Capacitor Sounds 5 - 1 µF choice - Electrolytic or Film ?

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Many capacitors do introduce distortions onto a pure sinewave test signal. In some instances distortion results from the unfavourable loading which the capacitor imposes onto its valve or semiconductor driver. More often, the capacitor generates the distortion within itself.

Capacitor generated distortions, for too long the subject of much speculation and opinion, can now be measured. Capacitors are not categorised for distortion in manufacture, so a distorting capacitor would not be accepted as reject by its maker. Using my easily replicated test method, audio enthusiasts can select capacitors when upgrading their equipment and designers can select capacitors for each circuit requirement.

For 100 nF capacitance we find the lowest distortions are generated by choosing either C0G multilayer ceramic, metallised film Polyphenylene Sulphide (PPS) or double metallised film electrodes with Polypropylene (PP) film. **Ref.1**

At 1 µF, C0G ceramic types are not generally available, reducing our low distortion choice to the above two film types or a selected metallised Polyethylene Terephthalate (PET). To guarantee low distortion we found that metallised PET types should be distortion tested and used with no bias or with modest DC bias voltages. The PPS and PP capacitor types produce exceptionally low distortions but are larger and more expensive. see **Fig. 1**

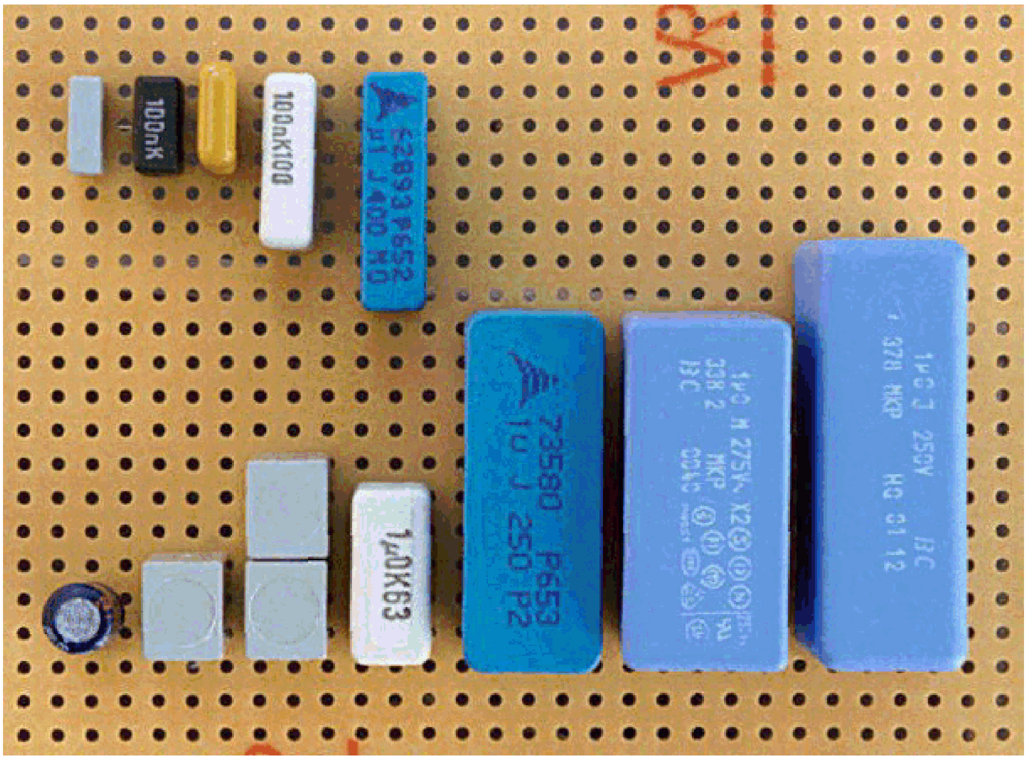


Fig. 1) Top row 0.1µF, the 50v and 100v SMR capacitors second and fourth, the B32652 fifth from left. Far left is the BC Components type 470 met PET, third from left is the 100 nF COG multilayer ceramic.

Bottom row left 1µF, the best electrolytic, the Bi-polar, was outperformed by the 470 type 63v metallised PET capacitor. The SMR capacitor is fourth and the B32653 fifth from left. Finally we have a type 338 MKP class ‘X2’ capacitor and 378 MKP both stocked by most distributors.

To minimise costs at 1 µF and above, many designers elect to use low cost polar aluminium electrolytic capacitors. We now explore this option.

Electrolytic capacitors.
At room temperature and 1 kHz, a typical 1 µF 63 volt polar electrolytic capacitor can sustain some 30 mA AC ripple current. By measuring its distortion using our two test signals at 1 kHz 100 Hz, we obtain a direct comparison of polar electrolytic distortions with the film capacitors of my last article. see **Fig. 1**

Aluminium Electrolytic capacitor myths.
As with other capacitor types, much has been written about the sound distortions they cause. However of all capacitor types, electrolytics are the most complex and the least well understood. Many false myths, specific to electrolytics have emerged, based more on speculation than on fact:-

a) Aluminium electrolytic capacitor dielectric has extremely high ‘k’.
b) Electrolytic capacitor distortion is mostly third harmonic.
c) For minimum distortion, electrolytic capacitors should be biased to half rated voltage.
d) Back to back polarised capacitors, biased by the supply rail, minimise distortion.
e) High ESR Electrolytics degrade sound quality, low ESR is always best.
f) Electrolytics are highly inductive at audio frequencies.
g) High voltage electrolytics sound the best.

As we shall see, a working knowledge of electrolytic capacitor construction combined with careful distortion measurements, leads to somewhat different conclusions.

Polar Aluminium electrolytic construction.

To begin to understand an aluminium electrolytic capacitor we must explore how it differs from other capacitor types including Tantalum. Every aluminium electrolytic capacitor comprises two polar capacitors in series, connected back to back. **Ref.2**

The dielectric for the wanted capacitance is a thin aluminium oxide coating which intimately covers the 'Anode' foil. The metal core of this anode foil, acts as one capacitor electrode. The second electrode is provided by a conductive electrolyte which permeates and surrounds the anode foil.

A 'Cathode' foil is used to make electrical contact between this electrolyte and the lead-out wire. This cathode foil is also intimately covered by a much thinner, naturally occurring aluminium oxide, the dielectric for our second capacitor. Electrically similar to oxide produced using a 1 to 1.5 volt 'forming' voltage, capacitance of this cathode is many times that of the anode.

The effective surface area of the anode and cathode foils is much enlarged, by mechanical brushing and electro-chemical etching. Low voltage capacitor foil areas may be increased perhaps one hundred times larger than the foils superficial or visible area. In this process a myriad of minute tunnels are created in the aluminium foils, which become sponge like and porous. **Ref.2**

An extremely thin layer of dielectric, aluminium oxide AL_2O_3 with a 'k' of eight, **Ref.3** is electro-chemically 'formed' or grown on the surface of the anode foil using a non-aggressive electrolyte. Depending on the desired end use, a general purpose capacitor anode foil may be formed at 1.25 times, a long life capacitor anode foil to double its rated voltage.

In many ways this is similar to the more familiar 'anodising' process, long used to provide a decorative and protective finish on aluminium. The main difference being the anodising oxide is formed using an aggressive electrolyte, which by simultaneously dissolving away some of the freshly grown oxide, produces a porous oxide layer. This porous layer accepts colouring dyes which can be sealed in situ, by boiling in water to hydrate and seal the outer oxide layers.

The thickness of our capacitor dielectric oxide is self limiting, being controlled by the voltage used in the forming process. As thickness approaches 14 Angstrom for each forming volt applied, oxide growth slows down and almost ceases. **Ref.2**

This electro-chemically 'formed' hard, non-porous, aluminium oxide produces an excellent, almost perfect insulator, which can be formed for use at least to 600 volts DC. It has a dielectric strength approaching the theoretical strength as predicted by the ionic theory of crystals.

Because aluminium oxide takes up more space than the aluminium which is converted in the 'forming' process, different etching methods are used according to the intended forming voltage. For the lowest voltage capacitors, the most minute tunnels are etched into both foils.

Formed to 50 volts, oxide growth would completely fill these minute tunnels. To avoid this the etching process is adapted to produce somewhat larger tunnels, which can be formed, perhaps to 100 volts. For higher voltages, progressively larger tunnels must be etched. **Ref.2**. Becromal, one supplier of capacitor foils, lists some fourteen different grades of etched anode and an even bigger selection of cathode foils.

As capacitor rated voltage increases, less conductive electrolytes and thicker, denser, separator tissues must be used. To reduce element size and cost, thinner, lower gain cathode foils will usually be chosen. These changes combine to produce a near optimum quality, low tanδ, low distorting capacitor when rated for 40 to 63 volt working. With notably poorer audio qualities above 100 volt and at the lowest voltage ratings.

Assembly.

The required length of anode and a slightly longer length of cathode foil are wound together, cathode foil out, onto a small rotating spindle. To minimise mechanical damage to the extremely thin, dielectric oxide coating, the foils are interwound together with soft insulating separators. Thin 'Kraft' or 'Rag' tissue paper the most common.

Aluminium has an electro-chemical potential of +1.66v. To avoid corrosion, no metal other than aluminium may be used inside the capacitor case. The external lead wires, copper at -0.337v or steel at +0.44v, must be excluded from all contact with electrolyte, to avoid corrosion of these metals.

Prior to winding the element, thin aluminium connecting 'tabs' are mechanically and electrically connected to both foils. Many years ago, these tabs were attached near the outer end of the winding. In 1968 I introduced into UK manufacture the use of 'Central' foil tabbing, which dramatically reduces the aluminium foil resistance, enhancing ripple current ratings and almost totally eliminates self inductance from the wound element. The most common tab attachment method is called 'eyeletting', when a shaped needle pierces both the connecting tab and its foil. Small 'ears' of tab material are burst through the foils, turned over and well flattened down effectively riveting both parts together. see **Fig. 2**

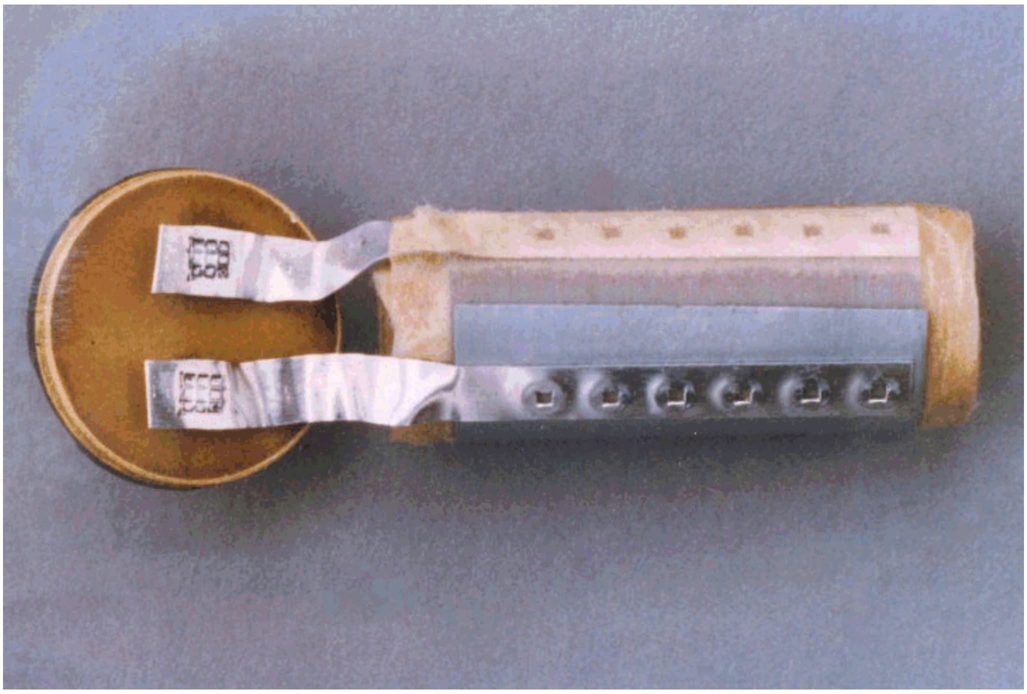


Fig 2) The 'eyeletting' type connections most often used to connect aluminium lead out tabs to the centres of both cathode and anode foils.
In this case because the winding was central tabbed, for clarity the outermost, almost half the wound turns, of both anode and cathode foils, have been removed.

A box of 'nine squares', tool marks indicative of the cold pressure welds used to reliably connect these tabs to the tag rivets, can be clearly seen.

Cold pressure welds, as seen in this photo connecting the aluminium 'tabs' to the outer tag rivets, provide a most reliable, low and linear resistance, connection of aluminium to aluminium. By applying pressure over small areas, metal is forced to flow between the two items which become intimately bonded and permanently welded together. This method is often also used to replace 'eyeletting' of tabs to foils in the best constructed capacitors.

The completed winding is vacuum impregnated with the electrolyte which becomes absorbed into both foils and separator papers. Producing a low resistance connection between the anode and cathode foil capacitances.

Bi-polar Aluminium electrolytic capacitor construction.
A Bi-polar electrolytic is made in exactly the same way as a polar capacitor, with one significant difference. In place of the cathode foil, we use a second formed anode foil.

We still have two polar capacitances in series, back to back. Both now the same value and working voltage. This Bi-polar capacitor will measure as half the capacitance of either anode foil. To make the required capacitance value, two anode foils, each double the desired capacitance are used.

Aluminium electrolytic capacitor designers are accustomed to mixing and matching their available materials, to suit the capacitor's end application. So it should not surprise that some designs are semi Bi-polar, i.e. they are made using a lower voltage deliberately 'formed' anode foil as cathode.

Equivalent circuit.
Using this constructional background, we deduce an equivalent circuit for a polar aluminium electrolytic capacitor. see **Fig. 3**

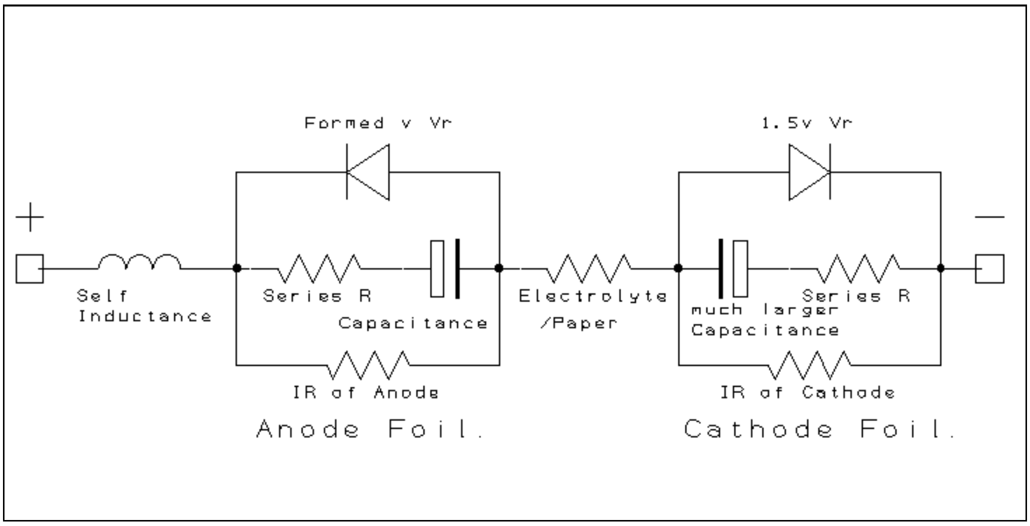


Fig 3) This simplified equivalent schematic illustrates how a polar electrolytic capacitor behaves. For clarity, components needed to account for dielectric absorption, have been omitted.

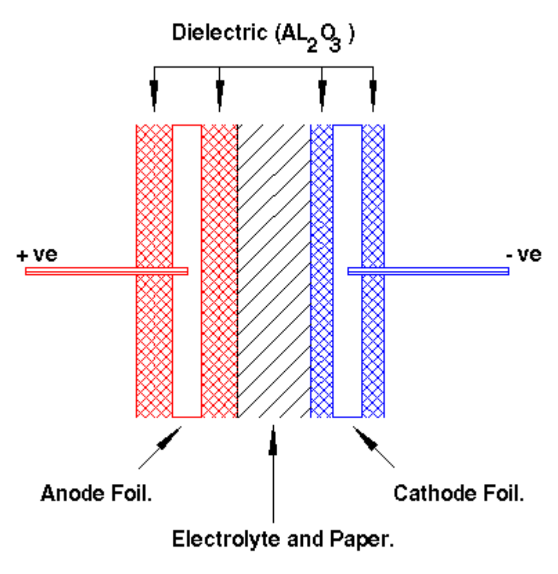


Fig 3A) Sectional view of anode and cathode foils showing their dielectric oxide layers and how the 'electrolyte/paper' function acts to provide a good electrical connection between the aluminium oxide dielectric capacitances of both foils.

Box **Capacitance of an electrolytic**.
The high capacitances available in an electrolytic are the result of the effective surface area of the etched and 'formed' anode foil combined with its exceptionally thin dielectric. This effective area is many times larger than the apparent or visible surface area. The extremely thin, electro-chemically 'formed' dielectric oxide film, has a modest 'k' value of eight. **Ref.3**

Capacitance = Electrode area × 'k' × 0.0885 / Dielectric thickness. in pF/cm**. Ref.6**

This increase in area or 'gain', is greatest for very low voltage rated capacitors, reducing with increasing voltage.

This 'k' of eight, compared to the 'k' of 3.3 for PET, more than doubles capacitance, but far more significant is the extremely thin dielectric thickness used in aluminium electrolytics and the much increased effective area resulting from the etching process. As a result, assuming a 50 volt rated capacitor, the aluminium electrolytic's oxide film produces some 1000 times more capacitance per unit of apparent electrode area. This gain increases significantly to some 5,000 times for an electrolytic capacitor rated for 6 volt working.

The cathode foil is covered by a naturally occurring, transparent oxide film, which coats all aluminium surfaces once exposed to air. Some 20 Angstroms thick, it is equivalent to a 1.5 volt electro-chemically formed oxide. Much thinner than that 'formed' on the anode foil even for the lowest voltage capacitors. This cathode foil oxide creates our second capacitor.

For example to make a 100 µF 6.3 volt rated capacitor we might use anode foil formed to 8 volts. This would have a dielectric thickness of some 110 Angstroms, almost 6 times thicker than the cathode foil's natural oxide film. We use an anode capacitance around 118 µF in series with a cathode capacitance around 660 µF to obtain our 100 µF capacitor. The oxide on the cathode foil, which creates our second capacitor, has a small usable voltage and much larger capacitance than the anode foil. **Ref.2** see **Fig.3**

This naturally occurring, extremely thin, low quality cathode foil oxide, has a larger voltage coefficient than has the anode foil. It is this cathode capacitor which allows a 'polar' aluminium electrolytic to operate on small AC voltages, without polarisation.

Correctly polarised the 'formed' aluminium oxide dielectric on the anode foil is an excellent insulator. When reverse polarised it becomes a low resistance as though a diode has been connected in parallel with a good capacitor.

In similar fashion, the naturally occurring cathode oxide film behaves like a capacitor in parallel with a diode. This diode's polarity is in opposition with that of the anode. Because the cathode oxide is thinner, it produces a more leaky diode.

Because a 'Bi-polar' electrolytic is made using two anode foils connected back to back in opposition, it can be used on relatively large AC voltages without polarisation voltage provided the resulting through current does not exceed the rated ripple current for that frequency and temperature. The Bi-polar electrolytic capacitor can also be used polarised in either direction.

The 'polar' capacitor should never be reverse polarised. Any DC polarisation voltage must be correctly applied with the positive voltage to the capacitor's anode terminal. **end of Box.**

Dielectric Oxide.
Aluminium oxide has a ‘k’ of eight, **Ref.3** similar to that of C0G ceramic or impregnated paper capacitors. It is rather higher than PET, which at 3.3, has the highest ‘k’ of commonly used films. A low value compared to the ‘k’ of several thousand, found in BX, X7R and Z5U ceramics. **Ref.4**

While the impregnant used in paper capacitors is an insulator and acts as the dielectric, the electrolyte impregnant used in electrolytic capacitors is a good conductor so cannot be a dielectric. This electrolyte is needed to provide a low resistance connection between the two capacitors.

More significant than ‘k’ value is dielectric thickness. Large capacitance values are possible because the dielectric of a 50 volt aluminium electrolytic capacitor is some 100 times thinner than that used in a film capacitor. **Ref.2** As a result, electrolytic capacitors are sensitive to dielectric absorption effects.

The dielectric oxide films have a measurable voltage coefficient of capacitance. When DC biased, the measured capacitance of a 1 µF 63 volt capacitor increased 0.15% at -0.5 volt. Initially decreasing 0.05% at +0.5 volt, capacitance then increased to +0.16% at +10 volt.

Voltage effects.
I explored these voltage effects by measuring the distortion produced by a 1µF 63 volt polar electrolytic capacitor, subjected to different AC test voltages. Commencing with 0.1 volt, capacitor distortion was measured at 0.1 volt increments to 1 volt then with a test at 2 volts. Initially I test with no bias, then with various DC bias voltages. Remember these voltages are those actually measured across the capacitor terminals and not the generator set voltage.

Small test voltages reduce measurement dynamic range. To compensate for this, distortion from the test capacitor will be compared with those produced by a near perfect film capacitor, tested exactly the same as reference. All tests for this article use my DC bias buffer and two frequencies, 100 Hz/1 kHz to observe intermodulation effects.

Electrolytic capacitor behaviour varies with small changes in temperature. To minimise the affect of temperature changes, all reported tests were performed at constant room temperature. Unless otherwise stated, all voltages are RMS as measured using a DMM.

Without DC bias.
Notably larger distortions were produced by this electrolytic than the film capacitor, even with a test signal as small as 0.1 volt, across the capacitor.

Tested with a 0.3 volt signal and no bias, distortion of this typical 1 µF 63 volt polar electrolytic capacitor, clearly dominated by second harmonic, measured 0.00115%. Almost three times greater than for the reference capacitor. see **Fig. 4**.

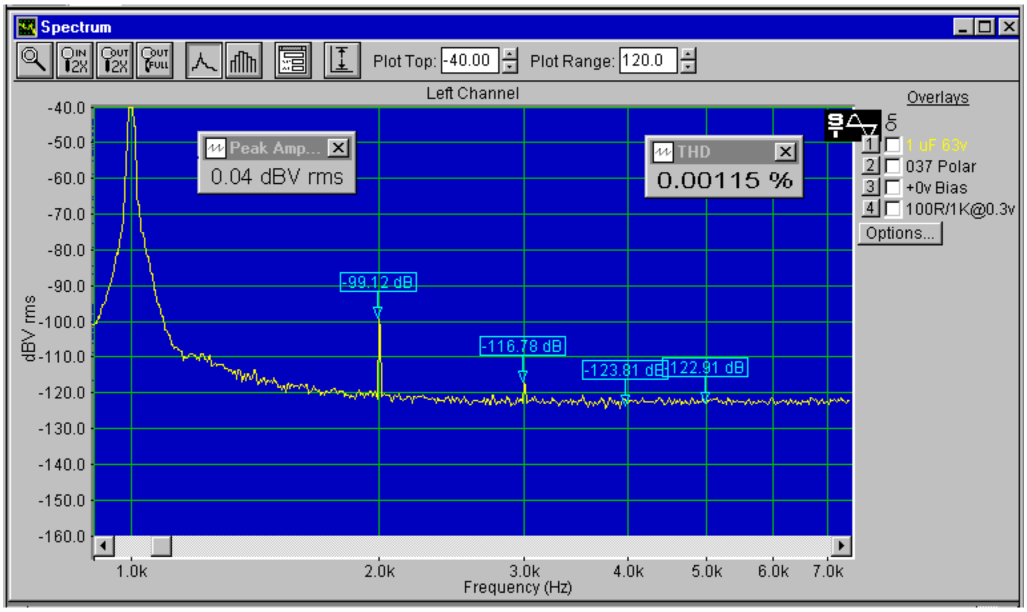
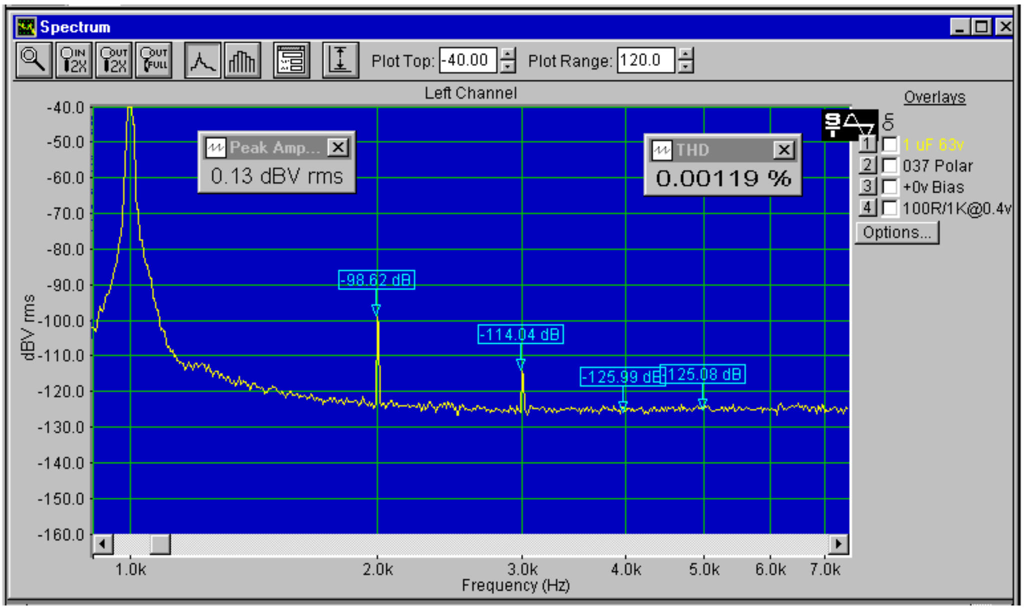

Plot Top: -40.00
Plot Range: 120.0
Peak Amp... 0.04 dBV rms
THD 0.00115 %

Fig 4) Distortions measured on our 1 µF 63 volt polar capacitor, using a 0.3 volt test signal without DC bias.

Note how the large second harmonic component dominates all others.

When the peak of the AC voltage applied across this unbiased polar capacitor exceeds some 0.5 volt, the cathode foil’s voltage dependency has more noticeable effect.

Tested at 0.4 volt RMS, both harmonics increase relative to the small change in test signal. Second harmonic voltage has almost doubled compared to the 0.3 volt test. Distortion is now four times greater than our reference capacitor. see **Fig. 5**


Spectrum

Plot Top: -40.00 Plot Range: 120.0

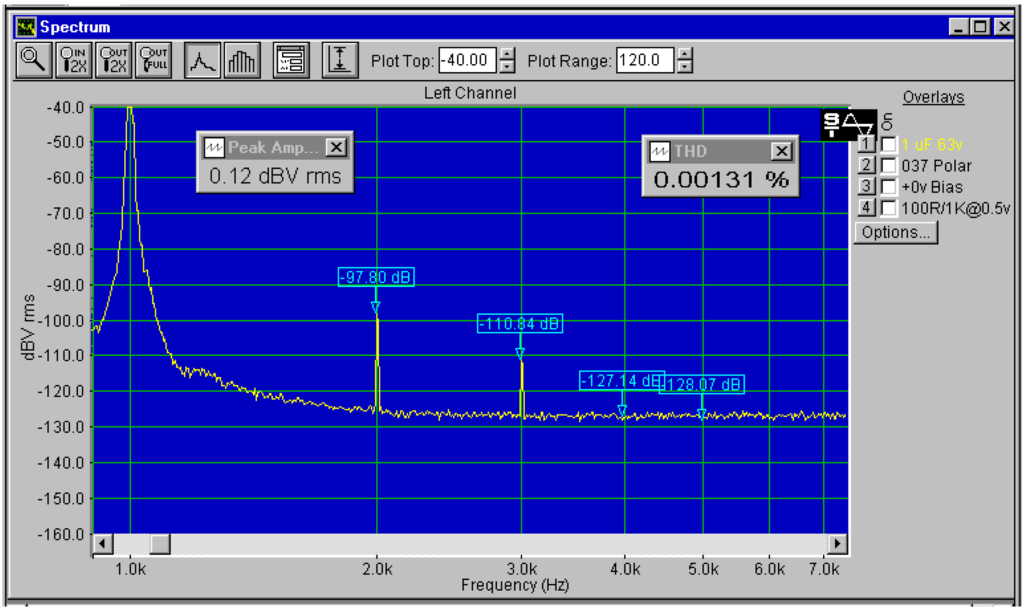
Peak Amp... 0.13 dBV rms

THD 0.00119 %

Overlays

1 ☐ 1 uF 63v
2 ☐ 037 Polar
3 ☐ +0v Bias
4 ☐ 100R/1K@0.4v

Fig 5) Both second and third harmonics have increased relative to the 0.4 volt test signal. The second has increased much more than the third. Intermodulation components remain buried in the noise floor.


Spectrum

Plot Top: -40.00 Plot Range: 120.0

Peak Amp... 0.12 dBV rms

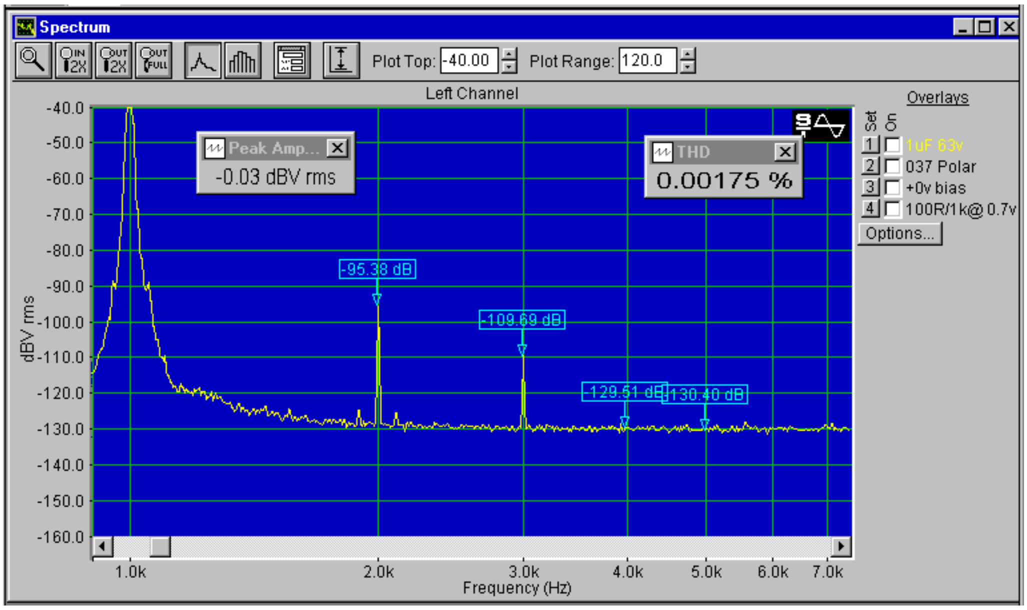
THD 0.00131 %

Overlays

1 ☐ 1 uF 63v
2 ☐ 037 Polar
3 ☐ +0v Bias
4 ☐ 100R/1K@0.5v

Fig 5A) Both second and third harmonics have again increased relative to the 0.5 volt test signal. The second very much more than the third. Intermodulation components remain buried in the noise floor.

When the peak voltage across this capacitor exceeds some 0.8 volt, intermodulation distortions appear. Tested at 0.7 volts RMS, second and third harmonic levels have again increased much faster than the test voltage. Distortion, dominated by the second harmonic, is now ten times greater than for our reference capacitor.


Spectrum

Plot Top: -40.00 Plot Range: 120.0

Peak Amp... -0.03 dBV rms

THD 0.00175 %

Overlays

1 ☐ 1 uF 63v
2 ☐ 037 Polar
3 ☐ +0v bias
4 ☐ 100R/1k@ 0.7v

Fig 5B) At 0.7 volt RMS, with the third harmonic some -110 dB below the 0.7 volt test signal, intermodulation products can be seen either side of the second harmonic.

When subject to a 1 volt sinewave, the cathode capacitance varies even more and its diode may conduct on signal peaks. Much larger increases of distortion result, now 22.4 times greater than measured on the reference capacitor. see **Fig. 6**

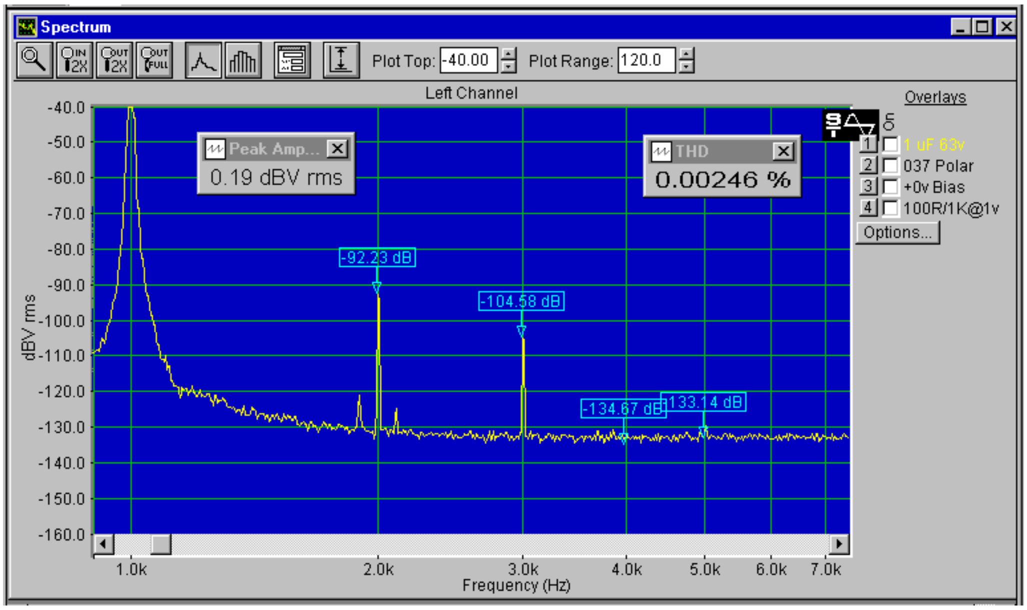


Fig 6) With a 1 volt test signal and no bias, the capacitor is producing 22.4 times more distortion than found with the film reference capacitor.
Second and third harmonic components continue to increase out of all proportion to the test signal.

We will use this 1 volt test voltage with various DC bias voltages to explore the affect bias voltage has on distortion.

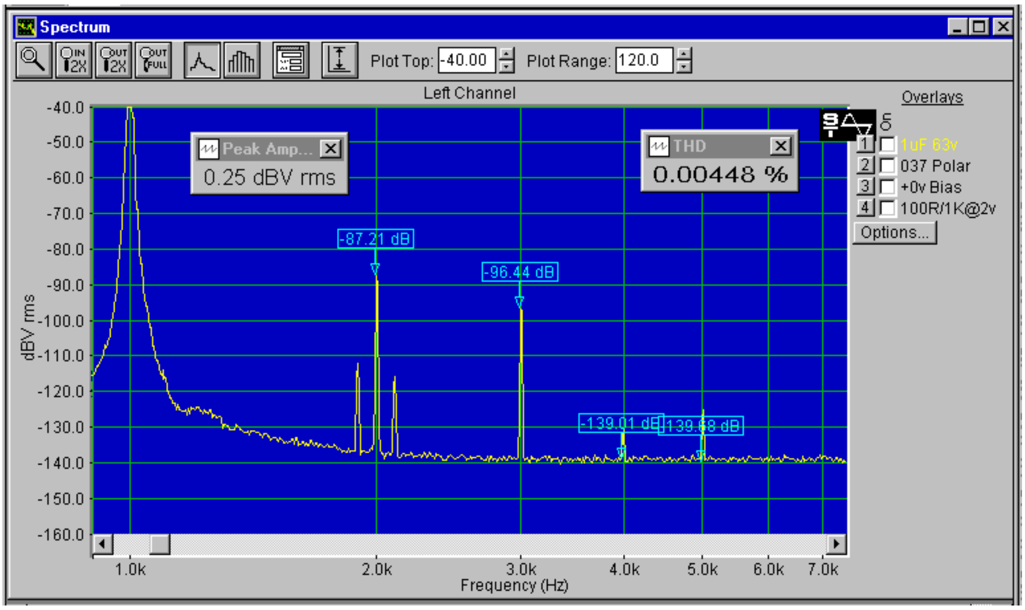


Fig 7) This 2 volt RMS test illustrates how both second and third harmonics together with intermodulation distortion continue to develop when an unbiased polar capacitor is subject to significantly more than 0.7 volts RMS across its terminals.

The above voltages/distortions apply to this particular test capacitor. With other combinations of anode voltage and cathode foil, distortions by voltage will vary. With larger capacitance and lower voltage capacitors the same effects are observed, but frequently at even smaller test voltages.

Regardless of capacitance, working voltage or manufacturer, the second harmonic was always the largest distortion component for every unbiased polar electrolytic capacitor I measured.

Myth

In the past various writers have stated that aluminium electrolytic capacitor distortion commences when a capacitor is subject to 1.4 volts peak, or 1 volt RMS sinewave. D. Self once described this 1.4 volts as the voltage “which appears to be when depolarisation occurs in practise. Naturally distortion results as the capacitor dielectric film starts to come undone.” **Ref.5**

On both counts this is completely wrong. As we have seen, significant distortions do occur at very much lower voltages.

While the thin aluminium oxide film is easily mechanically damaged, like anodised aluminium, electro-chemically it is extremely robust. It requires substantial time and/or electro-chemical energy, to revert the aluminium oxide structure. Capacitor maker’s specifications permit short term voltage reversals up to 1.5 volts, when the capacitor must remain undamaged.

If severely abused by significant reverse voltage applied for a long time or excessive ripple current, a conventional aluminium electrolytic may explode. Not because the aluminium oxide film has deteriorated but simply because these conditions result in large internal leakage currents. The subsequent hydrolysis action releases quantities of hydrogen and oxygen gases from the electrolyte. Internal pressure increases until the capacitor case breaks.

To help interpret the above results, I converted the 2nd and 3rd harmonic distortion dB levels into µV. Plotted against test voltage, both harmonic voltages clearly increase ever more rapidly with increase in test voltage.   see **Fig. 8**

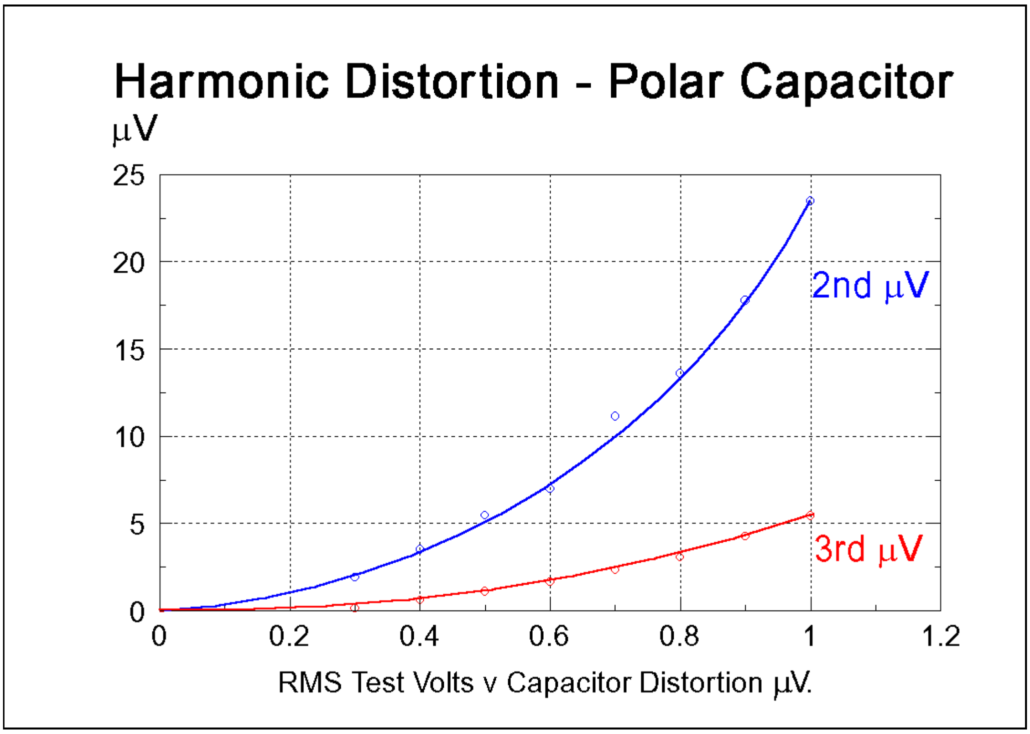


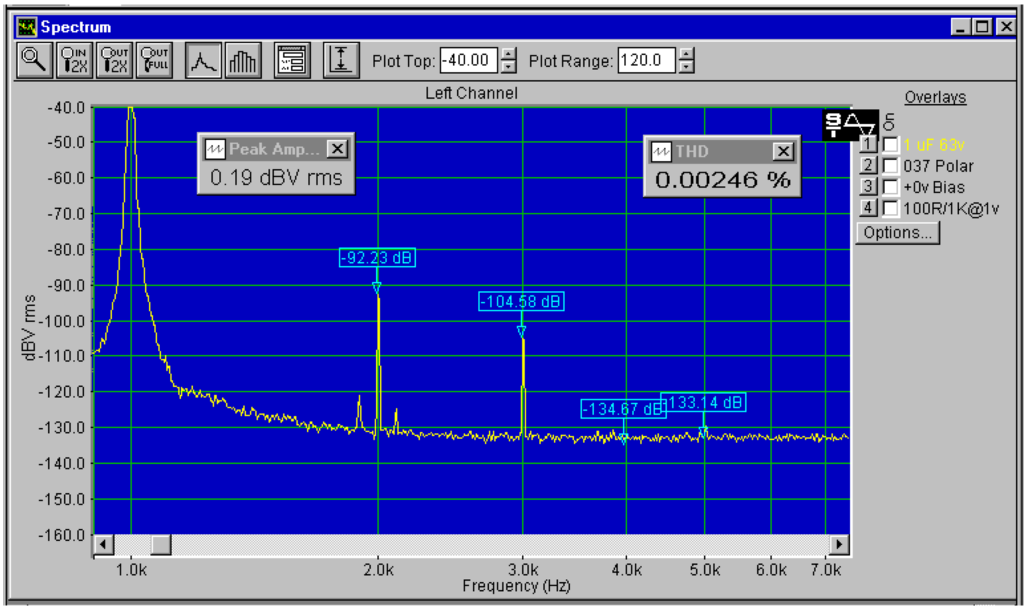
Fig 8) The dB levels in the above plots tend to disguise distortion increase with test voltage.
Translating measured dB values into µV, this plot of distortion versus test signal but with no DC bias voltage, provides a much clearer picture of how non-linearly our unbiased polar capacitor behaves, with increasing AC stress.

With DC bias.
Looking once more at our equivalent circuit we see the anode and cathode foil leakage resistances with the electrolyte, create a DC potential divider chain. Application of a small positive DC bias with no AC signal, raises the electrolyte voltage above the negative terminal.   see **Fig. 3**

However subject to an AC test signal and DC bias, the anode and cathode capacitance values with their respective diodes, modify the electrolyte's potential. Tested with AC only, the electrolyte potential becomes slightly negative with respect to the negative terminal, resulting in an increase of second harmonic distortion. Subject to a small DC bias and an AC signal, the electrolyte potential increases. It can become zero or even slightly positive with respect to the negative terminal, reducing second harmonic distortion.

These changes in electrolyte potential are easily confirmed by simulation using our equivalent circuit.

This positive shift has a beneficial reduction on the AC signal non-linearity produced by the capacitor, measurable as a substantial reduction in second harmonic distortion.

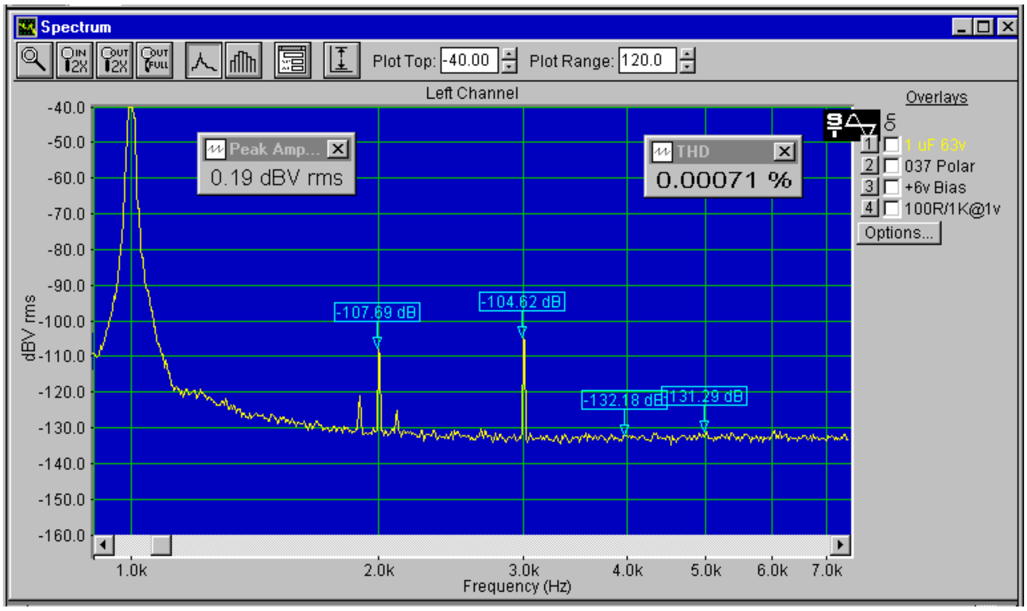

Plot Top: -40.00
Plot Range: 120.0
Peak Amp... 0.19 dBV rms
THD 0.00246 %
1 ☐ 1 uF 63v
2 ☐ 037 Polar
3 ☐ +0v Bias
4 ☐ 100R/1K@1v

Repeated for convenience

Fig 6) With a 1 volt test signal and no bias, the capacitor is producing 22.4 times more distortion than the film reference capacitor. Second and third harmonic components continue to increase out of all proportion to the test signal.

Using the results shown in figure 6 as our base reference, we will use this 1 volt AC test voltage together with various DC bias voltages, to explore the affect DC polarising bias voltage has on distortions produced by polar aluminium electrolytics.

With optimum DC bias, this change in electrolyte potential can result in the second harmonic becoming smaller in amplitude than the third harmonic. Tested at 1 volt with near optimum 6 volt DC bias, distortion was reduced from 22.4 to 6.5 times greater than the reference capacitor.   see **Fig. 9**



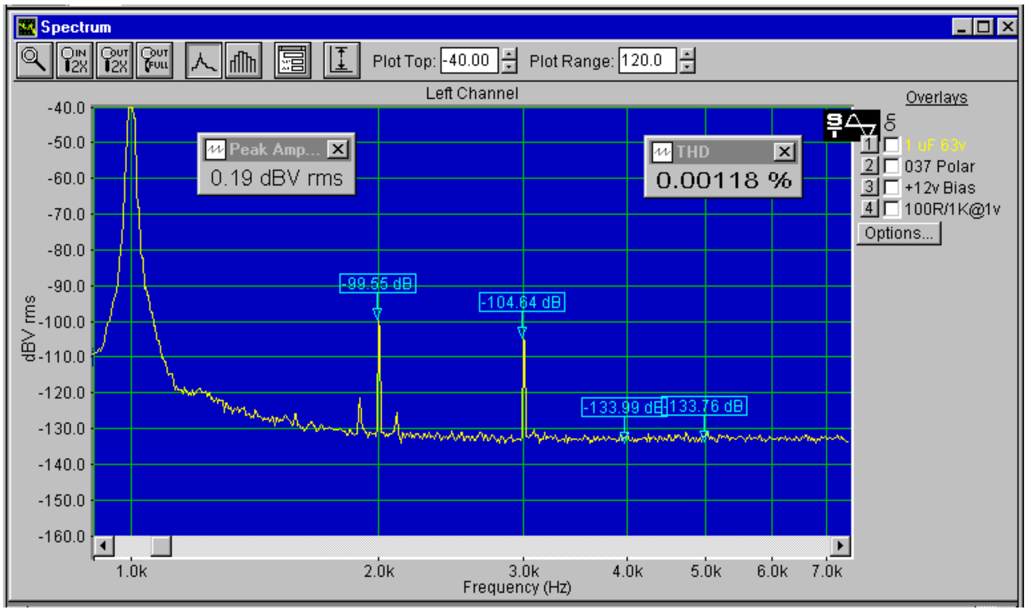
Spectrum

Plot Top: -40.00   Plot Range: 120.0

Peak Amp... 0.19 dBV rms

THD 0.00071 %

Fig 9) Measured as for figure 6, but now using a 6 volt DC bias. This capacitor is biased close to optimum, minimising its second harmonic distortion at this 1 volt AC with 1 kHz / 100 Hz test frequencies. Now just 6.5 times more distortion than found for our reference capacitor. Notice how the third harmonic and the intermodulation products remain constant despite this dramatic reduction in second harmonic level with this DC bias.



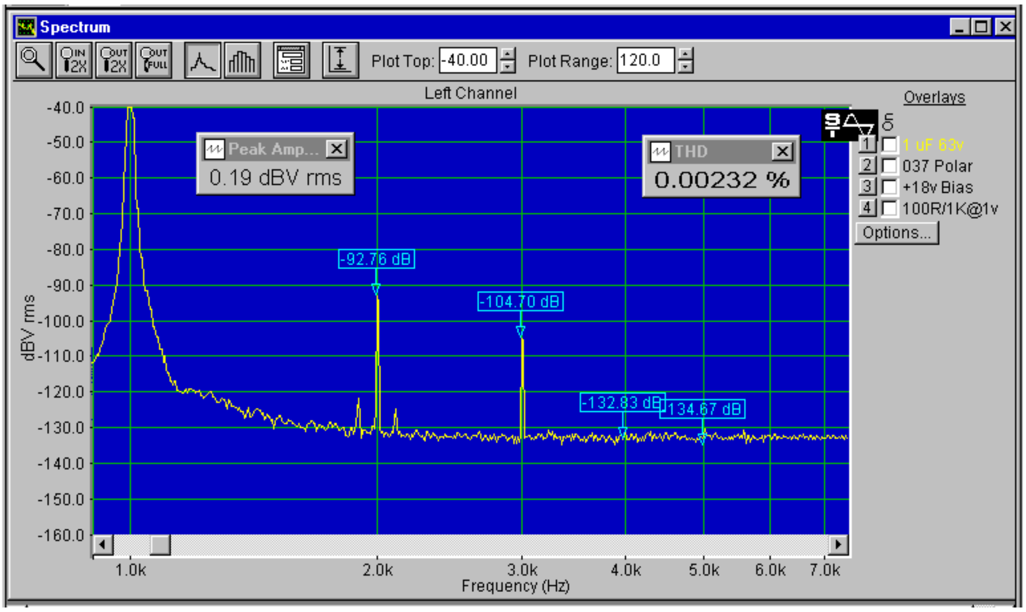
Spectrum

Plot Top: -40.00   Plot Range: 120.0

Peak Amp... 0.19 dBV rms

THD 0.00118 %

Fig 9A) Using the same AC test signals but with DC bias voltage increased to 12 volts, the second harmonic increased by 8 dB to become dominant over the unchanging third harmonic. Intermodulation distortions also remain constant.



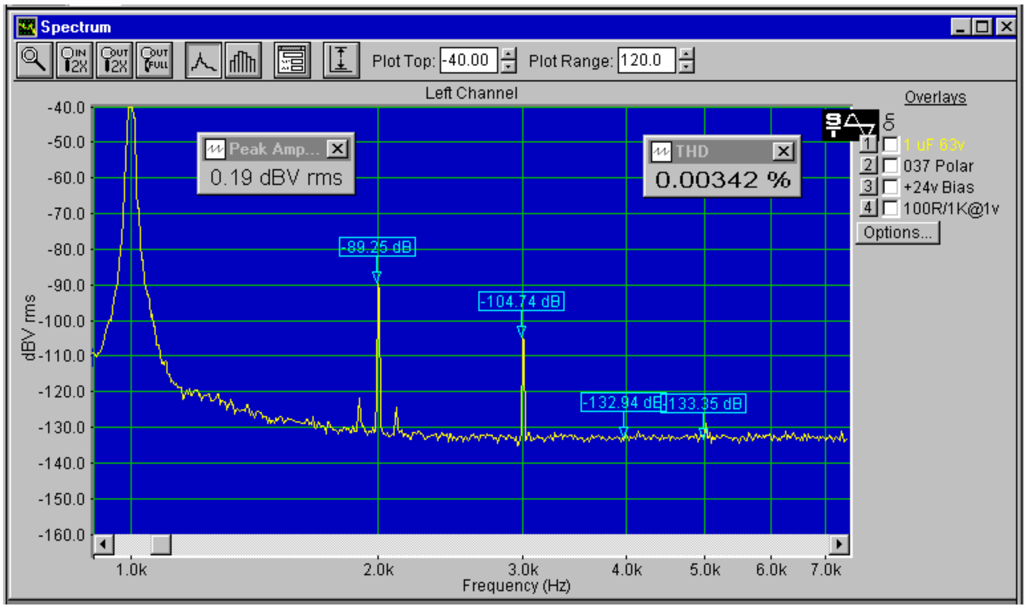
Spectrum

Plot Top: -40.00   Plot Range: 120.0

Peak Amp... 0.19 dBV rms

THD 0.00232 %

Fig 9B) Increasing DC bias to 18 volts and using the same AC test levels second harmonic has increased again by almost 7 dB, doubling the overall measured distortion.
Third harmonic and intermodulation levels remain unchanged.


Spectrum

Plot Top: -40.00

Plot Range: 120.0

Peak Amp... 0.19 dBV rms

THD 0.00342 %

Overlays

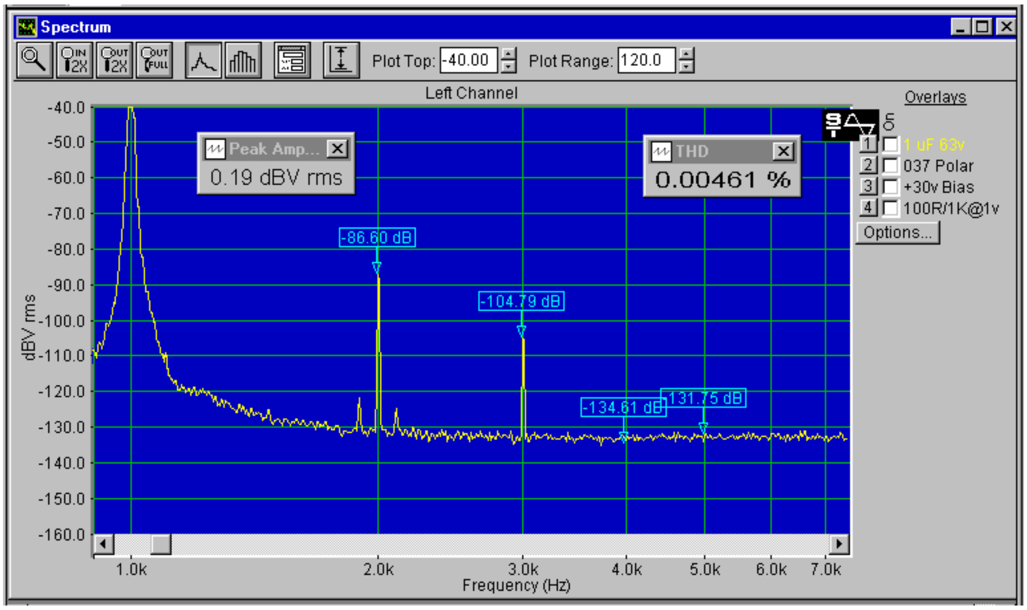
1 ☐ 1 uF 63v

2 ☐ 037 Polar

3 ☐ +24v Bias

4 ☐ 100R/1K@1v

Fig 9C) Increasing DC bias to 24 volts we find second harmonic increasing by 3.5 dB, rather faster than suggested by the 2.5 dB increase in voltage stress.


Spectrum

Plot Top: -40.00

Plot Range: 120.0

Peak Amp... 0.19 dBV rms

THD 0.00461 %

Overlays

1 ☐ 1 uF 63v

2 ☐ 037 Polar

3 ☐ +30v Bias

4 ☐ 100R/1K@1v

Fig 10) Measured as for figure 6 but now with 30 volt DC bias.
The capacitor is polarised to one half its rated voltage, the 'Myth' value. Second harmonic has increased dramatically and distortion doubled compared to no bias figure 6.
Compared with its optimum bias distortion, we find a 16 dB, more than 6 times increase. Intermodulation products and third harmonic have not changed, from no bias to this 30 volt bias.

Myth disproved.
Only when a polar electrolytic capacitor is biased near its optimum voltage does second harmonic reduce, its third harmonic may then dominate. Optimum bias varies with the applied AC signal, capacitor construction and even from capacitor to capacitor within a batch. I found not even one polar aluminium electrolytic capacitor which measured minimum distortion when DC biased anywhere approaching half its rated voltage. Biased to half rated voltage, almost all polar capacitors produced similar or even larger distortions as when measured with AC only and no DC bias.

From my tests, optimum bias for minimum distortion ranged from less than 0.5 volt for a Panasonic 100 µF 50 volt Bi-polar to a maximum of 12 volt for a 10 µF 50 volt Black Gate FK, but this Black Gate is unusual, it uses a low voltage formed anode as cathode so is of semi Bi-polar construction. Optimum bias for most conventional 25 volt polar electrolytics was between 1 volt and 4 volts DC, while for 50 - 63 volt rated capacitors, optimum bias ranged from less than 2 volts to some 7 volts DC.

Second harmonic.
With further increase of DC bias voltage above the optimum level for the capacitor, the effects of dielectric absorption outweigh this improvement. Second harmonic distortion then increases rapidly with increasing bias voltage. I re-measured this electrolytic and my reference capacitor both at 1 volt AC with 30 volt DC bias, the 'mythical' optimum bias for the electrolytic. Distortions for the electrolytic measured almost 42 times greater than for the reference capacitor. see **Fig. 10**

These changes in second harmonic amplitude, tested with and without DC bias, clearly result from the AC and DC voltages applied, dielectric absorption and the dielectric thickness/formation voltage used when making the capacitor.

Some contribution was found due to the voltage coefficients mentioned when measuring with no DC bias, but with DC bias voltage, the dielectric absorption effect is clearly dominant.

Third harmonic.
Non-linear effects, in the tab interconnections, the oxide dielectric and the electrolyte/paper combination, contribute the third harmonic distortion. Third harmonic distortion increases with the applied AC signal. It does not change with DC bias voltage, remaining almost constant from zero to 30 volt DC bias. see **Figs. 6, 9, 10**

With increasing AC signal, when third harmonic distortion exceeds some 0.0003% of the test signal, intermodulation distortions become visible above the measurement noise floor. Any increase in AC signal results in much increased intermodulation and harmonic distortions.

Typically the maximum signal voltage to avoid intermodulation distortion with this 1 µF polar capacitor is around 0.5 to 0.6 volt. However even at these small signal voltages it still produces substantial harmonic distortion. see **Figs. 5 and 6.**

Box **Dielectric Absorption**
In essence two major dielectric characteristics exist - polar and non-polar. By polar I am not referring to an electrolytic capacitor, but the way a dielectric responds to voltage stress. This stress is the voltage gradient across the dielectric, and not simply the applied voltage. It is stress in volts per micron, which matters.

Vacuum and air, are little affected by voltage stress. Solid dielectric which behave in a similar fashion are termed 'non-polar'. Most solid dielectric and insulators are affected to some extent, increasing roughly in line with their dielectric constant or 'k' value. This 'k' value is the increase in capacitance when the dielectric is used to displace air.

When a dielectric is subject to voltage stress, electrons are attracted towards the positive electrode. The electron spin orbits become distorted creating stress and a so-called 'space charge' within the dielectric. This stress produces a heat rise in the dielectric, resulting in dielectric loss.

Non-polar dielectrics exhibit small losses but polar dielectrics are much more lossy. Having been charged to a voltage, it takes longer for the electron spin orbits in a polar dielectric to return to their original uncharged state. Thin polar dielectrics, produce large, easily measured 'dielectric absorption' effects.

Dielectric behaviour with voltage, depends on the voltage gradient, in volts/micron and the characteristics of the dielectric. It's effects are more readily apparent at low voltages with very thin dielectric. The dielectric used in low voltage electrolytics is exceptionally thin. Consequently we find increased effects from dielectric absorption when measuring these types.

Dielectric absorption is usually measured by fully charging the capacitor for several minutes, followed by a rapid discharge into a low value resistor for a few seconds. The capacitor is then left to rest for some time after which any 'recovered' voltage is measured. The ratio of recovered voltage to charge voltage, is called dielectric absorption.

So how might dielectric absorption affect the distortion produced by a capacitor? Many fanciful, even lurid descriptions can be found, describing smearing, time delays and signal compression. My capacitance and distortion measurements do not support these claims.

The main difference I found which clearly does relate to dielectric absorption, is the magnitude of the second harmonic. This increases with applied voltage, especially so with electrolytic capacitors.

My measurements indicate it is the level of third and odd harmonics generated by the capacitor which determine intermodulation products. These harmonics are little affected by DC bias on the capacitor. No doubt intermodulation distortions would contribute to a muddled or smeared background sound.

Third harmonic distortion depends on the peak voltage across the capacitor as well as capacitor through current. For a given signal level, voltage across the capacitor will be greatest at the lowest frequencies. Capacitor current increases as the voltage across the capacitor reduces at higher frequencies. A low frequency, large signal peak, can trigger intermodulation distortions, which affect higher frequencies. end of **Box**

Bi-polar capacitor voltage effects.
This construction provides a balanced assembly of two near identical anode foil capacitances each subject to half the applied AC signal. Having no low quality cathode foil capacitance, it is freed from its non-linear effects so produces negligible distortion when unbiased. However since both anode foils may not be absolutely identical, application of a very small DC bias may further reduce distortions. Distortion at 0.00017% with no bias was ten times smaller than for the single polar electrolytic and just 50% greater than our reference capacitor. see **Fig. 11**

Any significant DC bias voltage does unbalance a Bi-polar capacitor, resulting in increased second harmonic distortion. With 6 volt DC bias, second harmonic distortion increased to -107.5 dB, distortion measured 0.00044%. But this is still little more than half the polar capacitor's distortion measured even when using its optimum DC bias.

Plot Top: -40.00 Plot Range: 120.0

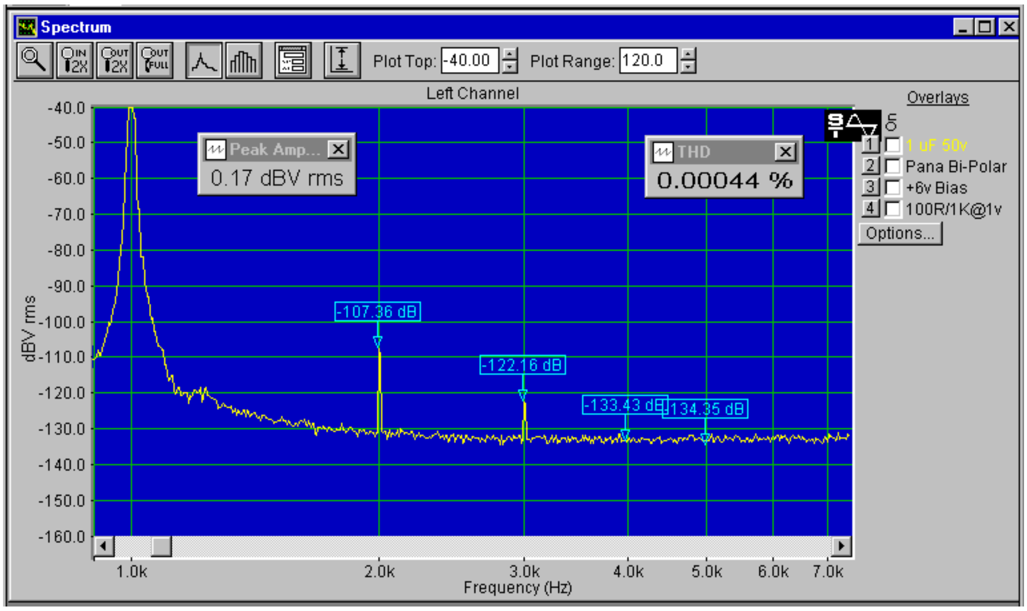
Peak Amp... 0.16 dBV rms

THD 0.00017 %

1 ☐ 1 uF 50v
2 ☐ Pana Bi-Polar
3 ☐ +0v Bias
4 ☐ 100R/1K@1v

Fig 11) The Bi-polar electrolytic of figure 1, measured unbiased with 1 volt AC as for figure 6. The Bi-polar shows minuscule harmonic distortions and freedom from intermodulation products, compared to the polar electrolytic.

Why do designers use polar electrolytic capacitors in the signal path of an amplifier?.



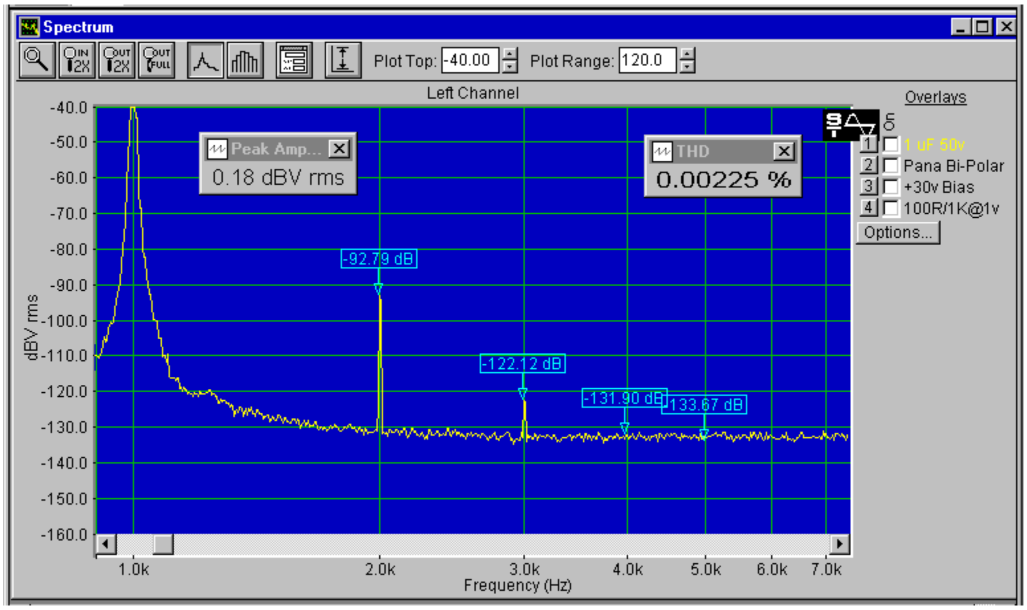
Plot Top: -40.00 Plot Range: 120.0

Peak Amp... 0.17 dBV rms

THD 0.00044 %

1 ☐ 1 uF 50v
2 ☐ Pana Bi-Polar
3 ☐ +6v Bias
4 ☐ 100R/1K@1v

Fig 11A) Re-measured as figure 6 but now using 6 volts DC bias, we find an increase in second harmonic of some 10 dB over its no bias value, but this distortion is only 60% of that measured for the polar capacitor at these voltages..



Plot Top: -40.00 Plot Range: 120.0

Peak Amp... 0.18 dBV rms

THD 0.00225 %

1 ☐ 1 uF 50v
2 ☐ Pana Bi-Polar
3 ☐ +30v Bias
4 ☐ 100R/1K@1v

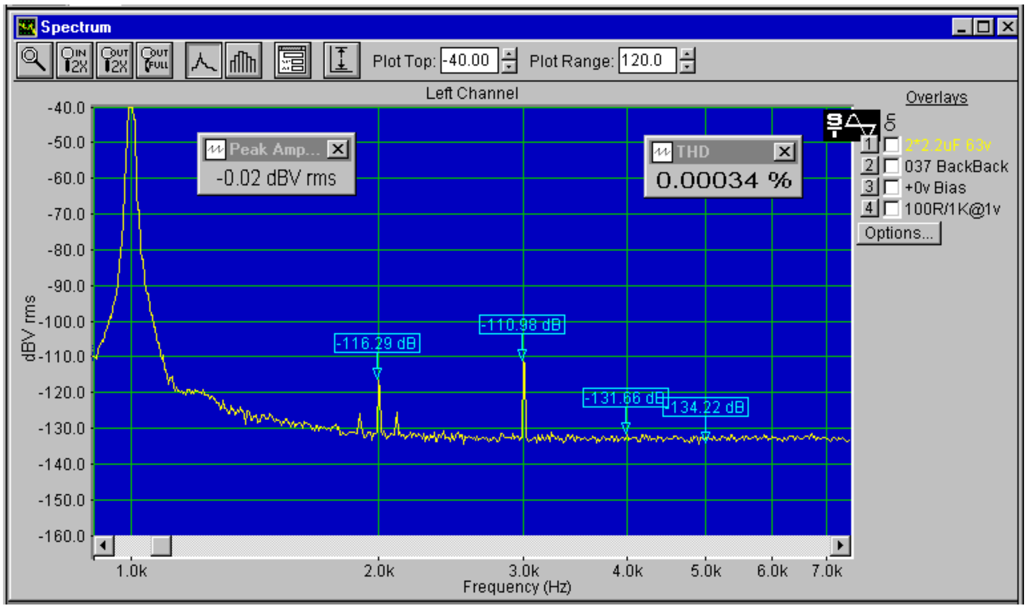
Fig 11B) With 30 volts DC bias this Bi-polar type produces less than half the distortion measured on the polar capacitor.

Perhaps more important we find no visible intermodulation distortions and the undesirable third harmonic level remains almost un-measurable at less than 0.8 ppm or just 0.8 µVolts

Subjected to 30 volt DC bias and a 1 volt test signal, second harmonic increased to -93 dB. Third and higher harmonics are unchanged. Distortion at 0.00225% is less than half that of the 1 µF polar capacitor and remains free from visible intermodulation and shows no measurable increase in third harmonic.

Two Polar capacitors back to back.

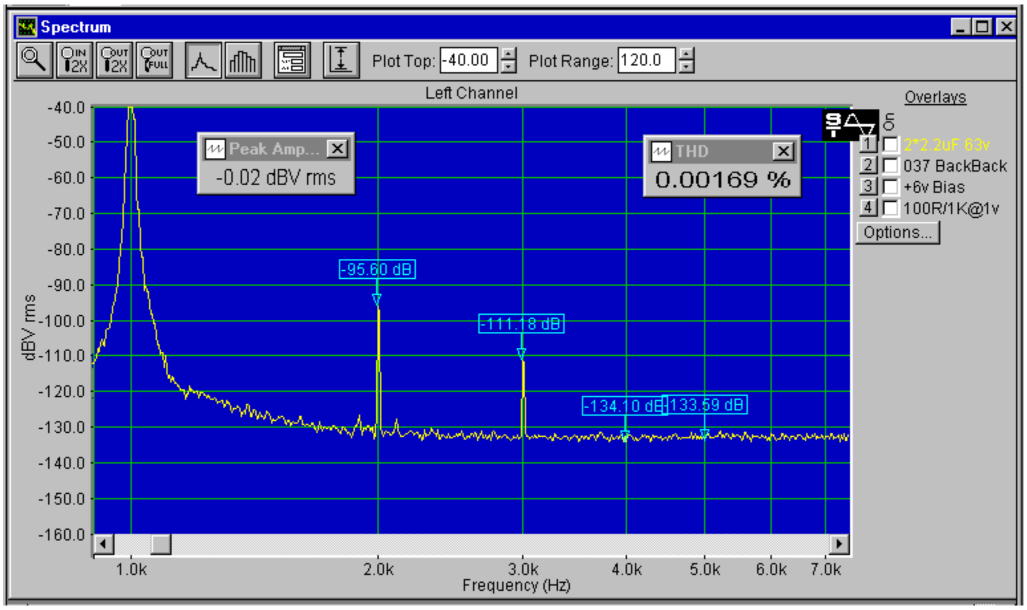
Using two polar capacitors each of 2.2 µF, connected in series and back to back, produces a chain of four capacitors, with a nominal 1 µF capacitance. With no bias voltage, each polar capacitor now sees half the AC voltage. Second harmonic is much reduced and distortion measured 0.00034%. While substantially less than for the polar electrolytic, because we still have distortion producing cathode foil capacitors, distortion is double that measured on the Bi-polar capacitor. see **Fig. 12**


Plot Top: -40.00 Plot Range: 120.0

Peak Amp... -0.02 dBV rms

THD 0.00034 %

Fig 12) Two 2.2 µF 63 volt polar capacitors connected back to back and measured unbiased as figure 6, produce less distortion than the polar capacitor.
However with intermodulation products and double the distortion of the Bi-polar capacitor, why use two polar capacitors, when one Bi-polar (see figure 11) is clearly better?


Plot Top: -40.00 Plot Range: 120.0

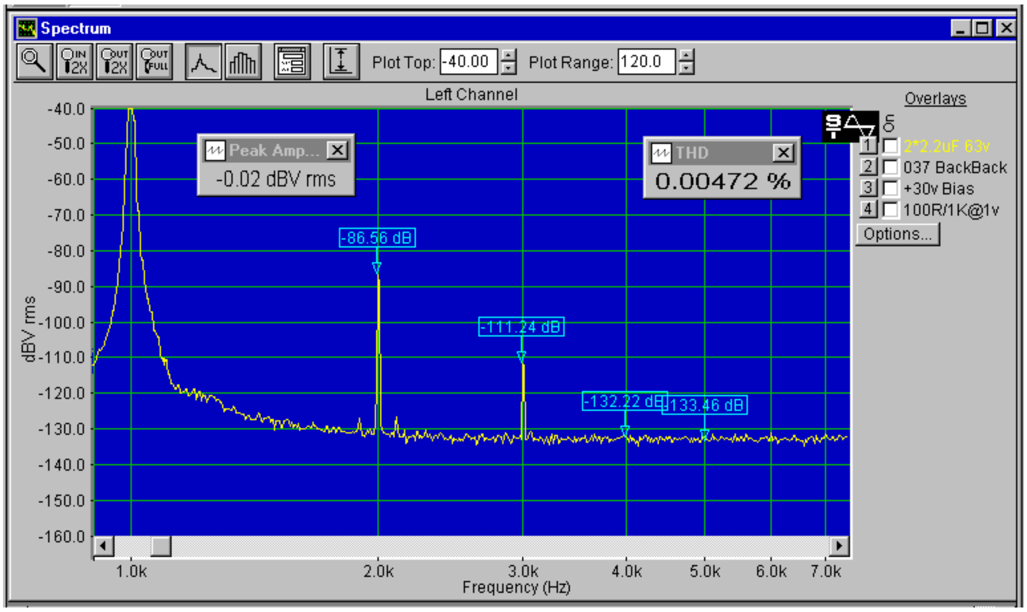
Peak Amp... -0.02 dBV rms

THD 0.00169 %

Fig 12A) Measured exactly as figure 6 but now with 6 volt DC bias, the back to back connection produces more than double the distortion of our single polar capacitor.

The Bi-polar type however is very much better than both.

With 6 volt DC bias it measured just 0.00044% distortion and has no visible intermodulation products.


Plot Top: -40.00 Plot Range: 120.0

Peak Amp... -0.02 dBV rms

THD 0.00472 %

Fig 12B) Measured exactly as figure 6 but with 30 volt DC bias, the back to back connection produces slightly more distortion than did our single polar capacitor.

The Bi-polar type is much better than both. With 30 volt DC bias it measured just 0.00225% distortion and shows no visible intermodulation products

Conclusions.
With 6 volt DC bias, distortion of our 1 µF polar capacitor reduced to 0.00071%, but more than 60% greater distortion than measured on the Bi-polar. **see Fig. 9A**

With 6 volt DC bias, second harmonic distortion of the back to back pair increased 20 dB becoming dominant and distortion increased fivefold to 0.00169%. see **Fig. 12A**

At 1 volt AC, regardless of bias voltage, the single polar capacitor and the back to back pair both produced visible intermodulation.

With 30 volt DC bias, second harmonic distortion for both the single polar capacitor and the back to back pair measured -86 dB. Both styles produced intermodulation and similar harmonic distortions, measuring 0.00461% and 0.00472% respectively. More than double that found with the Bi-polar. see **Fig. 10/12B**

In every distortion test, the Bi-polar capacitor produced much lower distortions than were measured on similar value and voltage polar capacitors.

Having proved that Myths a) b) c) and d) are clearly quite wrong, my next article will address the remaining three.

Metallised film/electrolytic comparisons.
To measure distortions produced by the best film capacitors in my earlier articles, I needed to use a 4 volt AC test signal. I then found several ‘bad’ capacitors measuring higher than normal distortion.

This 4 volt test signal is much too large when testing electrolytic capacitors. Measured using 12 volt DC bias and a 2 volt test signal, all polar electrolytics produced very high levels of distortion.

Reducing our test signal to 1 volt RMS to permit tests with and without DC bias voltage. Which capacitor produces less distortion. A good electrolytic or a poor metallised PET capacitor ?

Regardless of bias, all polar electrolytic capacitors I measured at 1 volt generated significant levels of intermodulation distortion.

The 1 µF Bi-polar types were intermodulation free at 1 volt with no bias and up to 30 volt DC bias.

Measuring a ‘known’ good 1 µF metallised PET at 1 volt with no bias and to 30 volt DC bias, I found no visible intermodulation distortions. With 30 volt DC bias, second harmonic distortion was -100 dB, distortion was 0.00089%.

The 1 µF Bi-polar electrolytic, tested at 1 volt and with up to 12 volt DC bias, measured almost identical distortions, which increased as bias increased. With 30 volt DC bias, second harmonic was -93 dB and distortion measured 0.00225%, some 2.5 times worse than the PET.

From these 1 volt tests the best 1 µF electrolytic, the Bi-polar type, was clearly beaten by the good metallised PET.

Much better film capacitors were listed in my last article but at 1 µF, a metallised PET capacitor provides the economic choice. For the lowest possible distortion, especially with increased signal drive or DC bias, the better quality film capacitor styles shown in figure 1 and recommended in my last article, should be used.

My final article explores our best choice for larger capacitance values and introduces my low distortion 100 Hz test equipment.

END.

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