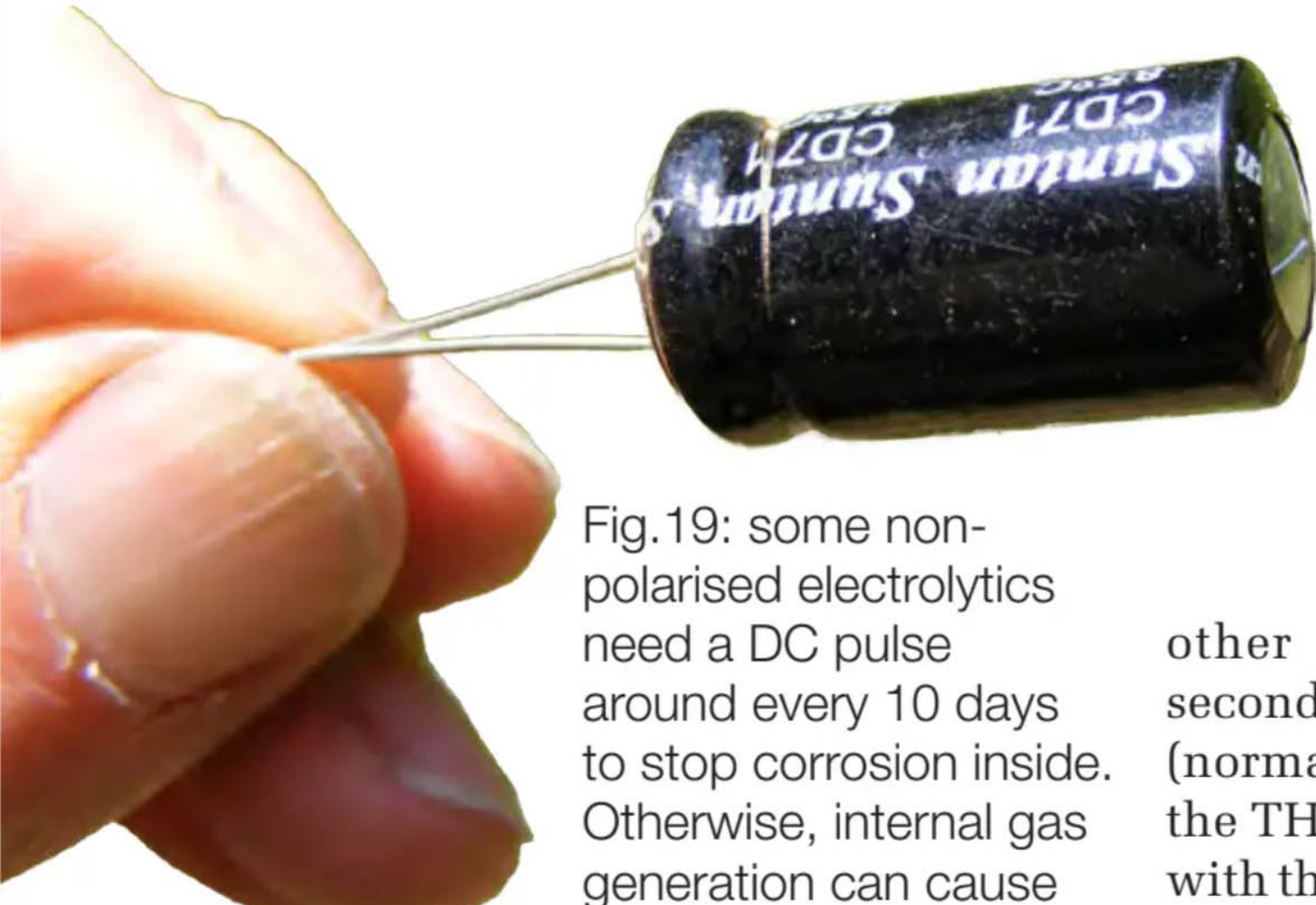


Fig.19: some non-polarised electrolytics need a DC pulse around every 10 days to stop corrosion inside. Otherwise, internal gas generation can cause swelling in storage.

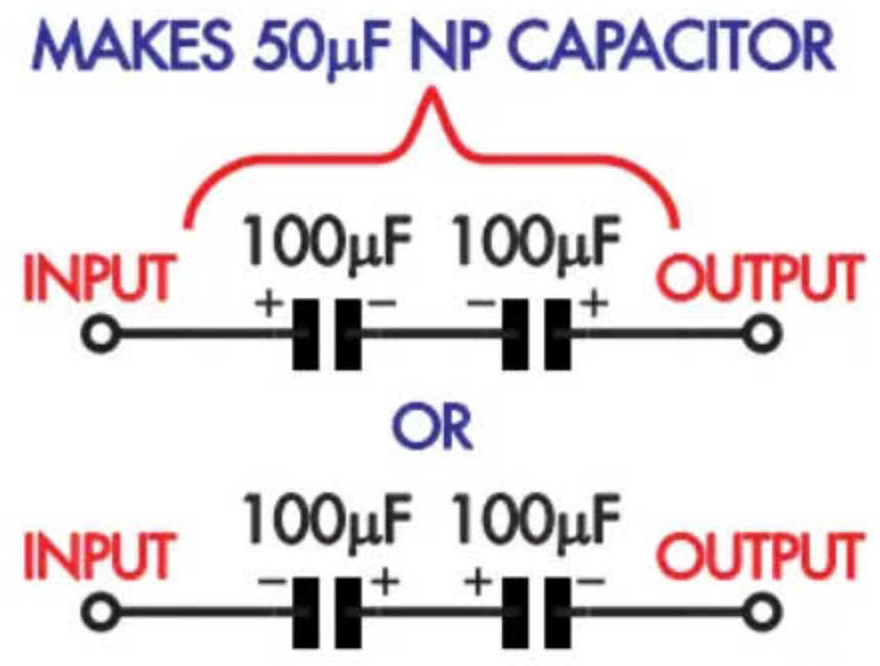


Fig.20(a): back-to-back polarised capacitors make a non-polarised unit.

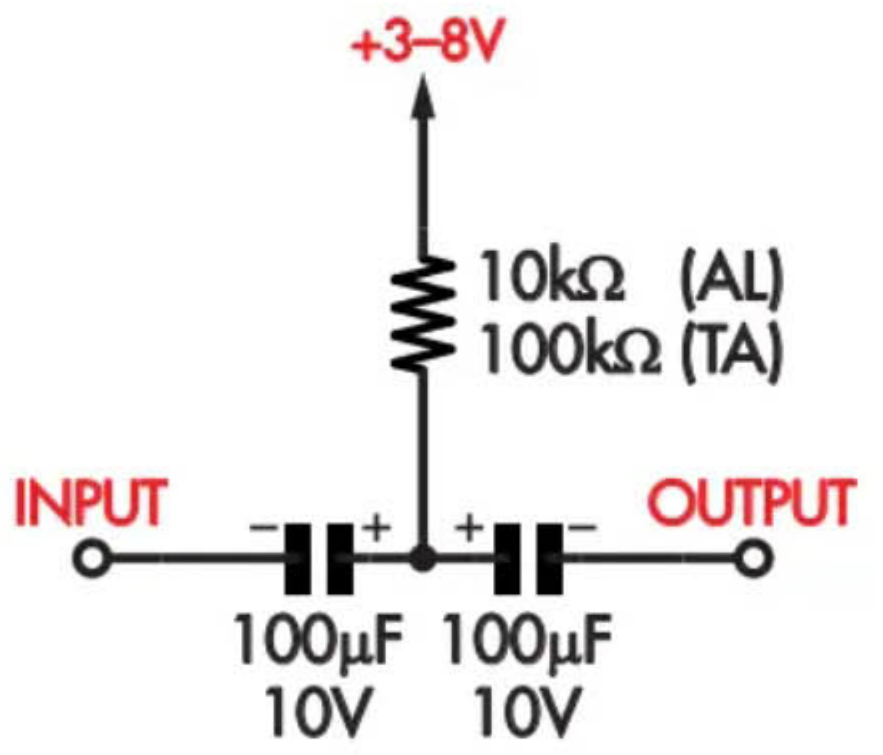


Fig.20(b): applying a centre bias.

a very expensive 100µF polypropylene cap in series with the capacitor under test for DC blocking (Fig.17), which had much lower distortion than the capacitor under test. The bias was applied to the junction of the two capacitors via a 10kΩ resistor.

I used to worry about using polarised electrolytics in circuits with no DC bias, such as op amp systems running on dual rails. Luckily, the corrosion inhibitors in most modern electrolytes, along with the DC pulses that occur on switch-on and switch-off, are enough to prevent degradation.

Solid tantalum capacitors don't degrade without bias, but the distortion is higher (Fig.18). Wet electrolytics do suffer from prolonged storage, especially the non-polarised (NP) types. In most NP data sheets, it says to polarise one way, then the other every 250 hours. If you don't do this, the capacitors can pop in the drawer after a few years.

I had this problem with some Suntan CD71 capacitors from Rapid electronics (Fig.19).

Distortion cancellation

Putting two polarised capacitors back-to-back, as shown in Fig.20(a), can reduce distortion. It does this in several ways: first, one capacitor protects the other against reverse polarisation; second, the second harmonic distortion (normally the biggest component of the THD) cancels out. This also occurs with the input capacitors on differential amplifier inputs.

Finally, there is a degree of self-biasing that occurs from the diode action when each capacitor is reverse-polarised. I've noticed the effect is more powerful with solid tantalum capacitors than wet electrolytics. This is because of their lower leakage and the fact that there is no additional cathode foil capacitor in series.

This self-biasing voltage takes a few cycles to build up and, with music signals, it will be unstable. It is easy to measure it with a scope or digital multimeter; it can build up to a few volts. It's much better to apply a stable bias to the centre junction, as shown in Fig.20(b).

To get best distortion cancellation, the capacitors should be matched in second-harmonic generation. Using capacitors from the same batch usually works. An example of the reduction in distortion with tantalum capacitors is shown in Fig.21.

Wet electrolytics can be very linear when used at high levels back-to-back with bias. I had to thrash these 100µF 35V Suntan units at the full 26V RMS output of the Audio Precision to generate the distortion also shown in Fig.21, with and without a 5V bias.

I adapted the Cherry circuit by adding a biased pair of back-to-back 100µF 20V tantalum bead capacitors, as shown in Fig.22. The distortion was very low (see Fig.23). Sometimes it is desirable to obtain a long lifespan, especially at studio rack temperatures, by removing wet electrolytics.

One possible problem with this circuit is switch on/off thumps and slow ramping of the power supplies reduces it. A discharge diode for switch-off may be a good idea. This can be reverse-biased diodes across the base-emitter junction of the input transistors; a sensible, cheap precaution against transistor damage.

Next month

I have plenty more information on capacitor distortion and how to avoid it. I will continue on this topic next month, including information on the effects of physical capacitor construction on performance, a discussion of classic and special types of audio capacitors and a ranking of capacitors for audio use. PE

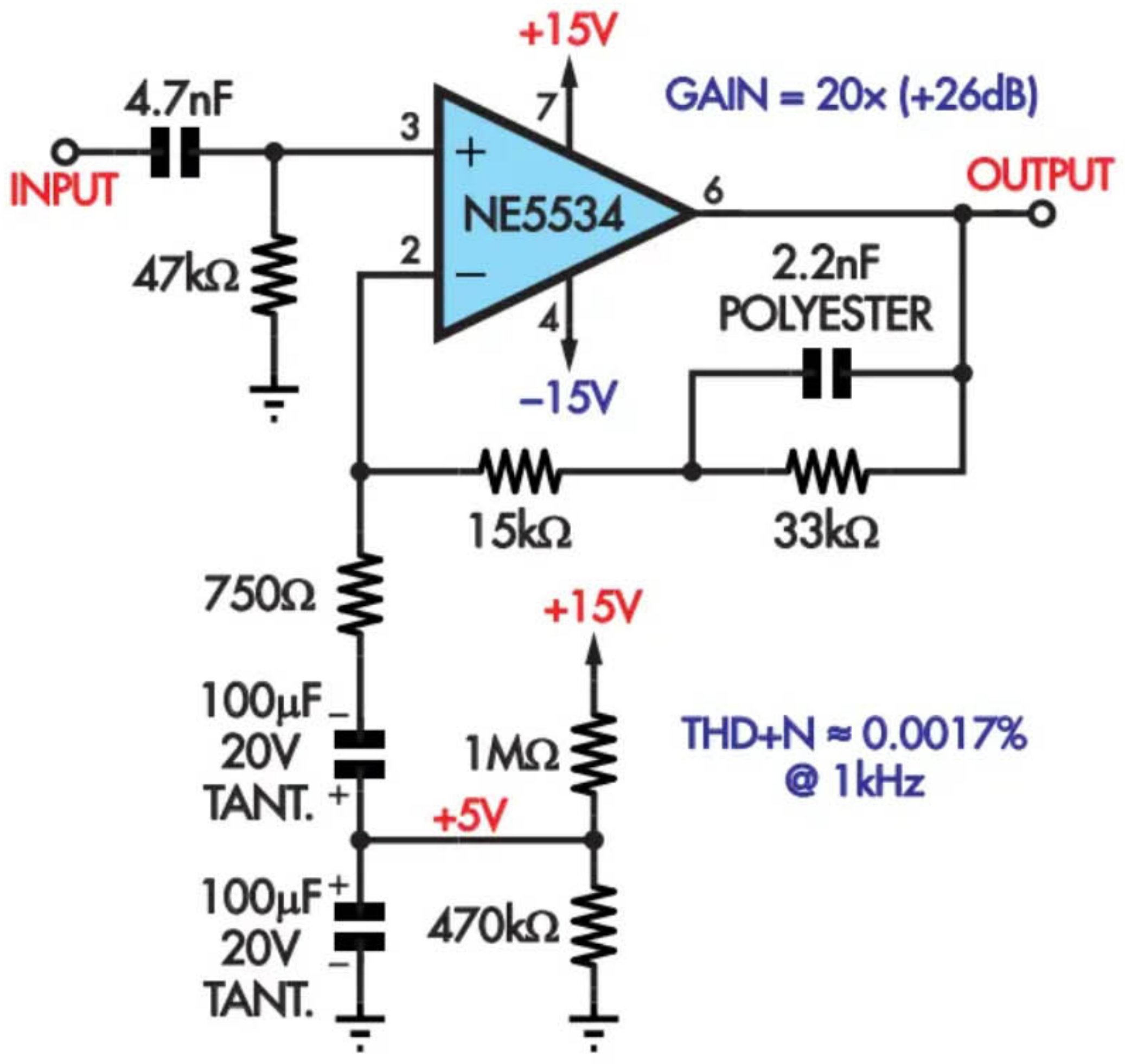


Fig.22: an adapted Cherry circuit with biased 100µF tantalums back-to-back.

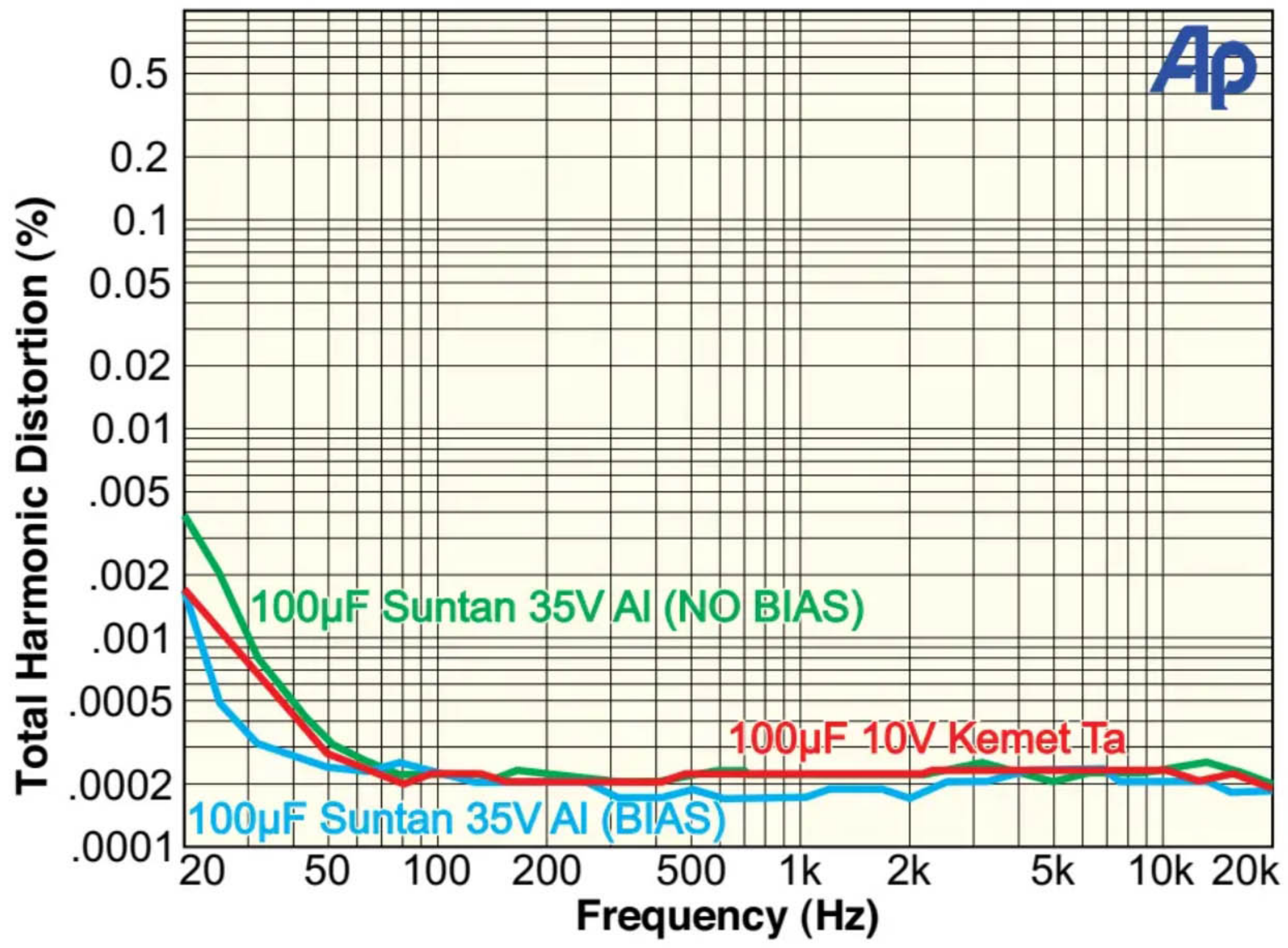


Fig.21: back-to-back tantalum beads, 4V DC bias at 4V RMS into 600Ω, plus two 100µF Suntan 35V electros back-to-back.

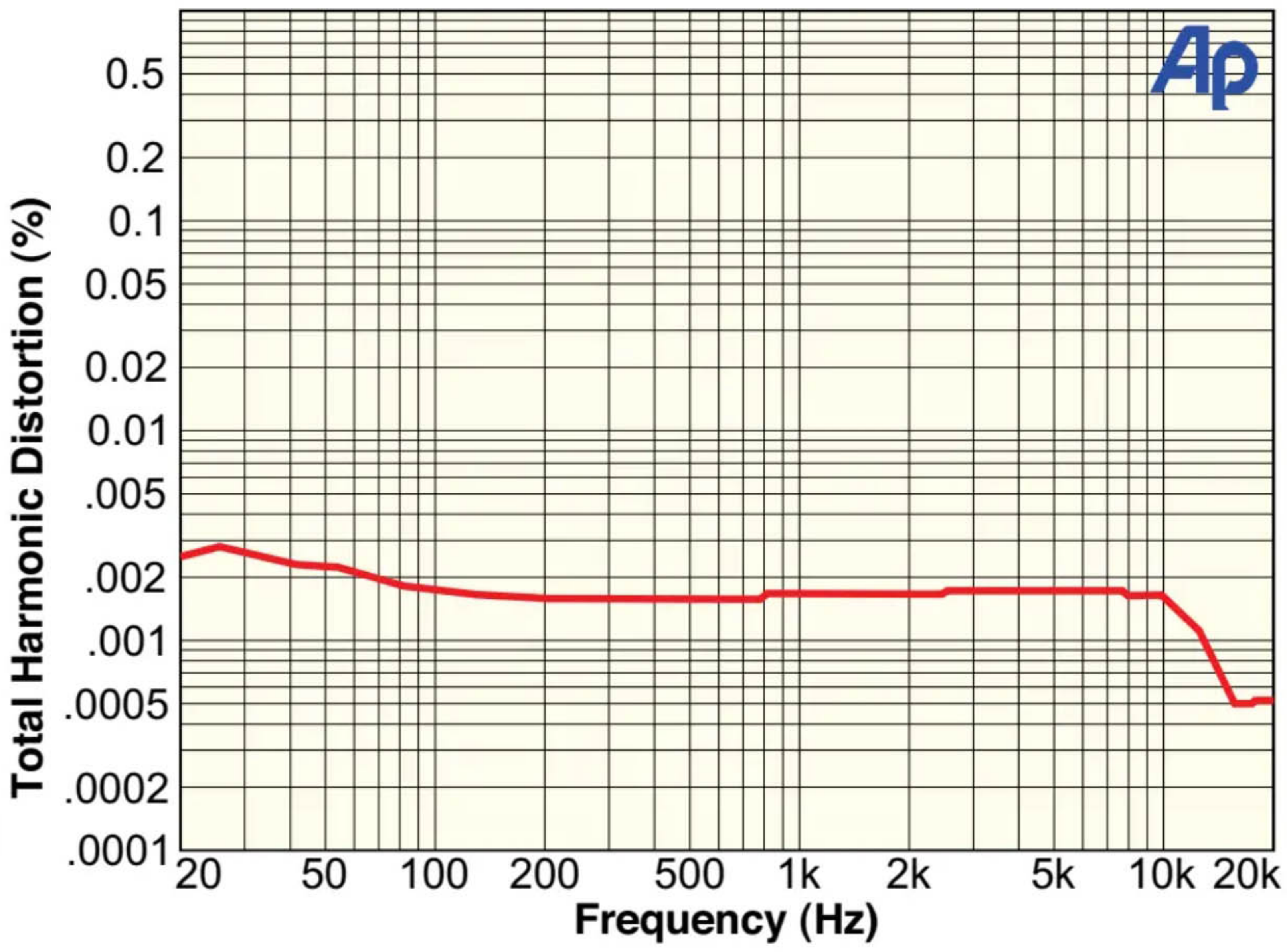


Fig.23: the distortion of Fig.22 delivering 20V RMS into 600Ω. It has a slight LF rise but not bad for a normal aluminium cap.