Capacitor Misunderstandings.

Cyril Bateman investigates common capacitor fallacies.

If the perfect capacitor existed, then many common capacitor misunderstandings would never occur, unfortunately the perfect capacitor simply can never exist, outside our tutor's lectures or in simulations which use only the basic SPice supplied models.

Many years ago when tasked to investigate serious capacitor failings which had resulted in many fires, I was reminded of the opening phrase used by my lecturer to introduce his capacitor lectures. "Capacitors don't take power", he explained that a perfect capacitor, having 90° phase difference between the applied voltage waveform and the capacitor through current, was able to create a voltage drop without dissipating any power. However "don't take power " could also mean that capacitors are unable to sustain any significant power dissipation, which sadly is only too true.

Every practical capacitor exhibits a not quite 90° phase angle, the result of two loss mechanisms. Caused by inevitable resistance R in it's connecting leadwires and metal electrodes together with fundamental dielectric losses tanδ. While these metallic loss resistances remain reasonably constant with frequency, the dielectric losses are strongly frequency dependant. Both loss mechanisms combine to degrade this nominal 90° to a lesser angle. With increasing frequency, the capacitor's self inductance, XL in the figure, acts to reduce the measured impedance as shown by the XC - XL vector. At some higher frequency when XL = XC the capacitor becomes series resonant. With further increase of frequency, our capacitor becomes an inductive impedance which increases with frequency. For example, the Elna 47,000μF 63v electrolytic, popular in amplifier power supplies, measured inductive as 23.7nH, +7.58° at 10kHz so was clearly inductive at audible frequencies even below 10kHz and 83.7nH, +78° at 100kHz.

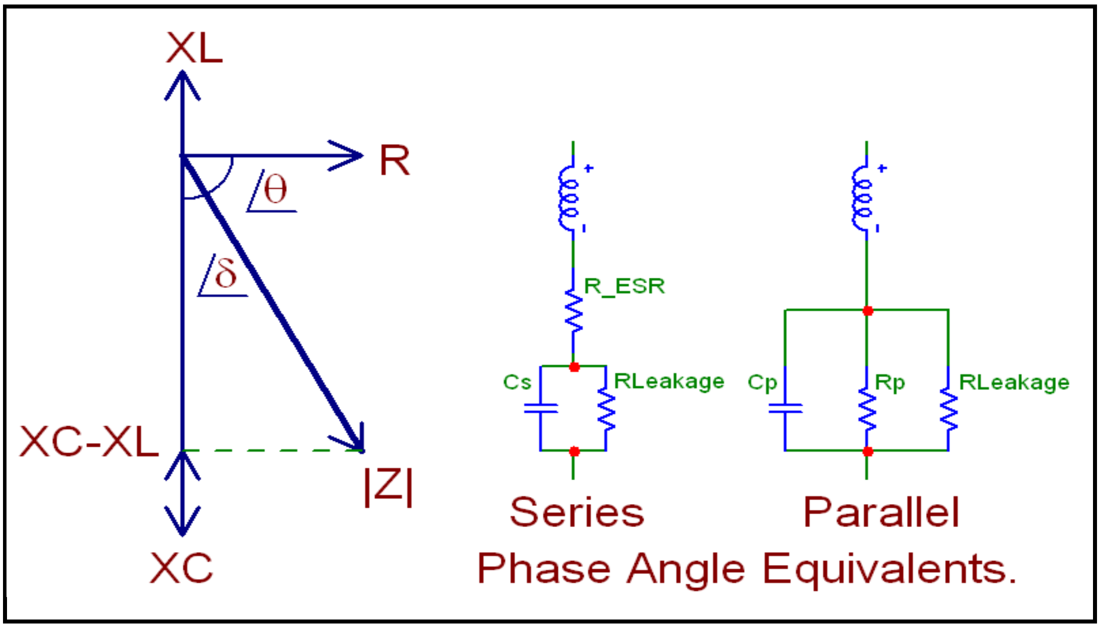


Figure 1. Many bridges default to the series equivalent measurement, but exactly the same tanδ loss angle can be translated or measured using the parallel loss components, as shown by the equivalent phase angle equations.

Even the most perfect capacitor dielectric insulator, having near constant losses with frequency, results in an ESR, shown as R_ESR in the figure, which must halve for each doubling of frequency. In practise this ideal halving is never possible because of the inevitable resistances which must be incurred in the capacitor end connections, metallic electrodes and any leadwires used. These effects are seen in these measured values of a very high quality Philips, near perfect, 1%, foil and polystyrene capacitor, which I measured at 1v AC, using a Wayne Kerr 6425 four terminal, digital, precision component analyser.

Frequency.	Capacitance, nF.	Tanδ	Phase ∠	Q	ESR Ohms.	Rp
1 kHz	9.9988	0.00005	89.997°	20,000	0.80	316.704MΩ
10 kHz	9.9986	0.00015	89.991°	6,500	0.26	9.745MΩ
100 kHz	10.0000	0.0005	89.971°	2,000	0.05	506.605kΩ

Subjected to an AC voltage or current, with or without any bias voltage, this ESR equivalent resistance dissipates power and the capacitor self heats above the local ambient temperature. A typical equipment local ambient temperature, may be say 50°C. The maximum permissible capacitor internal hotspot temperature for polystyrene dielectric should be less than 70°C at which temperature the capacitor might survive perhaps 2-3000 operating hours. In equipment terms that is unacceptably short so either this local ambient temperature or the capacitor self heating must be reduced.

Aluminium electrolytic capacitors housed in aluminium cases are supplied with a plastic oversleeve, which serves two purposes, it is easily printed with capacitance and voltage etc., but more important this sleeve actually dissipates heat more rapidly than does the bare aluminium can, so must never be removed. When I first worked designing electrolytics, like many people I queried this fact, so performed several practical test measurements of capacitors specially assembled with thermocouples to measure internal temperatures. Subjected to 50Hz test current, I measured the internal hot spot temperature of each capacitor after 3 hours, initially complete with its plastic sleeving then having removed this sleeve, retested each capacitor. In every case the sleeved version was several degrees cooler. Researching my reference books I found the answer, the low temperature infra-red radiation from the semi-polished aluminium cans was significantly lower than that from the near mat surfaced thin plastic sleeving.

Capacitor distortions.
My original series titled “Capacitor Sounds” published in the Electronics World magazine, now available for download from my web page, demonstrated the different levels of distortion produced by differing capacitor dielectrics and capacitor assembly methods, both with and without DC bias voltages. I first became aware of this from two quite different sources. I was then technically responsible for capacitor applications, at that time the company produced more than fifty quite different ceramic capacitor formulations, from N1500 through C0G up to K10,000, all having differing characteristics. One of my more interesting customers was Acoustical Engineering, who carefully researched how differing capacitors affected the sound from their pre-amplifier. As a result Quad decided to not use any ceramic capacitor with a “K” value higher than our K120051 material, a fairly low “K” material, which from their tests audibly degraded this pre-amp compared to lower “K” materials.

The second case was when one of our sales managers sold the then new X7R multilayer ceramic capacitors, for use in the trigger circuit of a triac lamp dimmer, because that maker wanted to size reduce his assembly. Some months later many thousands of these dimmers were returned under warranty for making an intrusive buzz, clearly audible in a quiet lounge. This noise was generated by the X7R multilayer capacitor body itself vibrating. This was long before invention of the ceramic tweeter speaker. Hence we have two ways a capacitor can affect our listening. Later when tasked to design new ranges of audio optimised aluminium electrolytic capacitors, I found these capacitors also generated clearly audible sounds, when stressed.

But why should even the very best capacitor assemblies generate measurable distortion ?
Capacitor dielectrics resolve into two main categories, polar and non-polar. I’m not talking here about the different aluminium electrolytic capacitor constructions, but characteristics of the actual base dielectric materials, especially for the various plastic film capacitors we use. This difference depends on the symmetry or otherwise of the dielectric’s basic molecular structure.

An insulator having a symmetrical molecular structure is defined as being “non-polar” and is characterised as having electrical characteristics effectively constant with frequency, minimal sound distortion and negligible dielectric absorption effects. Such dielectrics also have small dielectric constants, or “K” values, e.g. C0G/NP0 ceramic also Polystyrene, PTFE and Polysulphone films.

When the molecular structure is asymmetrical, it has a dipole moment which results in a much higher dielectric constant “K” value, it is called a polar dielectric, e.g. high K value ceramics such as BX, X7R, U2J, W5R, X5V and the notorious Z5U also Aluminium, Tantalum electrolytics, PET and Polycarbonate plastic films. Polar dielectrics are characterised by electrical parameters which change notably with increasing frequency and exhibit significant dielectric absorption. Capacitance values reduce and dielectric losses increase, with increase in frequency.

These polar and non-polar terms are a function of the basic materials used and should not be confused with the constructional terms polar and non-polar or bi-polar, as used for electrolytic capacitors.

For many designers, the non-polar PTFE dielectric, especially at high temperature and high frequencies provides the best plastic film dielectric performance possible but it is expensive and difficult to assemble so such capacitors are less readily available, especially in Europe.

At normal temperatures its performance is closely matched by the very low cost Polystyrene capacitors, for many years the material of choice for “Standard”, close tolerance, laboratory capacitors. Today the inexpensive polysulphone and polypropylene capacitors provide excellent, very low distortion, extremely stable and low cost alternatives. Both films are among the very best of the non-polar film dielectrics.

With the near disappearance of the polystyrene capacitor, many standard laboratories now use NP0, C0G ceramic capacitors, one of the very best non-polar, non-distorting, stable, dielectrics of all, as low cost transferable standards, paralleling multiple capacitors as needed to attain larger values. In recent years, makers have introduced values of 10µF and above as direct factory orders, but these are not usually distributor stocked items. Long term stability of C0G/NP0 ceramic is described as not measurable, being more stable long term than even the best commercial digital LCR meters are able to measure.

Polar dielectrics include ceramic capacitors with the “K” label, e.g. K120051 and higher dielectric constants, especially BX, X7R, U2J, W5R, X5V and the notorious Z5U. As to common plastic film types, polycarbonate and notably PET are both strongly polar dielectrics. However both films share the ability to be extruded or stretched to produce exceptionally thin plastic films, having sufficient strength to allow manufacture of low voltage capacitors having exceptionally small dimensions for their capacitance value. However their basic polar nature ensures increased distortions, especially for second harmonic when DC biased and parameter changes both with frequency and temperature.

DC bias voltage effect.

Measured using AC stress only, a few, unusually well manufactured polar dielectric capacitors are able to produce little distortion, almost comparable with the best non-polar types. However when stressed with a D C bias voltage, the asymmetric polar dielectric molecular structure rotation becomes notably extended, resulting in the much increased second harmonic distortion being measured. However usually intermodulation distortion and third harmonic levels are little changed. Measuring the very best PET dielectric 100nF capacitor, of the very large numbers of PET capacitors I tested, using 4v at 1kHz I found its second harmonic distortion increased six fold when biased with 18v DC, total distortion now measured 0.00027%, more than four times greater distortion than measured with a good non-polar capacitor. Most other PET capacitors tested measured at least ten times greater distortion.

Measuring a non-polar dielectric capacitor with or without DC bias voltage, second harmonic distortion levels remain almost unchanged and immeasurable, because bias voltage does not affect its symmetric molecular structure’s rotation. Using the above test levels, the 100nF C0G ceramic second harmonic distortion was less than -125dB and its total distortion measured just 0.00006%.

For capacitor values larger than a few microfarads, to reduce cost and space we are forced to use either Aluminium or Tantalum electrolytic types. These are available both as the traditional “polarised” style and non-polarised or “Bi-polar” types. The “Bi-polar”, non-polarised construction uses two anode assemblies connected electrically “back-to-back”, while physically larger they produce significantly less distortion, both with and without DC bias voltage, than any of the traditional “polar” types.

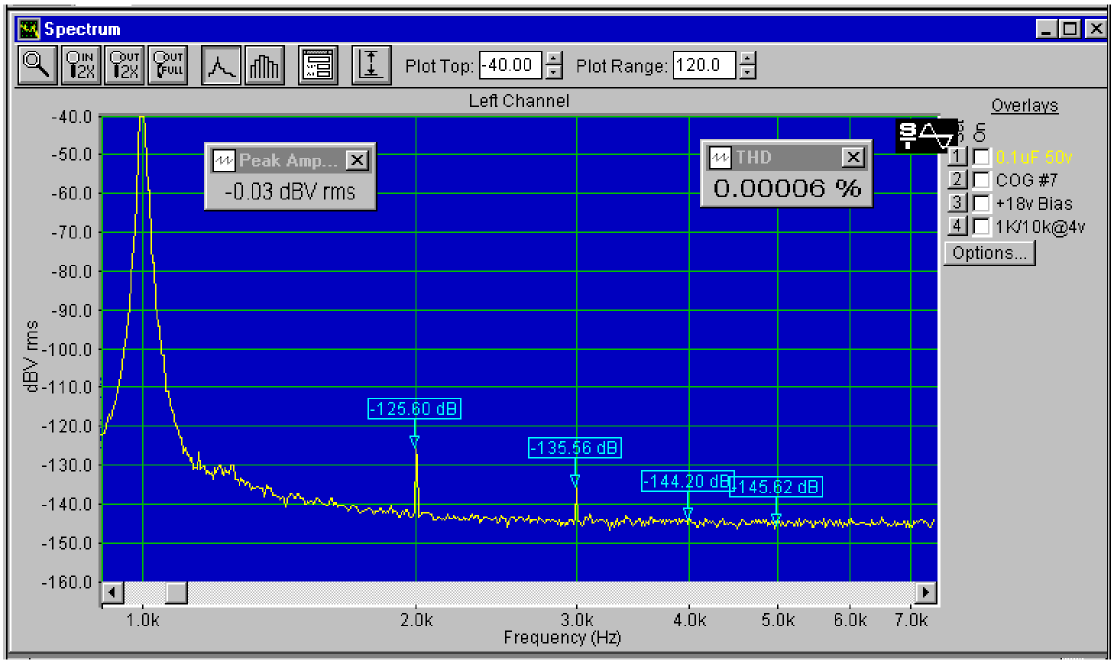


Figure.2. Tested with 4v at 1kHz and 100Hz, with 18v DC bias, this figure demonstrates the very low distortions possible using a C0G ceramic capacitor. This 50v rated 1% 100nF C0G multilayer was just 0.00004%, with 0v bias.

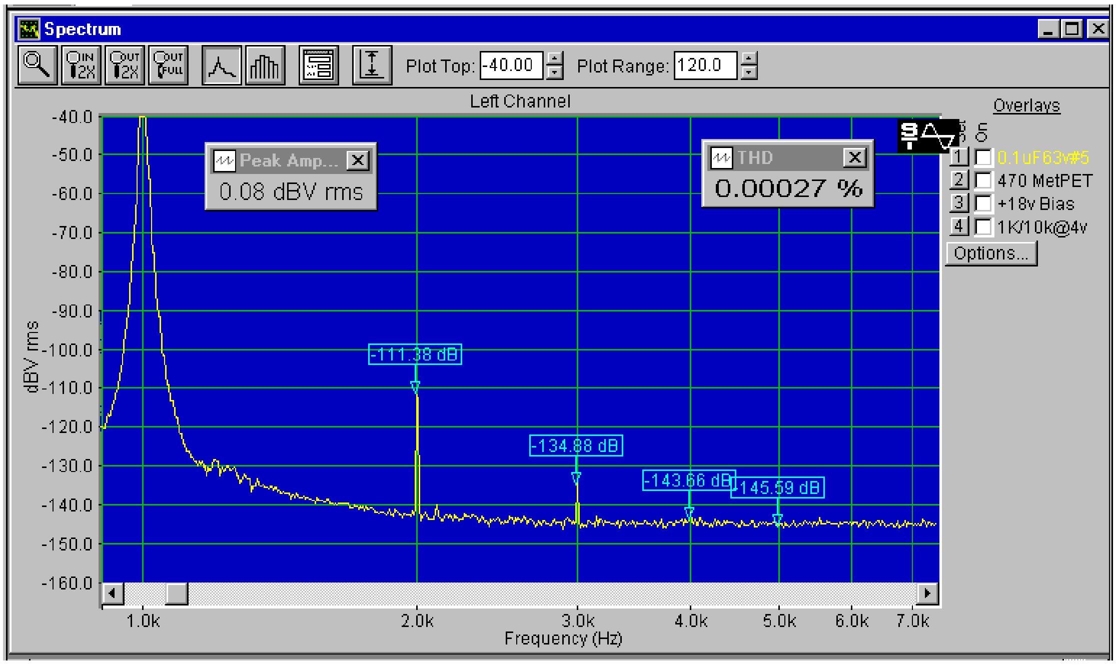


Figure. 3. Tested also with 1kHz and 100Hz and 18v DC bias, exactly as figure 2, above, this was the best sample of the many metallised PET capacitors I tested. Notice the much increased second harmonic.

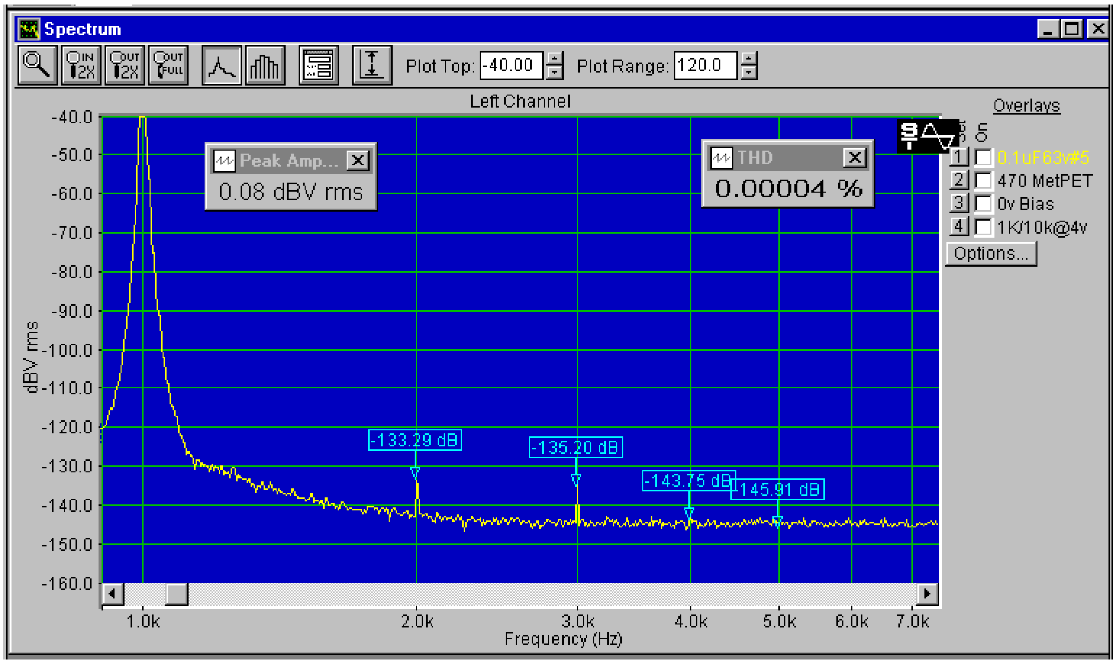


Figure. 4. The figure 3 capacitor but now tested with 0v DC bias, exhibits exceptionally low distortion, but as seen in figure 3, using a polar, PET metallised dielectric, any DC bias voltage causes second harmonic distortion.

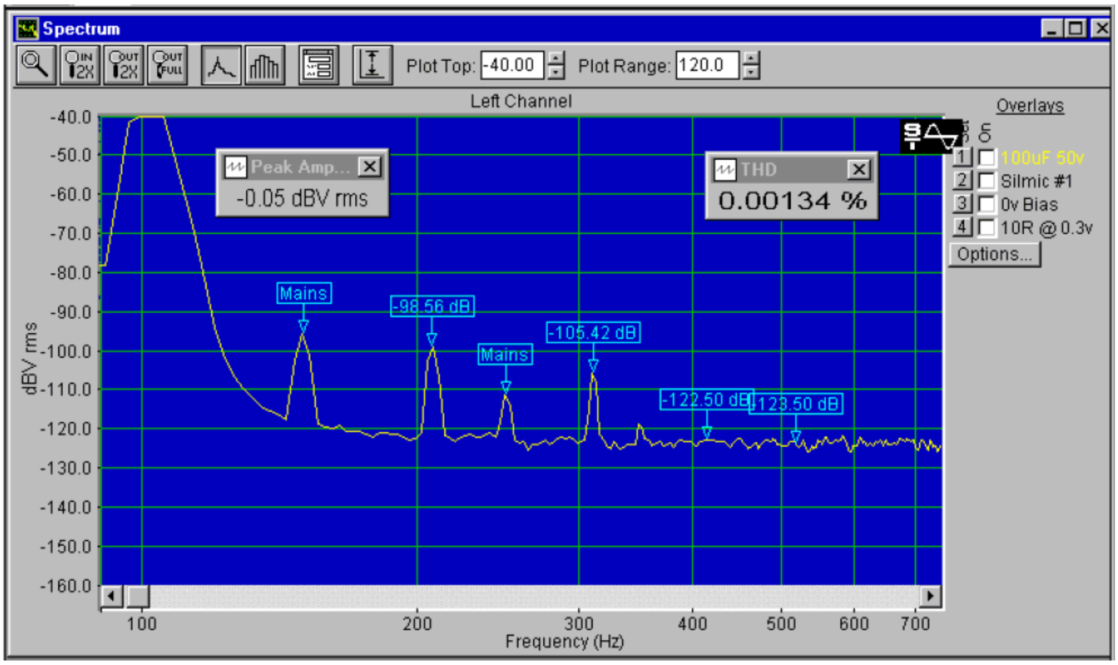


Figure.5. 100µF electrolytic capacitor is often used to DC decouple the negative feedback loop, but that can directly feed any distortion produced by this capacitor into the output. This capacitor was one of the best I tested at 0.3v AC.

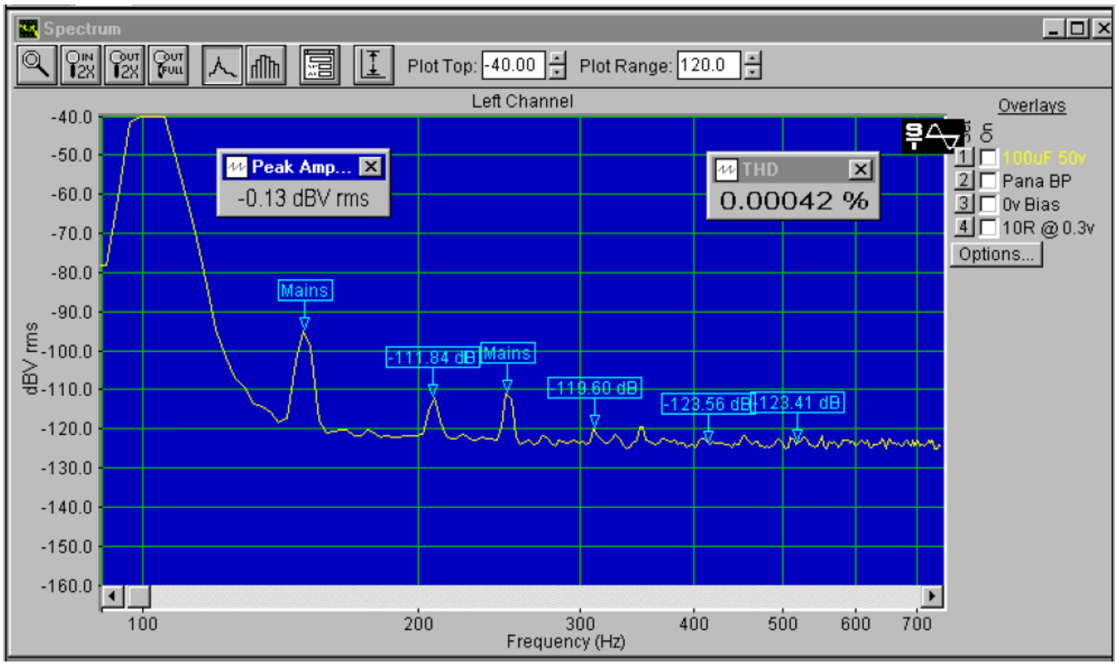


Figure.6. Replacing a conventional Polar Aluminium Electrolytic by a Non-polar (Bi-polar) type requires little extra board space or cost but reduces this distortion input by more than 300%.

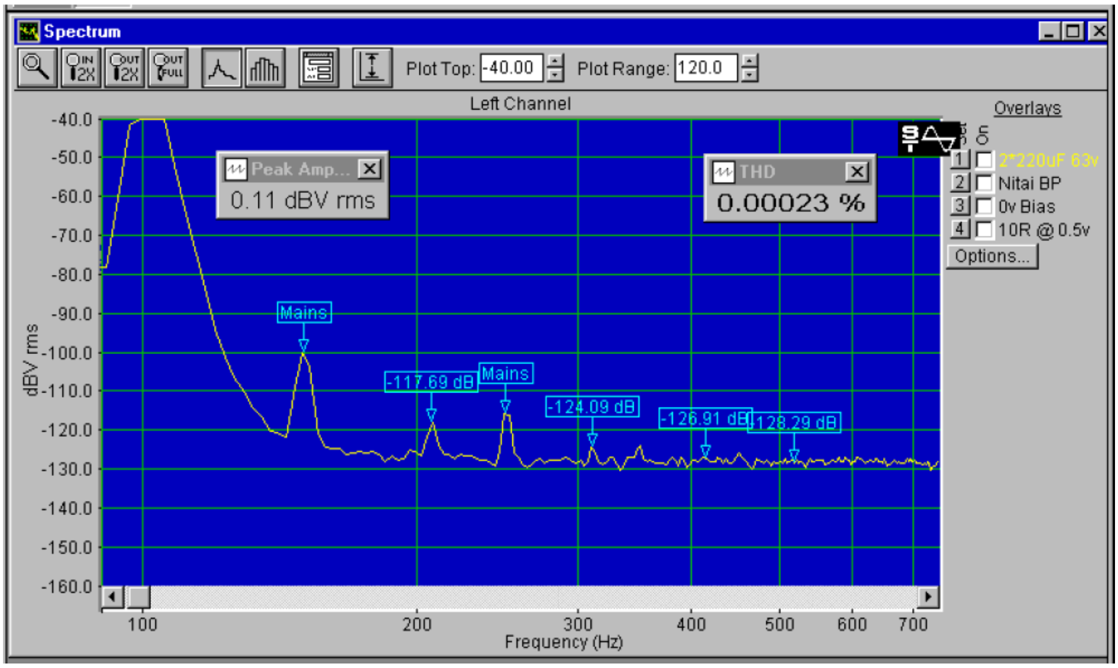


Figure.7. Perhaps you need low distortion but with voltages greater than the 0.3vac used for figs,5,6. By connecting two Non-polar types in series, distortion similar to that from metallised film capacitors can be assured.

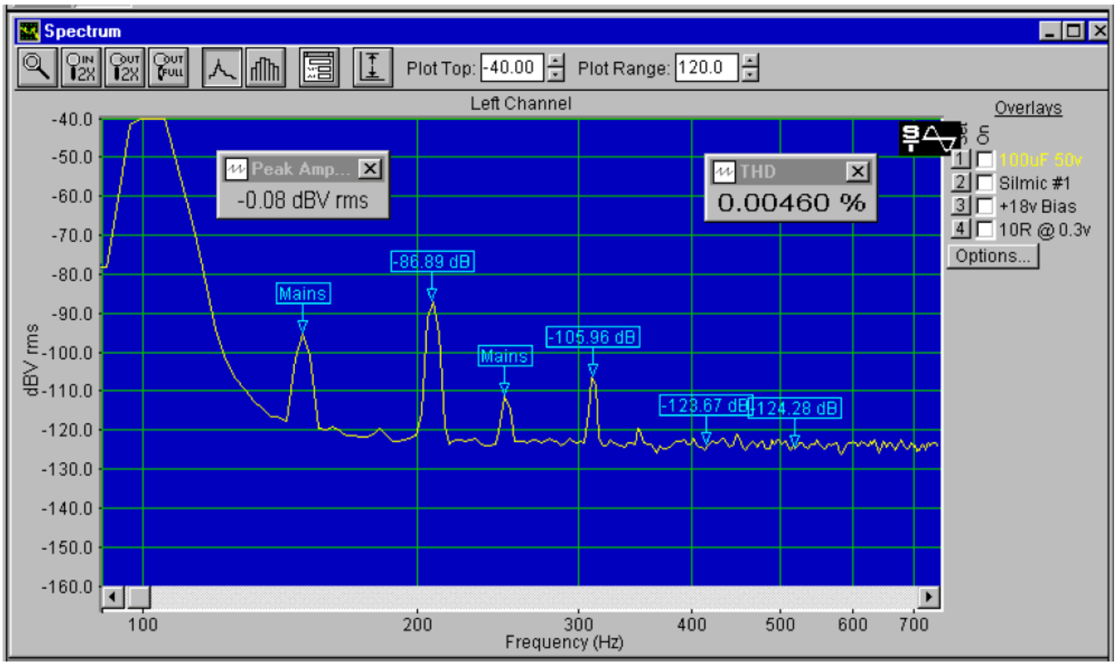


Figure.8. Any application of DC bias (polarisation) voltage to all aluminium electrolytic capacitors results in significant distortion, even with small AC voltages, 0.3v as used here. Distortions increase with AC and DC.

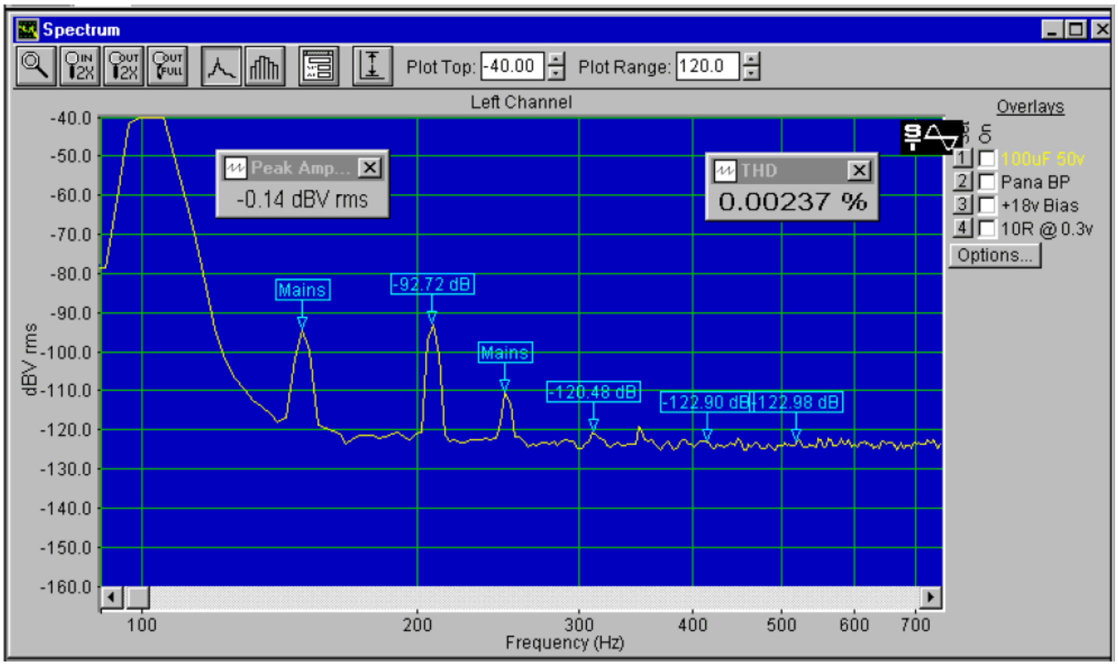


Figure.9. Using a Bi-polar Aluminium Electrolytic to replace even the best possible conventional Polar type, easily results in halving of distortions, and can be much less expensive. Both above capacitors are 100µF 50v parts.

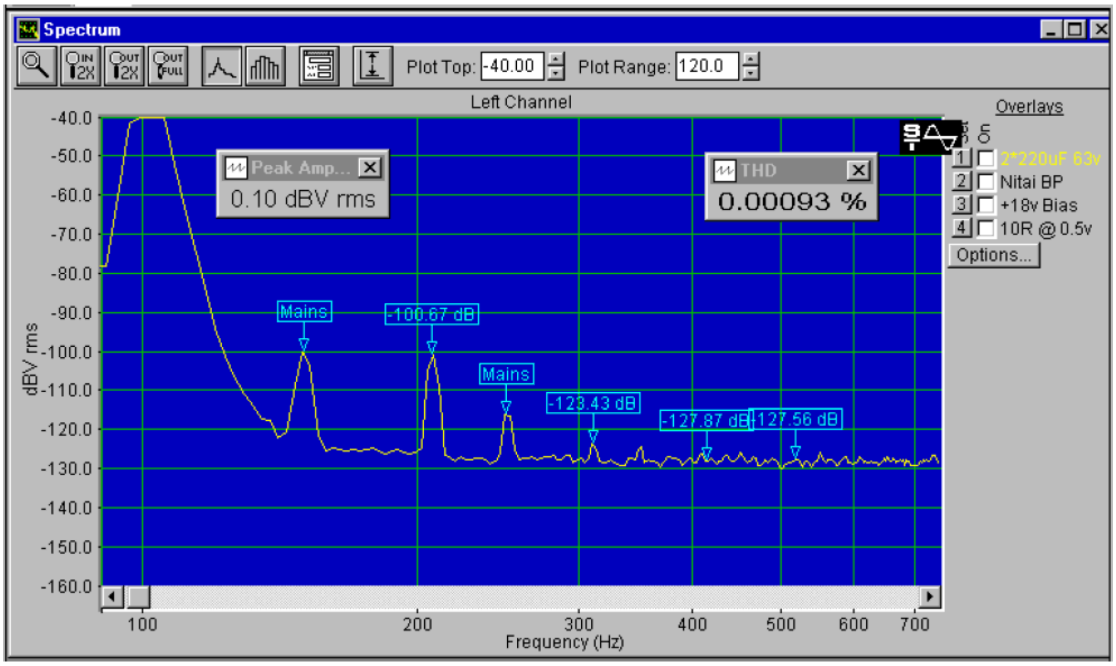


Figure.10. Using two Non-polar capacitors in series again dramatically further reduces distortions and allows use with increased levels of bias voltage and 0.5v AC signal voltages, providing acceptably low distortions even with 1v AC signal levels.

AC working versus DC rated capacitor applications.
Many years ago when impregnated metallised paper capacitors were the standard workhorse, it was considered that a capacitor rated for 400 v DC or above, could be used on 250 v AC mains. Since these capacitors were impregnated, depending on the impregnant used, this was just about feasible. Unfortunately this old saw tends to continue even today.

When the then new low cost, un-impregnated metallised PET capacitors became commonly available some forty years ago, the more expensive impregnated metallised paper capacitors were largely superseded. The best AC capable impregnant, based on chlorinated bi-phenols (PCB), was outlawed and to fill this gap the 400 v DC un-impregnated, usually flattened, metallised PET capacitors parts became adopted for many of these 250 v AC mains requirements. A great many of these capacitors dramatically failed. If you were lucky the end terminations eroded, effectively disconnecting the capacitor, but if unlucky the capacitor caught fire, as happened in a notable Bond Street, London, shopwindow.

Even today I have vivid recollections of this unhappy time when my task was to withdraw from all such 250 v AC mains applications and de-rate these capacitors to 160 v AC, on behalf of my employer, for this particular flat metallised PET capacitor construction.

Why should this problem arise ?
Given an impregnated or otherwise solid, void free, capacitor construction, 250 v AC and above, causes no insuperable problems. However un-impregnated capacitors inevitably contain many minute pockets of air, trapped inside the windings. The lower "K" value of the air dielectric void is then subjected to increased voltage stress, so may become liable to internal ionisation leading to "partial discharges" which can release nascent hydrogen, which then quickly degrades the plastic film dielectric.

According to Paschens curve of ionisation, an air filled void having optimum size and air pressure, with aluminium electrodes, can exhibit ionisation inception at voltages as low as 185 v AC. Hence my adoption of 160 v AC, to ensure some small safety margin for voltage spikes.

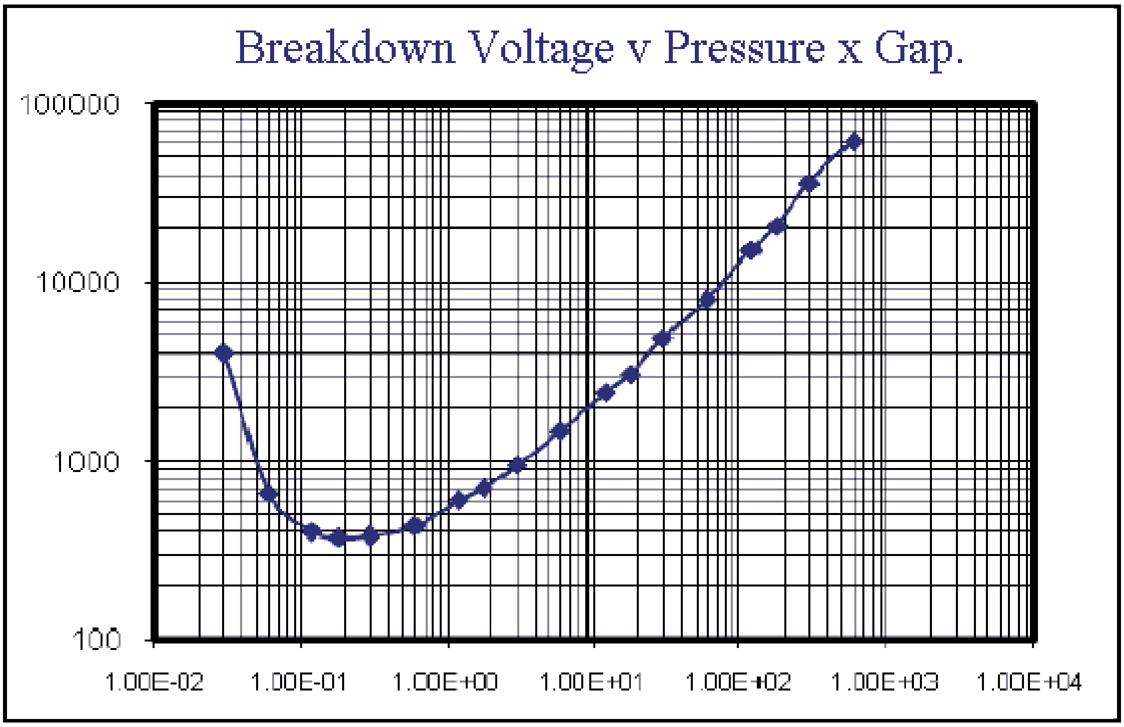


Figure. 11. In 1889, Friedrich Paschen investigated discharge inception voltage by air pressure, using two parallel 3/8" spaced electrodes.

Subsequent work found these voltages varied up/down with different gases and metal electrodes.

This ionisation discharge current once triggered, is self sustaining at lower voltages, almost down to zero volts. Thus once triggered, the resulting discharge continues for almost 50% of the alternating waveform. This ionisation discharge is damaging to almost all dielectric materials, resulting ultimately in a short circuited capacitor. Aluminium electrodes inception commences at much lower voltages than above.

From these unhappy experiences, International and National safety rules for class X capacitors, used across the 250 v AC domestic mains, together with a re-evaluation of the levels of mains born spikes which must be withstood, were developed. Two main capacitor class X styles then emerged, a much updated resin impregnated metallised paper capacitor from Sweden and the two-in-series metallised Polypropylene style originated by Erie Electronics UK in 1970, the world's first, approved, 250 v AC mains rated metallised capacitor. This two-in-series construction, wound using the "lost core" technique, worked well since with two capacitor elements in series, each shared around half of the applied voltage and the lost core winding technique maintained a tight, well controlled, element winding.

These ionising discharges damage capacitors by two methods. The insulating property of the dielectric becomes reduced and any metallised electrodes slowly disappear. In most cases the capacitor is totally destroyed, but I was fortunate to retrieve some development two-in-series motorstart/run capacitors which had been on AC endurance trials, by a world renowned washing machine maker based at Halifax in UK. Having been stressed for many hundreds of hours, these capacitors had been badly damaged, now have less than 50% of their initial value, but were not totally destroyed.

When I opened their hermetically sealed cases, the characteristic smell of polypropylene dielectric which had been ionised was un-mistakable. When unwound, the metallised electrodes were "moth eaten" with more than 50% of their original electrode area missing, it had simply been burnt away.

One final comment about the latest, sub-miniature electrolytics.
With any normal aluminium electrolytic capacitor, its small leakage current ensures the capacitor becomes discharged unless deliberately powered.

With small, low voltage electrolytics, the aluminium oxide which forms naturally on the cathode foil when exposed to air, acts as a second capacitor in series with that of the anode foil, reducing the net capacitance, increasing costs and physical size. Recent work by some foil suppliers coating the cathode foil with a thin coating of another metal which does not form an insulating oxide, has reduced this effect, thus reducing both cost and size of some low voltage, miniature, polar capacitors.

Provided the capacitor is used in a reasonably low impedance circuit, all seems well, however used in high impedance circuits these capacitors can exhibit a "battery" effect, generating a small DC voltage which depending on the metals used, can approach 1 volt. Test capacitors loaded with a 10MΩ resistance have been observed generating a steady DC voltage over a twenty four hour period. Loaded with an additional 4M7Ω this voltage reduced but again recovered when this second resistor was removed to leave the original 10MΩ.

In many, perhaps most circuits, this may not matter, but when used to de-couple the negative feedback arm in a conventional power amplifier, these capacitors have created problems. My suggested remedy is to use a non-polarised, Bi-polar electrolytic capacitor for this position, which has the added bonus of reduced distortions.

Capacitor Sounds 1 - Low Distortion (sub 1PPM) 1 kHz Test Oscillator.

Updated & expanded March 2003

Original version Pub. Electronics World July 2002 - C. Bateman.
Many capacitors introduce distortions onto a pure sinewave test signal. In some instances this distortion results from the unfavourable loading which the capacitor imposes onto its valve or semiconductor driver. In others, the capacitor generates the distortion within itself.

Most properly designed power amplifiers measure less than 0.01%, or 100 PPM distortion when sinewave tested at 1 kHz. Such small distortions are believed inaudible, yet users often claim to hear distortions from these amplifiers when listening to music.

As a result many articles can be found on Internet and in specialist magazines, claiming to have identified differences in sound, between different capacitor types. Not by measurements, but by listening tests having upgraded a capacitor. This has led to a retrofit market supplying 'better' audio grade capacitors, at substantially elevated prices compared to mass market types.

A common subjectivist claim is that oil impregnated paper capacitors sound better than film types in valve amplifiers. Others claim that a PET capacitor sounds 'tubby' while a Polypropylene sounds 'bright' and that all ceramics sound awful. Naturally these claims have no supporting measurements.

Many such writers even decry measurements, presumably in case such measurements disprove their subjectivist claims.

As a result I have regularly received requests for advice about capacitors from readers, who have read the many, often conflicting, subjectivist views, about capacitor types.

Over the years these Electronics World pages have also echoed to disputes between amplifier designers and music enthusiasts regarding capacitor sound distortion. Culminating in a particularly acrimonious debate a year ago, during which I offered to perform some comparative measurements.

As a long term capacitor designer and measurement engineer, I believe that any truly audible differences must be both understandable and measurable. Understanding should be in terms of the capacitor constructions. Measurements may however require a change in traditional measuring techniques.

Since then, in order to develop suitable test methods, large numbers of capacitors, of many types have been measured. The expected distortion differences between capacitor constructions have now been measured. Not expected however and rather more disturbing, is that within a small batch of capacitors, some will exhibit abnormally higher distortions. These anomalous capacitors typically exhibiting some ten times greater distortion than others even those taped onto the same card strip.

In this, the first of a short series of articles, I begin to honour my commitment. Having now a test method at 1 kHz, which is able to differentiate between capacitor types and between good or bad capacitors within a type. see **Fig.1 Fig.2**

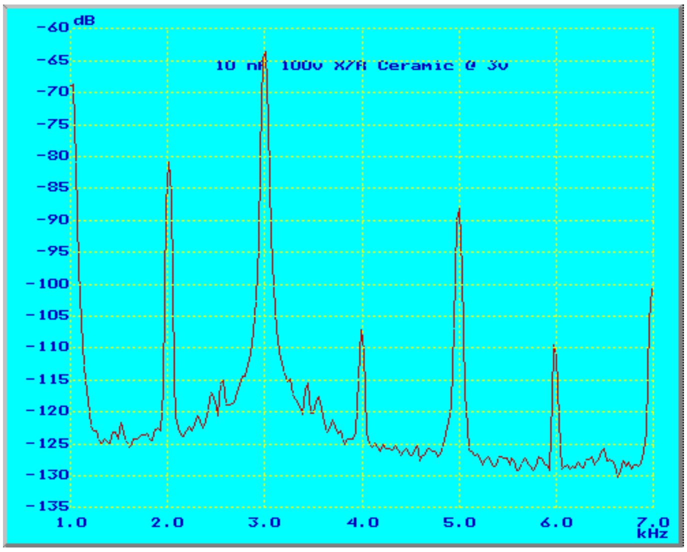


Fig 1) Some capacitors distort even a pure 1 kHz sinewave. This 10 nF X7R ceramic was made by a CECC approved European manufacturer. It was tested at 1 kHz and 3 volt in series with a 10 kΩ current limiting resistor. Measurable distortion exists down to my 0.5 volt minimum tested level.

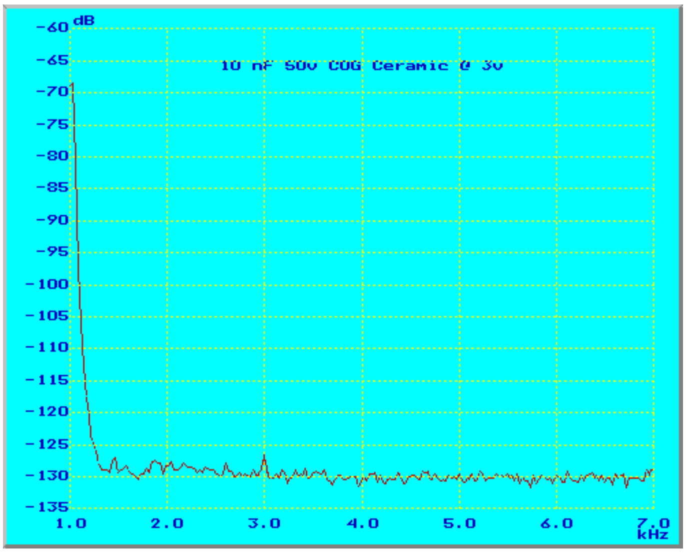


Fig 2) Some capacitors distort very little. This 10 nF COG ceramic was also made by the same maker as the capacitor for Figure 1 and co-purchased from the same distributor. Both were tested at 1 kHz, under identical conditions and within a few seconds of each other.

Measurements.
In all performance plots, the 1 kHz fundamental has been attenuated some 65 dB using a Twin Tee notch filter. The test capacitors for this article were each subjected to a three volts test signal, as measured across the capacitor terminals.

Rather than simply perform measurements using equipment not readily available, I determined to develop a low cost method easily replicated by any interested reader. Hoping thus to improve understanding of capacitors and reduce such disputes in the letters page.

I commenced work in August 2001. To bring to a satisfactory conclusion, it became the longest private development project I have completed. Had I realised how long it would take to develop suitable low cost test methods, I might never have started.

Initial investigations.
Many years ago as part of my investigation into a particularly difficult and costly capacitor reliability problem, I used a Radiometer CTL1 component linearity tester. **Ref. 1** The CTL1 was a large and expensive very low distortion oscillator / third harmonic measuring meter. The many references about it and other methods then used, which I still had on file, formed the basis of my first experiments. see appendix **Other measuring methods.**

I quickly decided the equipment needed to replicate this third harmonic method would prove too complicated and expensive so I reviewed other established methods. Simple measurement of harmonic distortions produced by capacitors, seemed the only practical solution.

In hindsight had I not taken this route, I might not have seen how it is the second harmonic which dominates distortion for almost all capacitors, and not the third harmonic as usually believed . In that case I could never have related how in practise, capacitor dielectric absorption does affect capacitor distortions.

Since few readers would have access to a Spectrum Analyser, performance measurements would be made using more popular equipment. A Pico ADC, such as the ADC-100, once an Electronics World reader's special offer, or a computer soundcard with FFT software, would be much more easily available. Using these I commenced some capacitor intermodulation tests. **Ref. 2**

Intermodulation measurement tests, using good low loss capacitors, certainly revealed differences. When testing less good capacitors, a great many distortion products were revealed. The differences between capacitors then became much too difficult to interpret.

Initial experiments of simple harmonic distortion testing revealed easily interpreted differences when testing less good capacitors. Testing good capacitors however confirmed my available signal generators introduced far too much distortion. Using them I simply could not identify between say a PET and a Polypropylene capacitor.

A much better generator.
Having reviewed past low distortion oscillator designs, I breadboarded the more promising ones. Using these I tested a number of capacitors but with only partial success. From these results it slowly became clear I would need to generate an extremely low distortion 1 kHz sinewave. At least 3 volts amplitude, into a 100 Ω / 1 µF near perfect, low distortion capacitor load and without this load distorting my test signal. see **Fig.3**

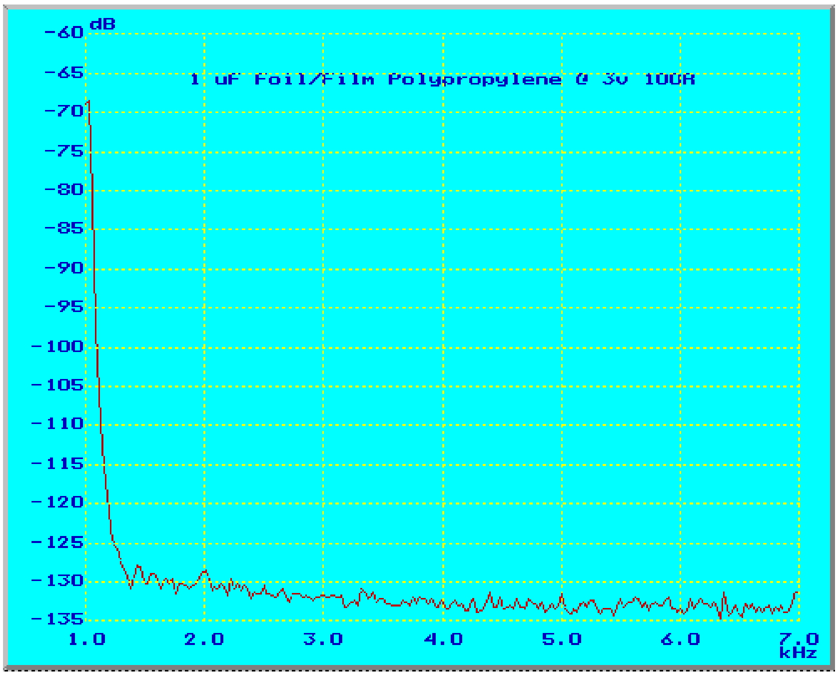


Fig 3) Plot of a near perfect 1 µF foil/film Polypropylene capacitor, tested at 3 volts in series with a 100 Ω current limiting resistor. Clearly shows that my target test specification has been attained.

This excellent result depends as much on my output amplifier as on the test oscillator, because even allowing for the 100 Ω current limiting source resistor, this 100 Ω / 1 µF represents a most difficult load for any low distortion output amplifier.

Equipment.
To test this best possible capacitor, measured distortions of my complete equipment should be less than 1 PPM or 0.0001%. This is approaching the order of oscillator distortion produced by expensive measuring instruments such as made by Audio Precision.

So began the design of a suitable test oscillator. One which could be easily replicated and at little cost, by readers.

The design of this oscillator forms, the subject of this article.   see **Fig.4**

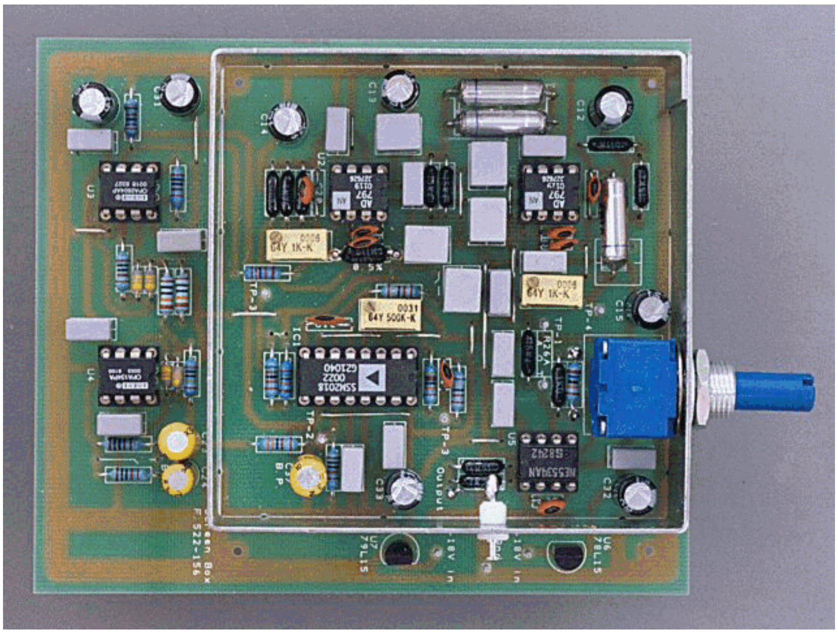


Fig 4) Final design for the 1 kHz test oscillator, with its screening lid removed. Fitted with its lid but no other shielding and with normal fluorescent room lighting, it was used on my bench within 1 metre of the test PC, for all measurements.

This picture shows my final oscillator prototype, which was specially assembled using one of the first off production professionally manufactured PCB's, to prove the performance of these boards matched that of my original oscillator made on my handmade PCB's.

This board is double pierced to permit using either 1% Tombstone or the traditional axial leaded extended foil Polystyrene tuning capacitors as shown.

Initial Researches.
My attention was caught by a remark about 'future Wien bridge oscillator design' in John Linsley Hood's 1981 description of a 0.001% Wien bridge oscillator. **Ref. 3**

Most Wien bridge oscillators use a single amplifying stage. John suggested a method spreading the capacitor/resistor elements over two stages. Reducing the drive into his A1 amplifier and thus reducing its distortion.

I ran some simulations which supported John's earlier views about lower distortion using this configuration. These simulations also suggested a possible improvement. Usually the two Wien bridge arms use equal value components. With John's new arrangement this results in his A2 having double the voltage output of his A1.

I decided to double the capacitance and halve the resistance of the series combination. This would provide equal output voltage from each amplifier with no change in oscillator frequency. With two equal voltage output stages, I could take the amplitude control voltage from one amplifier, leaving the other able to provide my output signal.

Needing 200 µV drive into the negative inputs of both amplifiers to produce a 3 volts output, this arrangement promised a high 'Q' and low distortion.

Many oscillators use a thermistor to control oscillator amplitude. Distortion is then mostly third harmonic, which has been blamed on the thermistor. For my needs, at all costs third harmonic had to be minimised. I needed a different amplitude control.

After some catalogue searching, I choose to design my amplitude control system around the Analogue Devices SSM2018P. This IC was expressly designed as a low distortion, audio frequency, voltage controlled amplifier. Its lowest distortion of 0.006% at 1 kHz is produced with a 3 volt input and 0 dB gain. For 0 dB gain, a control voltage a few mV above 0 volt is needed.

Provided this IC's output was used to supply only a tiny portion of that drive needed to maintain oscillation, its 0.006% distortion should contribute little to the circuits output.

I breadboarded the circuit using a manual control voltage and with NE5534A IC's for the oscillator. Encouraged by these results I designed a simple rectifier and DC control amplifier and tested the composite assembly.

With a 3 volts drive this produced the desired near 0 volt control voltage to the SSM2018P. Distortion however was far worse than my simulations had suggested. Time to rethink.   see **Fig.5**

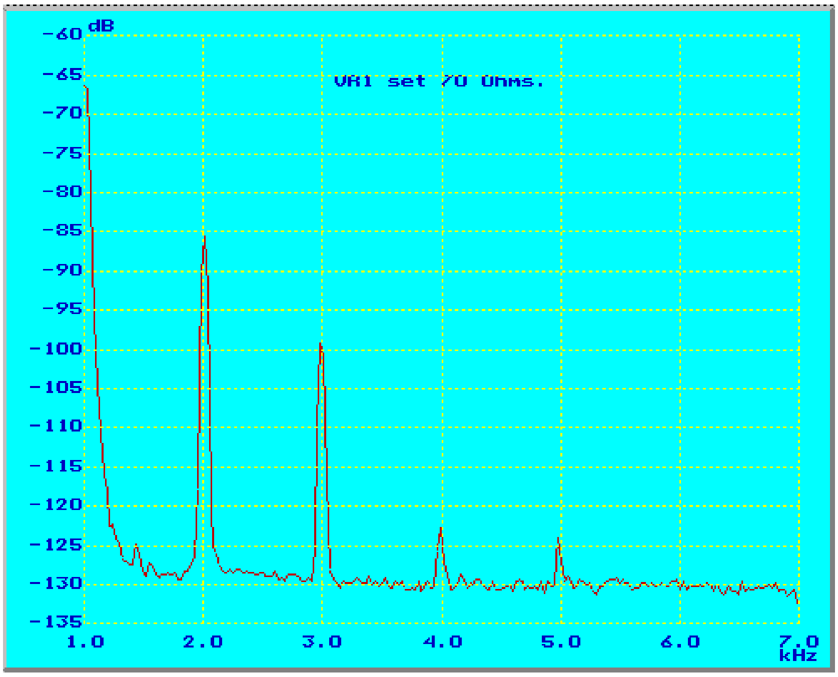


Fig 5) Oscillator output with VR1 set to 70 Ω, well below the optimum value, when using NE5534A IC's.
Distortion at 3 volts output measured 57 PPM or 0.0057%.

Accident or design ?
I returned once more to my simulations. To approximate the actual ESR losses of the tuning capacitors I had inserted some resistance in series with each capacitor. At some time during my many simulation runs, I had miss-typed the entry of this ESR estimate for the shunt feedback capacitor. Instead of 10.0 Ω I had input 100 Ω. Could this explain my differing results.

Going back to my breadboard I inserted a 1K ten turn variable resistor, set to its minimum value. I would adjust this to replicate my typo while measuring the circuit. To my amazement as I increased the resistance value above 100 Ω, the distortions almost instantaneously disappeared. Why ?

Certain that I was somehow mistaken, I repeated this adjustment and measurement many times. It was repeatable. Even better with the variable resistor left above this value, the oscillator could be powered down and restarted, and each time settled to the new, lower distortion, output. see **Fig.6**

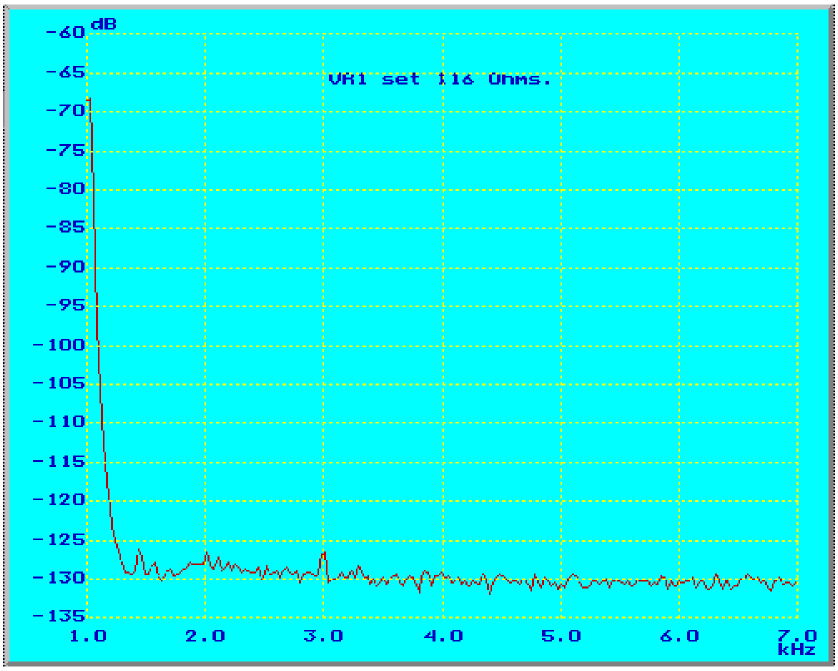


Fig 6) Increasing VR1 to 116 Ω, still slightly below optimum, distortion has suddenly and dramatically almost dissappeared.
It is now mostly third harmonic and at -126 dB is well below 1 PPM.

Why ?
Careful study of several audio amplifier IC datasheets failed to produce an explanation. Eventually I re-read that for the AD797 amplifier, which I hoped to use in my final builds. This IC claims the lowest distortion figures of all the popular audio op-amps, but costing some £7, is expensive. Especially beneficial is that simply using a small 50 pF capacitor between its pins 6 and 8 allows almost complete cancellation of the IC's output stage distortion.

After re-reading more carefully I spotted a paragraph I had previously ignored. This dealt with using a small feedback capacitor ‘CL’ in parallel with the feedback resistor ‘R2’. “When R2 is greater than 100 Ω and CL is greater than 33 pF, a 100 Ω resistor should be placed in series with CL”.

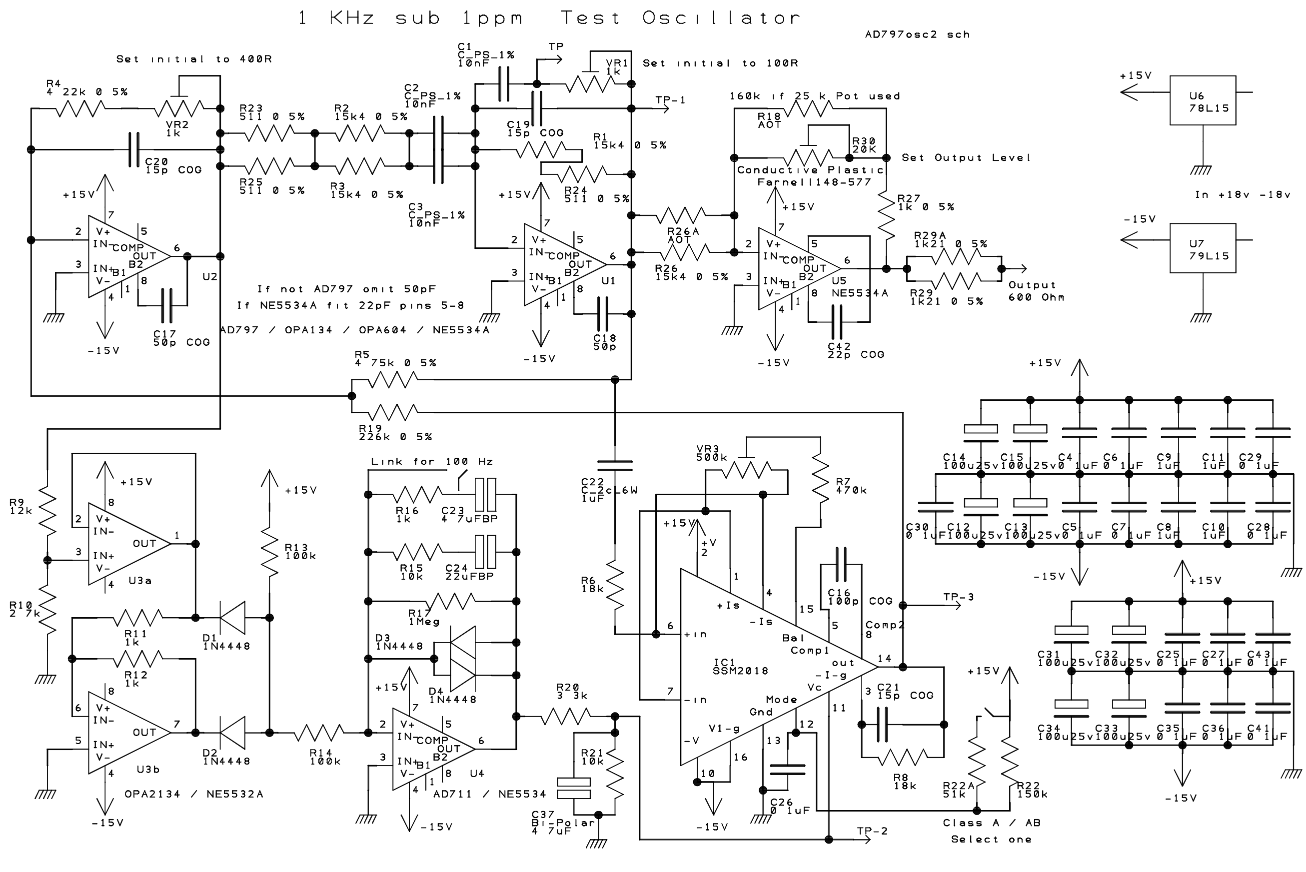
Clearly like many Wien bridge and Sallen Key filter designs, I was using a much higher feedback resistor(15,911 kΩ) in parallel with a very high feedback capacitor (10 nF).

I re-examined the datasheets for the NE5534 and several other IC’s I had considered using, but did not find the same recommendation. This added resistor however was found to work well in circuit with my NE5534A and all other IC’s I tried in the circuit, virtually eliminating all third harmonic distortions.

Proving the design.
Accidents easily happen when breadboarding and testing prototype designs. To avoid expensive mistakes, I used the inexpensive NE5534A devices while developing my printed circuit layout.

To stand any chance of attaining my desired low distortion, the circuit would need screening, good earthing between sections and careful supply rail decoupling. Perancea makes a 75 mm * 75 mm PCB solder mount screening can with removable lid, available from Farnell. This size could accommodate just the oscillator components. The next size can however was much too large, so my amplitude control components would be left unscreened.

This prototype PCB layout worked extremely well except for the output amplifier. Driven with 3 volts, my original output amplifier distorted badly. Following more breadboard experiments, the board was modified to accept another NE5534A. This was arranged as a variable gain, inverting amplifier, driving into a 600 Ω load. see **Fig.7**



Level Potentiometer.
Choice of the type of output level potentiometer used was crucial. I evaluated four types in practise, wirewound, cermet and two different conductive plastic types.

The wirewound created intolerable distortion, the cermets were better but not adequate. The Bourns 91 type shown in the photograph, combined with a selected NE5534A IC, contributed almost no additional distortion when set to produce a 3 volts output. see **Fig.4**

With a 600 Ω load, distortion was now much lower than I could measure using either the ADC-100, my computer soundcard or Hewlett Packard 331A distortion analyser. Equipped with a passive Twin-Tee pre-notch filter and the above instruments I re-measured the oscillator output. Making allowance for the notch filter's reduction of the second harmonic, I estimated that at 5 volts output, distortion was approximately 1-2 PPM.   see **Fig.8**

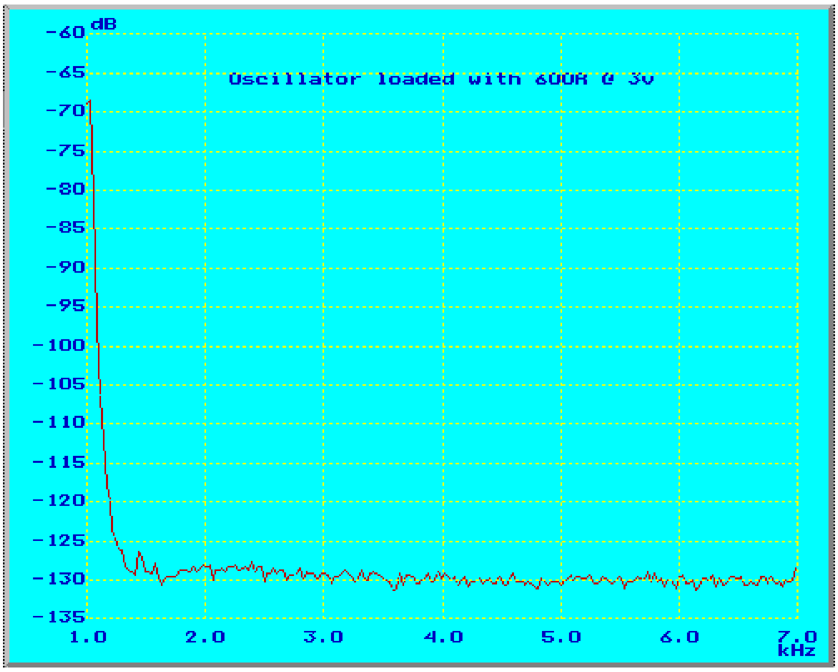
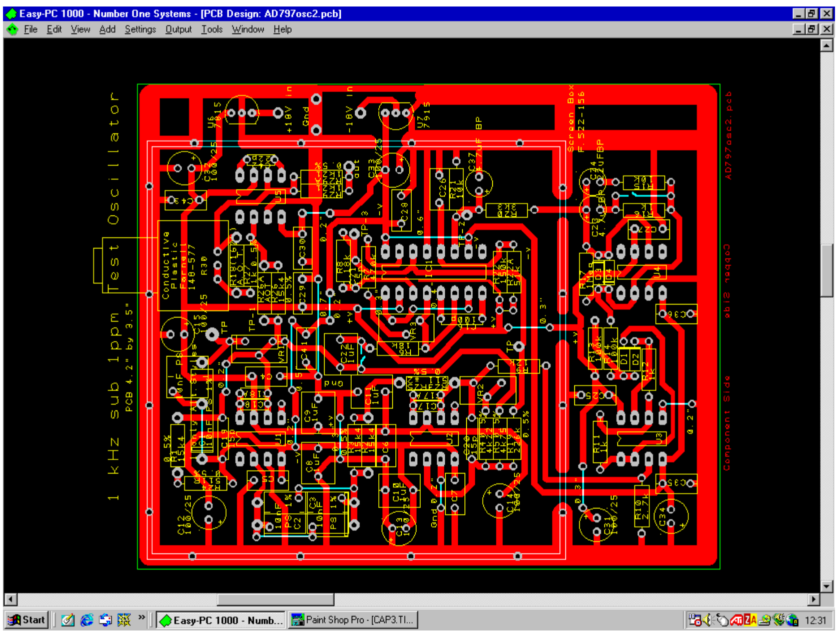


Fig 8) Output distortion of the complete oscillator design shown in Figure 7. Outputting 3 volts into a 600 Ω load, distortion of this prototype measured using my pre-notch filter/amplifier is buried in the measurement noise floor at -128 dB, or less than 0.5 PPM.

Final design.
Having attained what seemed a satisfactory distortion I updated the printed board to accommodate this revised output amplifier. Five Vero Pin test points were added to facilitate calibration. Space was provided for a couple of A.O.T. resistors and links to allow the SSM2018P to be set to either class A or AB operation.   see **Fig.9**



9) The version 2 PCB design as used for this article and the production PCB's. This board can be assembled using a variety of oscillator IC's, and is pierced allowing a choice of oscillator capacitor styles and values. The PCB tracks have been arranged for easy one off PCB etching and assembly.

While class AB is the recommended mode and my PCB's default mode, simply linking the free end of R22A to R22 sets the SSM2018P into class A. Set to class AB it provides both low noise and low distortion. Reset to class A it produces a higher noise level but slightly lower distortions.

Output stage distortion of the AD797 IC can be cancelled by connecting a 50 pF capacitor between its pins 6 and 8. For minimum distortion using this amplifier, the 50 pF capacitor should be fitted.

If using the NE5534A devices this 50 pF capacitor must not be used, but instead a 22 pF capacitor can be connected between pins 5 and 8. The revised circuit board provides for both options.

Note however it is crucial to use only close tolerance and low distortion capacitors for both these positions. Preferred types being 1% Foil/Polystyrene or COG disc ceramic.

Box **Alternate IC's/Components.**
While I used the ultralow distortion but expensive AD797 IC's for U1 and U2 when building my final 1 kHz oscillator, almost all its circuit development was done using the low cost NE5534A IC's. I found some 6 dB difference in distortion between these two IC types in my oscillator. Other IC's have also been tried for the oscillator including the low distortion OPA134 and OPA604. To facilitate evaluating IC's I used Harwin turned pin sockets for each position.

For U1 and U2 but only when using the AD797, it is preferable to fit a 50 pF capacitor between pins 6 and 8. If using NE5534A IC's it is preferable to fit a 22 pF capacitor instead between pins 5 and 8. Neither capacitor is needed when using OPA134 or OPA604 IC's.

The oscillator tuning capacitors must be low distortion types, preferably 1% extended foil with Polystyrene, as shown in the photograph. However I have also built satisfactory working prototypes with 1% extended foil with Polypropylene also 1% metallised Polypropylene, in order of preference. Obviously a good COG ceramic capacitor would work almost as well as my first choice of Polystyrene, provided the COG capacitor is available selected to 1% tolerance. The printed board provides mountings for a variety of suitable capacitors.

Depending on which type IC and tuning capacitors are used, then the value of VR1 needed to minimise distortion will vary.

I found only the NE5534A IC provided low distortion when used for the output buffer, U5. For this low/unity gain position, the 22 pF capacitor is essential. Also for its gain control, I found only one satisfactory variable resistor, a Bourns 91 series conductive plastic, obtained as 148-557 from Farnell. Other similar types may well be OK but these I have not tried.

However do not use either cermet or wirewound controls for this position, I have tried several and they certainly do not work acceptably for this position, in this design.

The 50 pF/22 pF capacitors must be low loss, low distortion types, preferably Polystyrene parts alternately COG only disc ceramics. Similarly for the remaining low pF capacitors used. For my builds I used COG ceramics. The PCB drawing provides for both alternatives.

In each case my preferred IC choice is the first type listed on the schematic drawing.

To produce such a low distortion oscillator it is important to use resistors having a small voltage coefficient of resistance. To ensure an easily reproducible design, I used only 0.5% Welwyn RC55C metal film resistors, visible as black in the photograph, in the signal path. These are marked as 0.5% on the schematic.

These resistors use plated steel endcaps, which I prefer for reliable long term end contact stability. Many subjectivists claim non-magnetic endcaps are better. I do not subscribe to that belief. Over my years investigating capacitor problems and applications, I found many examples of intermittent contacts caused by non-magnetic end caps.

Undoubtedly some of the oscillator output distortion is generated inside the three multi-turn cermet trimmers used. For two positions these trimmers are essential. However the printed board does provide mounting pads for a fixed resistor, which could be substituted for VR1, once its value has been determined during calibration. To date however I have retained this trimmer.

While these RC55C types could be used throughout, for economy I used my standard, inexpensive 1% metal film resistors, for all other positions.

Three Bi-Polar electrolytic capacitors have been used in the gain control circuits. These are the yellow cased 'Nitai' types visible in the photograph. Equally suitable are the slightly larger Panasonic BP types, both are stocked by Farnell. Do not use a conventional polar electrolytic capacitor for these positions.

For such a low distortion oscillator, it is essential to use good quality capacitors to decouple the power supplies. For the 0.1 µF value, Black in the photograph, I used Evox-Rifa SMR, metallised Polyphenylene Sulphide film. I consider this film produces the best, low cost and small, 0.1 µF and larger capacitors. They were obtained from RS, but unfortunately RS has since stopped supplying.

Alternately a good metallised PET capacitor should be satisfactory, such as the Evox-Rifa MMK or BC Components (Philips) 470 series. I used many of both these types, in my Tanδ project.

For the larger capacitors, I used the BC Components 1 µF 470 series, grey in the photograph and Rubycon YXF polar electrolytics. Again other types should be OK but they have not been tried in the circuit.

In use the oscillator is powered from my lab supply, set to output ±18 volts.

End of **Box.**

Final testing.
To permit accurate measurements of this oscillator's distortion and facilitate calibration, using either the ADC-100 or a soundcard, a pre-notch filter is essential. The ADC-100 in Spectrum mode provides selectable peak input levels up to 20 volts. Its 0 dB reference being fixed nominally at 1 volt. Being only 12 bit, its dynamic range is limited to just 70 dB. Most soundcard ADC inputs are limited to 2 volts peak or less, but having 16 or more bits, can provide an increased dynamic range.

To measure down to -130 dB below 3 volts with either of the above, the fundamental should be reduced by some 60/65 dB. To minimise the influence of ambient interfering noise levels and attain a more easily measured signal, this reduced fundamental and the harmonic voltages, must be pre-amplified by some 40 dB. To minimise wideband noise and extraneous pickup from AC mains or your PC, the signal should also be bandpass filtered.

Using a 3 volts test signal. this pre-notched and amplified fundamental and distortions, results in a measurement voltage around 0.3 volts RMS.

Measuring capacitor distortions.
I have designed a second printed circuit board which houses a low distortion, passive Twin Tee notch filter. To permit matching the notch frequency to that of the oscillator output, the notch is tuneable by some ±10% from its nominal frequency.

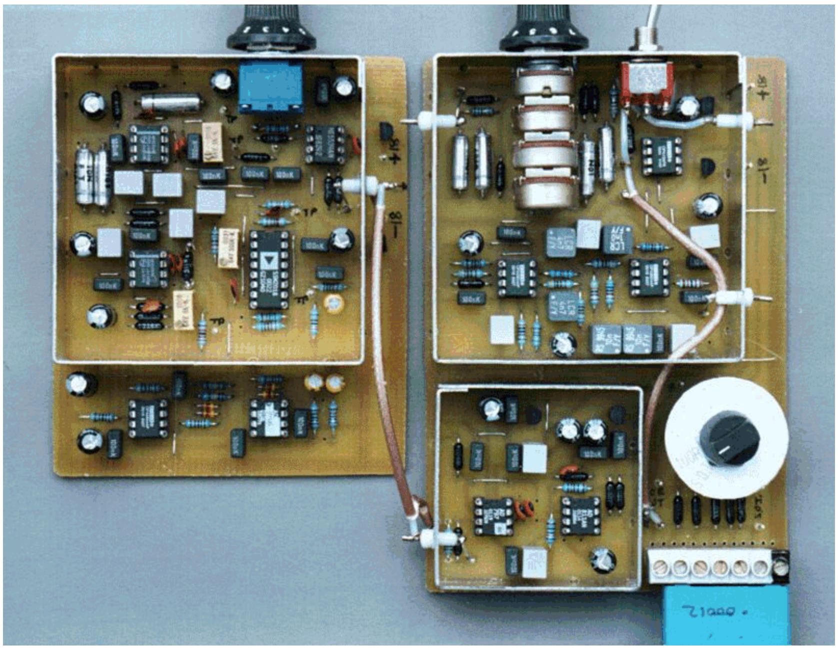
It's nominal input impedance is 10 k Ω. A high impedance unity gain, low noise pre-amp can be switched into circuit, should this passive notch loading be excessive.

This notch filter is followed by four stages of low noise, low distortion, amplification and bandpass filtering. All measurements shown in this article were made using this pre-notch filter/pre-amplifier as the input into my ADC-100 converter. While care was taken to minimise noise and distortion in this amplifier/filter, obviously its contribution is included in my results. Using this method, the distortion of my oscillator into 600 Ω load when built with AD797 IC's, measured less than -130 dB or less than 0.5 PPM. see **Fig.8**

Less expensive alternative IC's can also be used. By selecting from a batch of 10, I was able to attain an output distortion of -126 dB using the much less expensive NE5534A IC's.

This excellent quality signal driving into 600 Ω can be used to measure distortions in amplifiers etc. However a more powerful output buffer amplifier, providing increased drive current must be used when testing capacitors. Designing a suitable buffer power amplifier able to drive into a series resistor/capacitor load without increased distortion, proved difficult. It required almost as much development time as was needed for the oscillator itself.

After evaluating many potential buffer amplifier configurations, I have designed a very low distortion circuit having a gain of two, able to drive 7 V RMS or 40 mA into a 100 Ω/1 µF capacitor series combination. I have found this buffer circuit sufficient to measure distortions produced by capacitors from a few hundred picofarads up to 1 µF, at 1 kHz.



Above 1 µF it is common practise to change to using electrolytic types, both tantalum and aluminium. To avoid overstressing these capacitors and maintain similar test voltages, a reduced test frequency must be used.

For this I have also developed an alternative buffer amplifier, able to drive up to 7 volts and 400 mA at 100 Hz, albeit with slightly greater distortion than for my 1 kHz design. Since electrolytic capacitors distort more than the lower value, better quality film and ceramic types this small increase in distortion is acceptable when testing electrolytics.

My I kHz pre-notch filter/pre-amplifier (top box) and output buffer amplifier (lower box) can be seen in the photograph. Both will be fully described in my next article.

Fig 10) The prototype measurement system displayed. Test oscillator on the left with low output impedance amplifier and pre-notch filter/amplifier on the right. This design has been used down to 100 Hz and up to 10 kHz, by changing the Wien Bridge and filter capacitor values.

Box **Calibration.**

Calibration of this oscillator requires use of a suitable spectrum analyser, distortion meter or preferably my low cost pre-notch filter/40 dB preamplifier. This is shown in Figure 10 and will be detailed in my next article.

Prior to inserting the SSM2018P, trimmer VR3 should first be set to its mid value. Similarly prior to inserting U1 and U2, trimmers VR1 and VR2 should be set to the starting values shown on the schematic drawing.

These values give a good starting point and should ensure the oscillator starts reliably. Output at the test point adjacent to VR1/R26 should be around 3 volts.

Monitor the test point 2 adjacent to C37 using a DC millivoltmeter. Adjust VR2 only to attain near zero volts. With the top screening cover fitted in place, allow the circuit to fully warm up for at least 20 minutes.

Observing the output spectrum at the test point 1 adjacent to VR1/R26 using the high impedance preamplifier input to the notch filter, you will probably see significant distortion products. see **Fig.5**

Slowly increase the resistance of VR1 and simultaneously trim VR2 to maintain near zero volts on the test point adjacent to C37. This adjustment affects mostly the third and higher odd harmonic components. These adjustments will also slightly change the oscillator frequency. If using a pre-notch filter, re-adjust this filter tuning to maximise notch depth.

Distortion products should suddenly and dramatically reduce as you approach the optimum resistance value for VR1. see **Fig.6**

Relocate your test probe to the test point 3 adjacent to R8 and adjust VR2 to minimise the second harmonic component only. This adjustment has little affect on the higher harmonics which should be ignored.

Return to monitoring the test point 1 adjacent to VR1/R26 and slowly adjust all three trimmers as above to minimise distortion. This completes the oscillator calibration. see **Fig.8**

Test or select U5.

Attach a 600 Ω resistor load to the 'out' test point and adjust the conductive plastic potentiometer to give 3 volts across this resistor. Monitor the distortion spectrum at this out test point, and compare with that previously attained at the test point adjacent to VR1/R26.

Both should be almost identical. If not replace U5 and retest.

While monitoring the 'out' test point, you may be able to slightly reduce the overall output distortion by making small adjustments of the three variable trimmers, as above.

Distortion with 3 volts output into 600 Ω, should be considerably less than 1 PPM. **Fig.8**

By varying the output potentiometer, the output voltage loaded with 600 Ω should range from less than 0.2 volts to more than 4 volts. 'Adjust on test' resistor positions have been provided for R26A also R18 to ensure attaining this output voltage range.

End

References.

1) CLT1 Component Linearity Test Equipment data sheet. RE Instruments AS. Copenhagen.

2) Trial by three tones. Ivor Brown. Electronics World February 1991. p.131.

3) Wien-bridge oscillator with low harmonic distortion. J.L. Linsley Hood. Electronics World May 1981 p.51.

4) Harmonic testing pinpoints passive component flaws. V.Peterson & Per-Olof Harris. Electronics July 11, 1966.

5) If the Cap Fits. W.Jung and J.Curl. Hi Fi News & Record Review. April 1986

Appendix **<u>Other measuring methods.</u>**

CLT1 Component Tester.
Early carbon film resistors were trimmed to value by grinding a spiral groove into a resistive element coating on a ceramic former. Resistor noise and non-linearity was significantly reduced, compared to the older composition resistor. Incomplete or badly ground spirals frequently resulted in early component failures when tested under load.

In the sixties, engineers at Ericsson believed that non-linearities in capacitors and resistors could be detected. They measured the level of third harmonic distortion generated in a component subject to a very pure sinewave test signal. Non-linearities were believed to result from badly ground resistor spirals, poor electrical contacts and the use of non-linear materials. **Ref. 4**

Their original non-linearity detector design produced low distortion test signals at 10 and 50 kHz. Third harmonic distortion generated by the component under test was passed through bandpass filters for measurement. Subsequently the 50 kHz test frequency was dropped and a commercial instrument, the CTL1 component linearity tester, was produced by Radiometer of Denmark. **Ref. 1** To accommodate the range of component impedances and test voltages needed, a low distortion output transformer was used. Having seven adjustable tappings, it was used to tightly couple the instrument to the component under test. Component impedances from 3 Ω to 300 kΩ could be measured.

Today an updated version can be obtained from Danbridge A/S, Denmark, a specialist manufacturer of capacitor test instruments.

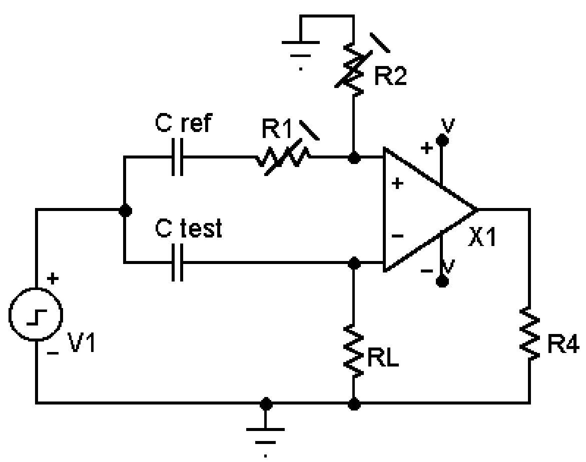
Using such equipment makes testing resistors also small value capacitors very quick and easy, however the extremely low impedance of many capacitors at 10 kHz requires using extremely small, even millivolt level test voltages. Bad and oxidised connections will be discovered. From my work however I find detection of certain capacitor distortion effects, especially with electrolytic types, requires a much increased test voltage. These capacitor distortions cannot be measured at very low test voltages. To avoid overstressing the test capacitor, this increased voltage test must be performed at lower frequencies.

Extremely tight coupling between the test capacitor and the linearity tester is implicit in the CLT1 equipment design. From my early work measuring capacitors, I found it necessary to loosen this coupling in order to clearly reveal anomalies found in many modern capacitors. By trial and error measuring known good and bad capacitors at 1 kHz, I found that 100 Ω in series with a 1 µF capacitor at 1 kHz provided the best compromise between measuring current and capacitor voltage. Adjusting this resistance value according to the capacitors impedance, at the test frequency. see **Fig.1**

This test measures only any third harmonic. It is completely blind to the second harmonic distortion levels I found testing capacitors. In addition it makes no provision for testing with DC bias voltage. I found DC bias was the most important test.

Jung-Curl test.
Some twenty years ago a simple capacitor test method, used an instrument amplifier to compare the differences between a test and reference capacitor. **Ref.5** These capacitors were connected in series with each of the in-amp inputs, then subjected to a rectangular test wave. As described this test also makes no provision to apply any DC bias to the capacitors, a most important omission. Applying signals with variable DC bias is the most important test of all, when evaluating capacitor distortions.

Forming a traditional Wheatstone bridge, using a sinewave stimulus this circuit can be used to compare the test capacitor with a known reference capacitor. However used with a rectangular wave test signal, interpretation of the output waveform was difficult and impractical, unless both capacitors were of similar value, dielectric and construction. see **Fig.11**



For almost all capacitor constructions, capacitance does vary with test frequency and test voltage. For all capacitors, using dielectrics other than air or vacuum, ESR is totally frequency dependant. Usually ESR reduces with frequency, reaching a minimum at the capacitor's series self resonant frequency.

Differing dielectrics and constructions thus result in significant differences in ESR and impedance, with test voltage and frequency, which simply cannot be adequately resistively nulled. This inbalance led to a variety of unsatisfactory explanations and interpretations, often involving dielectric absorption.

Having tried and failed to reconcile the output waveforms, when using previously characterised capacitors, my advice is to use this circuit only with a sinewave test signal, as a resistance or capacitance bridge.

Fig.11 Simplified schematic of the Jung/Curl capacitor test.

Capacitor Sounds 2 - Output Buffer and Twin-Tee Notch/Preamp.

Updated & expanded March 2003.

Original version Pub. Electronics World September 2002
Many capacitors introduce distortions onto a pure sinewave test signal. In some instances this distortion results from the unfavourable loading which the capacitor imposes onto its valve or semiconductor driver. In others, the capacitor generates the distortion within itself.

Most properly designed power amplifiers measure less than 0.01%, or 100 PPM distortion when sinewave tested at 1 kHz. Such small distortions are believed inaudible, yet users often claim to hear distortions from these amplifiers when listening to music.

As a result many articles can be found on Internet and in specialist magazines, claiming to have identified differences in sound, between different capacitor types. Not by measurements, but by listening tests, having upgraded a capacitor. This has led to a retrofit market supplying 'better' audio grade capacitors, at substantially elevated prices compared to mass market types.

A common subjectivist claim is that oil impregnated paper capacitors sound better than film types in valve amplifiers. Others claim that a PET capacitor sounds 'tubby' while a Polypropylene sounds 'bright' and that all ceramics sound awful. Naturally these claims have no supporting measurements.

A year ago, a particularly acrimonious letters page dispute arose in Electronics World regarding capacitor distortions. It seemed some of the issues raised could only be resolved by providing proof positive, that many capacitors do cause distortion. I offered to perform some comparative distortion measurements.

Commitment honoured.
To measure the distortion level for most capacitors, a very low distortion generator complete with a matching low output impedance, low distortion, buffer amplifier must be used. An easily replicated, low cost, extremely low distortion test generator was described in my last article. **Ref.1** This equipment can be used to measure amplifier distortions as well as capacitors.

This article describes a matching very low distortion, low output impedance, buffer amplifier needed to generate a pure sinewave voltage across a test capacitor. Having a near 600 Ω input impedance this buffer amplifier could equally be used with many commercial generators as well as with my design. see **Fig.1**

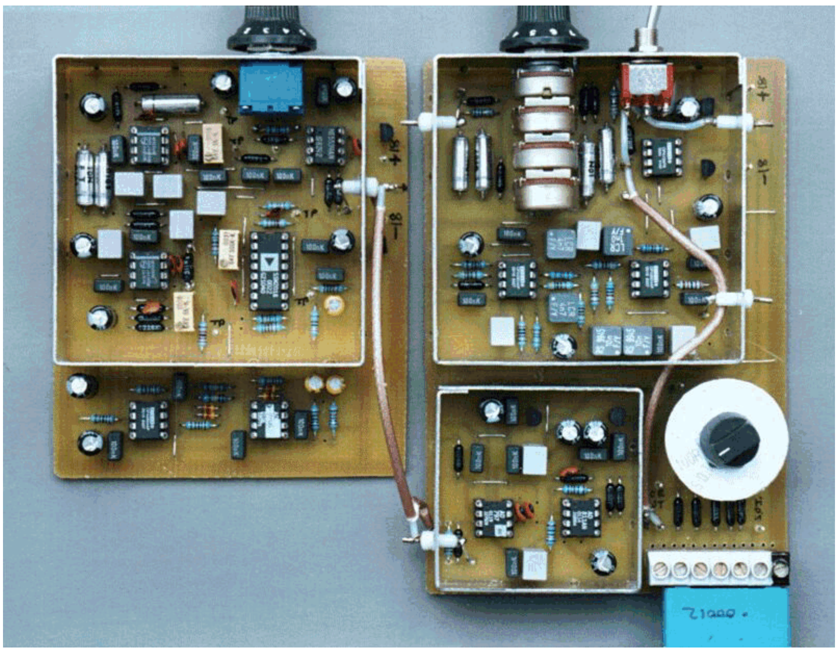


Fig 1) Very low distortion, low output impedance buffer amplifier, with passive Twin Tee notch filter, bandpass filters and 40 dB gain preamp printed circuit board (right).
This arrangement used with my low distortion 1 kHz oscillator (left), can measure capacitor distortions down to -130 dB.
Switchable source impedances from 100 Ω to 100 kΩ, together with the test jig as shown, facilitates measuring different value capacitors to a common test standard.

Notch Filter.
To facilitate measuring capacitor distortions using low cost instrumentation, the 1 kHz test fundamental should first be attenuated some 65 dB in a passive Twin Tee notch filter. Reducing the dynamic range to be measured.

Using a typical 3 volts test signal, this attenuated test fundamental plus distortion components, is reduced to a few millivolts. This small signal should be bandwidth filtered and pre-amplified by 40 dB, to allow measurement using a 16 bit computer soundcard or the 12 bit Pico ADC-100 converter.

An easily built, low cost buffer amplifier together with a notch filter/pre-amplifier, have been designed on a second PCB. Together with my 1 kHz test generator **Ref.1** these two provide a complete system able to measure distortions as small as -130 dB, 0.3 PPM or 0.00003%, below a 5 volts test signal.

To replicate common circuit drive voltages, this buffer should be able to generate up to seven volts RMS across a 1 µF capacitor, fed via a 100 Ω current limiting source resistor.

Test Requirement.
Perhaps you already have a low output impedance test generator. The simple method I used to decide when my equipment was suitable for capacitor distortion measurements, will determine whether your existing equipment can be used.

Using a 100 Ω source impedance, connect a 511 Ω resistor to ground. Increase the generator output so as to measure 3 volts or more across this 511 Ω using a DVM. Remove the DVM and perform a distortion measurement across the 511 Ω resistor.

If 1 PPM or less, replace the resistor by a good, nearly perfect 1 µF capacitor and without changing the generator output voltage, perform a distortion measurement across the capacitor If less than 1 PPM the equipment can be used to measure capacitor distortions.

The best test capacitor for this would be either a COG ceramic or an extended foil/Polystyrene. These are not distributor items so are impossible to obtain in small quantities.

Next best is an extended foil and film Polypropylene, closely followed by extended metallised film electrodes with unmetallised Polypropylene dielectric. This last, manufactured by BC Components (Philips) is stocked by Farnell as part 577-881, 0.47 µF 250v. I used two of these, type 376 KP 0.47/250v connected in parallel. see **Fig.2**

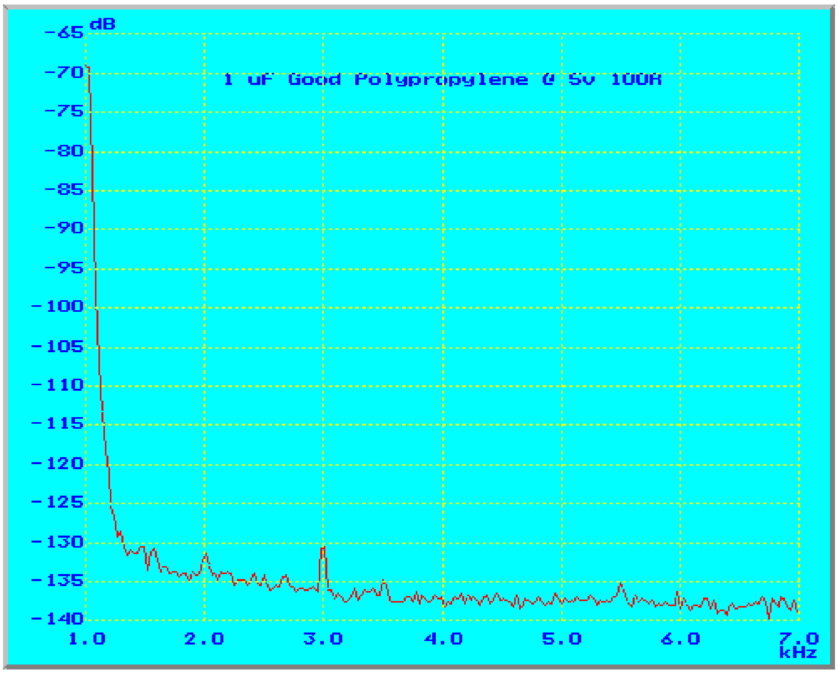


Fig 2) Plot of a near perfect 1 µF foil and Polypropylene capacitor tested at 5 volts in series with a 100 Ω source impedance. This plot includes not only any capacitor induced distortion but also that of my test system.

If you have a generator able to provide suitably low distortion into a 600 Ω resistive load, then my buffer amplifier may allow your generator to be used.

However it is important to note that the series input resistance seen by my buffer, some 1120 Ω inclusive of the 511 Ω R38, is essential for its low distortion. This total value should not be changed.

Buffer amplifier design.
The buffer amplifier must not itself contribute measurable distortions. Since distortion levels measured in good capacitors are -130 dB, 0.3 PPM or less, designing a suitable generator and buffer amplifier was no simple task. Designing a suitable buffer amplifier required almost as much development time as was needed for my low distortion oscillator. **Ref.1**

To drive 7 V RMS into a 100 Ω/1 µF capacitor combination using my generator, a gain of 2 buffer was required.

Many potential buffer amplifier configurations were breadboarded and rejected. While able to drive a resistive load, they were not able to develop a few volts across a 1 µF capacitor without distorting.

An open loop buffer IC, the Burr Brown BUF634P used with an OPA604 in the makers suggested circuit, worked well at low drive voltages or with smaller capacitors. Loaded with a 100 Ω/1 µF capacitor test load, it distorted at increased drive levels. By closing one link, this combination can be used on my PCB.

The most nearly suitable circuit I tried was described in the Analog Devices AD797 datasheet. With an AD811 as the output driver, this combination claimed to be able to drive a 600 Ω load to 7 volts RMS at 100 kHz with less than -109 dB distortion.

When breadboarded this design produced less distortion driving into my capacitive test load than did the BUF634P circuit. For minimum distortion however the circuit required critical matching of the impedances seen at both AD797 inputs. I was working to ensure suitable matching in November, when my only spare AD797 was damaged. Replacements not being available until February, I was forced to try other IC options. This combination of AD797/AD811 can be used in my PCB.

A low cost NE5534A worked quite well with this AD811 output stage but again required careful input matching to minimise distortion.. An OPA604 distorted at high drive, but the OPA134/AD811 worked best of all the combinations I tried.

Performance plots in this and my earlier article, were made using this OPA134/AD811 buffer amplifier.

With maximum drive into a 1 µF load, the AD811 heats up so should be fitted with a small heatsink, half of Maplin RN69. To minimise noise pickup the circuit was screened using a small 50 mm * 50 mm Perancea solder mounting screening can and lid. To reduce heat build up, eight 8 mm holes were distributed around the box sides with twelve 6 mm holes in the lid.

Capable of more than seven volts output, I found this buffer circuit sufficient to measure distortions produced by capacitors from a few hundred picofarads up to 1 µF, at 1 kHz.   see **Fig.3**

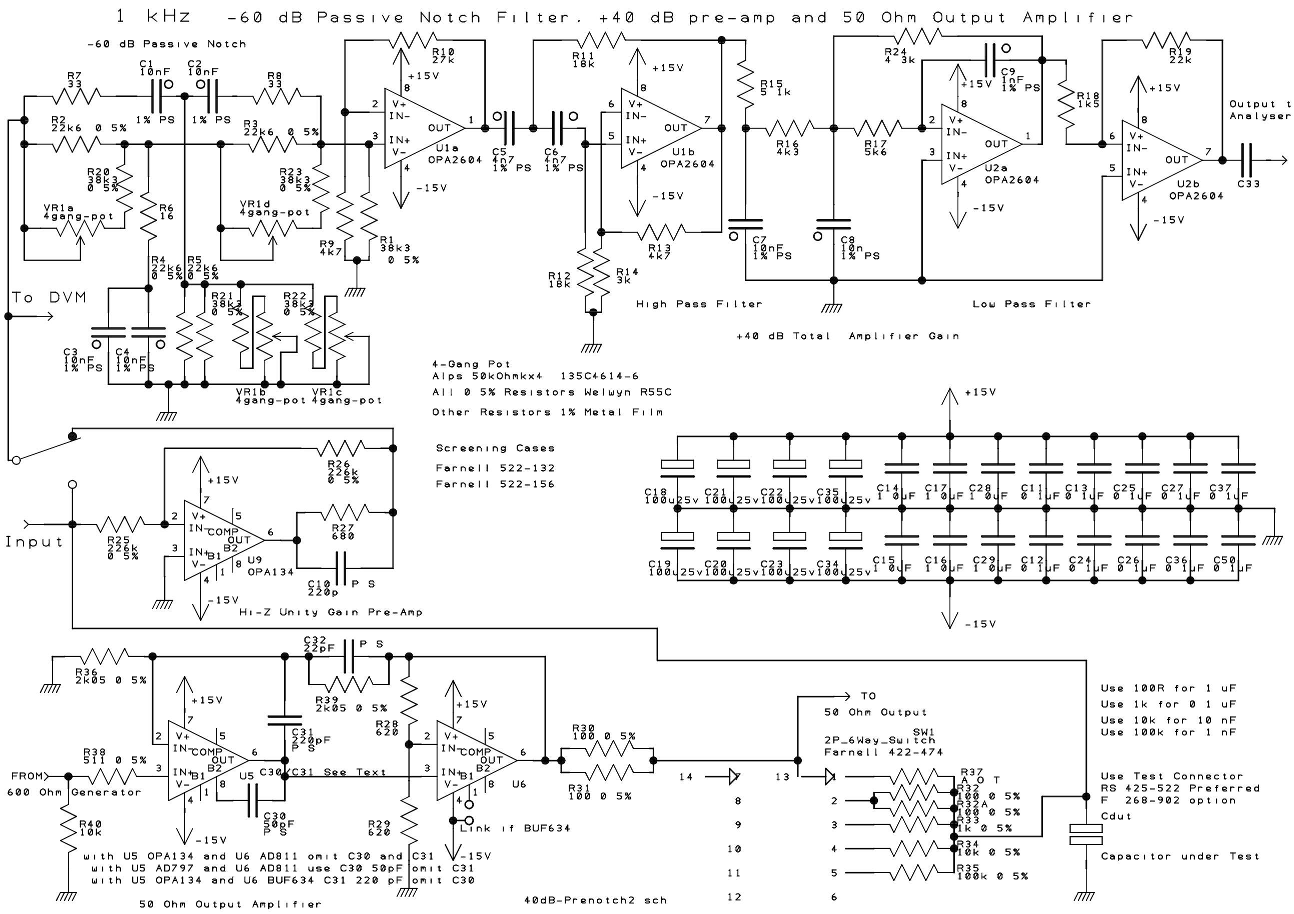
Notch filter/pre-amplifier design.
To ensure minimal distortion of the test signal, a passive Twin Tee notch filter, with a nominal input impedance of 10 kΩ is used. To track the oscillator frequency, this notch is tuneable by some ±10% from its nominal 1 kHz frequency. Measuring source impedances greater than 1 kΩ, the loading of this passive notch filter is excessive. A high input impedance unity gain, low noise low distortion pre-amp can then be switched into circuit.

The notch filter is followed by four stages of low noise, low distortion, amplification and bandpass filtering. To minimise hum pickup, the filtered input is 50 dB down at 100 Hz. To reduce high frequency input into the measuring ADC, output is 20 dB down by 22 kHz. Amplified by 40 dB, harmonics from the 2nd to 9th are maintained flat within 0.5 dB

All measurements shown in this and the previous article, were made using this pre-notch filter/pre-amplifier as the input into my ADC-100 converter.

While care was taken to minimise noise and distortion in this notch filter/pre-amplifier, its contribution is included in all my test results. Using this notch filter/pre-amplifier, the distortion of my oscillator, built using AD797 IC's and the OPA134/AD811 buffer, driving 5v into my 100 Ω/1 µF test capacitor load, measured -130 dB, or 0.3 PPM.   see **Fig.3**

In most circuit applications, a capacitor is used either connected as shunt to ground or in series with the signal either to tailor the frequency response or simply block DC. Our test method should permit testing capacitors in either configuration.



Capacitor jigging.
To avoid soldering the capacitor under test, some form of test jig, permitting easy exchange of various size capacitors, is required. The test jig must provide very low resistance and secure connections to the test capacitor. The slightest connection insecurity introduces significant distortion due to the connection, not the capacitor.

I tried a number of spring contact terminal blocks. All but one required excessive capacitor lead lengths to ensure secure connections and that needed at least 5 mm wires. Farnell part 268-902. My PCB accepts this terminal block as well as the cage type. see **Fig.4**

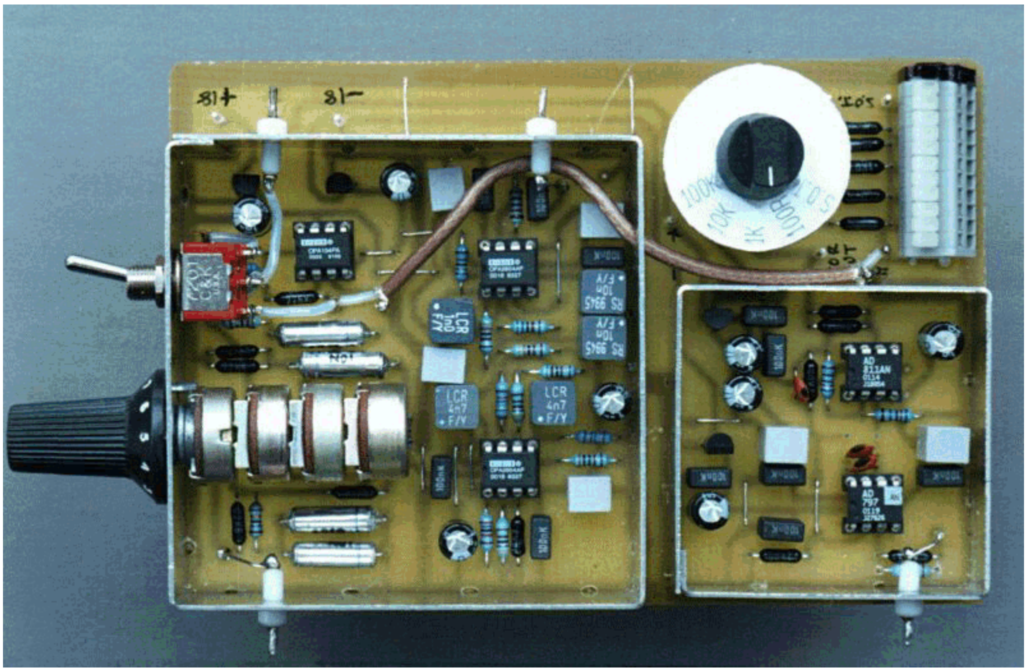


Fig 4) The PCB is double pierced so as to accept either the screw cage terminal test jig, as shown in figure 1, for capacitors with lead spacing up to 30 mm. Alternately this 'spring contact' terminal strip, accepts lead spacing up to 27.5 mm centres.

My test jig choice.
Ultimately for my own use I choose a 5 mm centres, cage type, screw terminal strip, able to measure capacitors having 4 mm long wires. RS part no 425-522.

Designed to accept thick wires, it easily accepts 2.5 and 7.5 mm spaced leads within its cage mouth. These cage terminals grip a wire tightly but without bending flattening or otherwise noticeably damaging the capacitor leads. This terminal strip 'jig' was used for all my 1 kHz/100 Hz capacitor distortion measurement plots.

The buffer amplifier/test jig shown can be used to test either series or shunt connected capacitor configurations. My preference is to shunt test, exactly as shown in the photo. The switchable current limiting resistor in series with the test signal, the capacitor being connected between signal and ground. see **Fig.1**

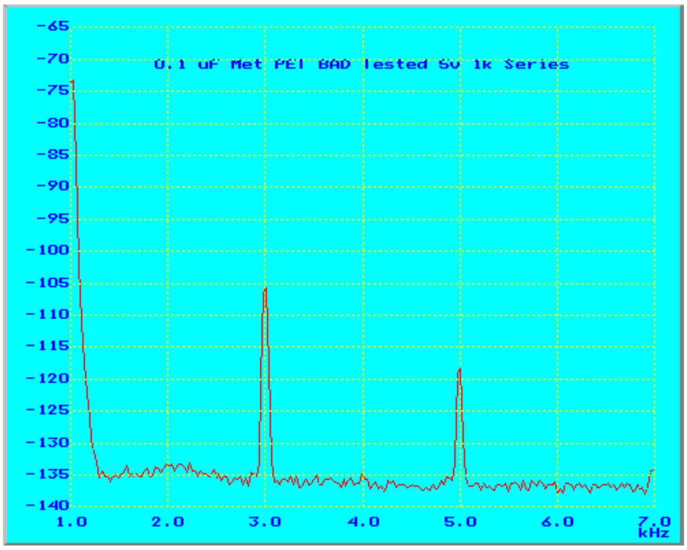
This provides two benefits:-

1)A good capacitor acts to slightly reduce any test generator harmonics, while a bad capacitor clearly shows much increased harmonic amplitudes.
2)The capacitor test voltage can be measured directly, using a high impedance meter attached to the DVM output test point. This test point measures the voltage at the input to the passive Twin Tee notch filter..

A test capacitor connected in series with the test signal, depresses the lower frequencies while slightly increasing higher harmonics, relative to the shunt connection.. The test voltage can only be measured by connecting a DVM directly across the capacitor. This DVM must always be removed before the capacitor can be tested.

Harmonic levels between the two methods differ by only one or two dB for the same capacitor voltage. A good capacitor looks good, and bad capacitors look bad, regardless of testing in the series or shunt connection.

By way of comparison, using a 1 kΩ source impedance, I plotted test results of a known bad, 0.1 µF Metallised PET capacitor, measured in both series and shunt modes at 5 volts. In comparison the third harmonic distortion peak of a good 0.1 µF Metallised PET capacitor tested at the same voltage, measures substantially lower, around -125 dB. see **Fig.5, Fig.6**



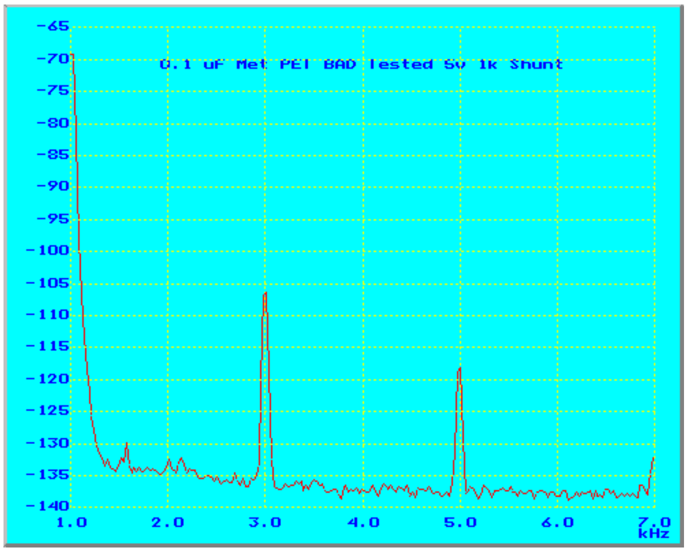


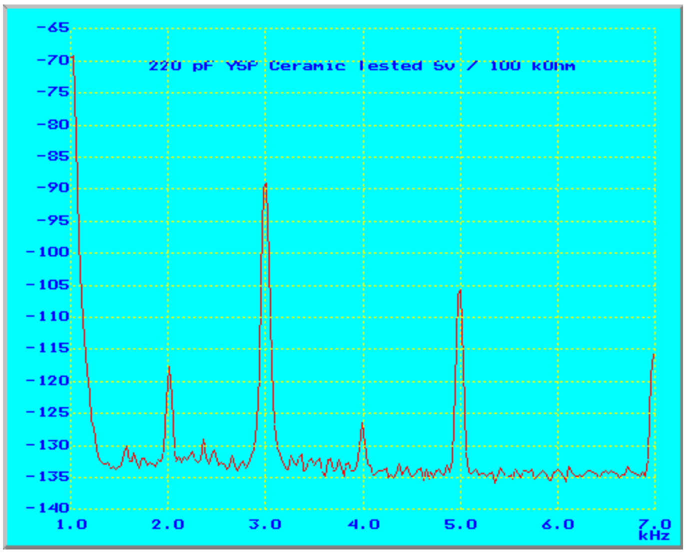
Fig 5) Distortion plot of a known 'bad' 0.1 µF metallised PET capacitor tested at 1 kHz with 5 volts across the capacitor, using the optional 'series mode' connection. The capacitor is in series with the test voltage, the 1 kΩ current limiting resistor, is to ground.

Fig 6) Distortion plot of the figure 5 capacitor and with the same 5 volts 1 kHz signal, using my standard 'shunt' connection. The 1 kΩ current limiting resistor in series with the test voltage, the capacitor connected to ground as in figure 1. Almost identical distortion was measured in both configurations.

Series tests.
To test in the series mode, the test capacitor and current limiting resistor are simply interchanged. The test capacitor is connected to the A.O.T resistor Vero Pins and the switch is set to the O.A.T position. The current limiting resistor is fitted to the test jig terminals, replacing the test capacitor shown in the figure.   see **Fig.1**

Test Capacitor Source Impedance.
The buffer amplifier output switch provides selection of four values of current limiting, or source impedance resistors. In principle any resistance value can be used to test any capacitance. However this resistor value determines the maximum test voltage which can be developed across the capacitor as well as the test's sensitivity.

By way of illustration I plotted test results for a 220 pF Y5P 50v ceramic capacitor, Farnell 896-524, using each value of current limiting resistor in turn. At 1 kHz a 220 pF capacitor has an impedance around 720 kΩ. These clearly show that as the capacitor is more and more closely coupled to the generator output, its distortion peaks are mucch reduced. Tested with 1 kΩ the third harmonic peak had fallen to -121 dB and with 100 Ω to -127 dB. see **Fig.7, Fig.8**



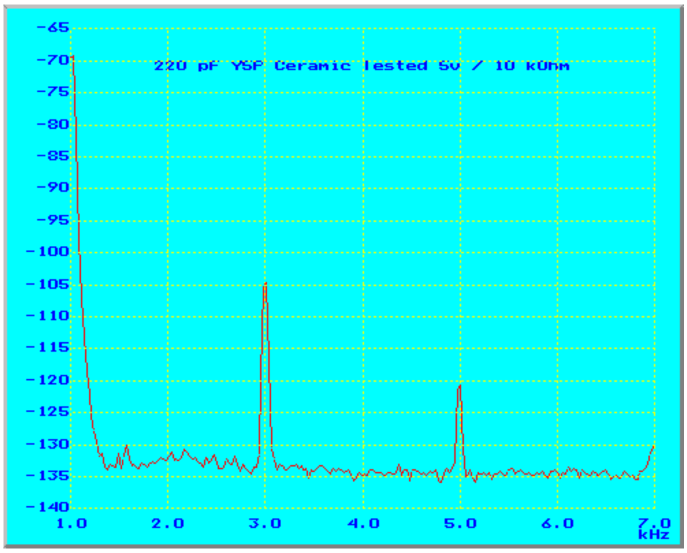


Fig 7) Distortion plot of a 220 pF Y5P disc ceramic capacitor tested using a 100 kΩ current limiting resistor and with a 5 volts 1 kHz test signal across the capacitor. Clearly shows significant distortion products when tested using this source impedance.

Fig 8) Distortion plot of the figure 7 capacitor, tested exactly the same except for the current limiting resistor, now 10 kΩ. Because the capacitor is more tightly coupled to the very low distortion test source, its distortions are partially decoupled, so appear much smaller.

For consistent test conditions, I would normally test such small capacitance values using the 100 kΩ, source impedance.

Using very low source and load impedances, makes even a badly distorting capacitor look relatively good. This is my main objection to the test method used by the CTL1 tester. see Appendix.

This is a measurement quirk, the capacitor still generates the same distortion currents, but the measurement cannot see them. Similarly when testing with a reduced test voltage, the distortion still exists but can be lost in the noise floor and so not seen.

From many measurements of known good and bad capacitors, I found that a compromise between these impedance extremes should be used. Using a 100 Ω current limiting resistor with a 1 µF capacitor gave the best and most consistent results. Good capacitors looked good and bad capacitors looked very bad.

Thus I would normally use the 100 kΩ source impedance when measuring test capacitors of 1 nF and below, 100 Ω source impedance for a 1 µF capacitor at 1 kHz, 1 kΩ source impedance for a 0.1 µF capacitor at 1 kHz, 10 kΩ source impedance for a 10 nF capacitor at 1 kHz and pro-rata for other values/frequencies.

Whether these measured capacitor distortions are audible or not depends on the capacitors location in the circuit, the subsequent gain of the circuit, capacitor voltage levels and whether the capacitor is inside a negative feedback loop.

I cannot determine that. My object was simply to prove absolutely, using easily repeatable methods, that many capacitors can and do distort a very pure sinewave test signal.

Intermodulations.

Is it not possible that any measurable capacitor distortion using a single tone test signal, say distortion greater than -110 dB, will be made many times worse, when subject to a multiplicity of signals ? Thus contributing notable intermodulation distortion.

Intermodulation distortion measurements of such capacitors using just two pure tones, 100 Hz and 1 kHz, do show a multiplicity of distortion products, almost regardless of dielectric. Similar intermodulation distortions have been measured in 'bad' metallised film capacitors, i.e. those which show significant distortion above -110 dB, using a single tone.

Testing good capacitors with the same two tones, no intermodulation products have been seen.

Comparing the single tone test in figure eight with the dual tone test in figure nine, we see distortion products around 2 kHz and 4 kHz in this dual tone test. They are not visible in the single tone test, even though both tests used the same capacitor, voltage levels and source impedance. see **Fig.8 Fig.9**

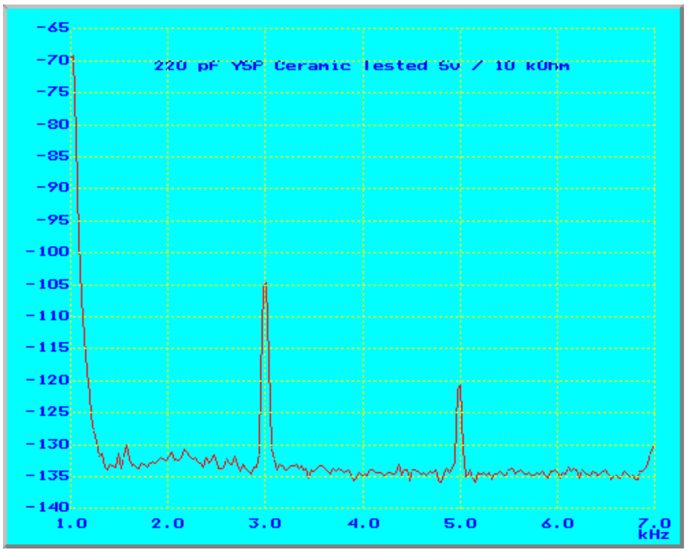


Fig 8) Repeated for convenience. Distortion plot of the figure 7 capacitor, tested exactly the same except for the current limiting resistor, now 10 kΩ. This single frequency plot was made using 10 kΩ for 1 kHz to allow direct comparison with the dual frequency plot of figure 9, made using 100 kΩ source for 100 Hz and 1 kΩ for 1 kHz.

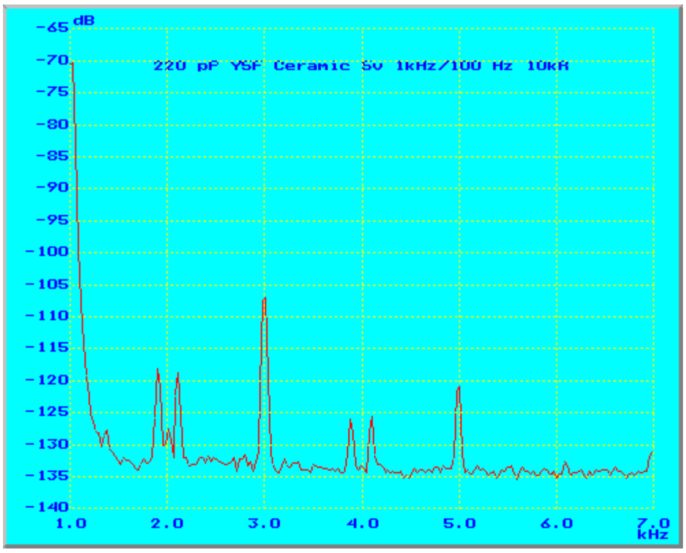


Fig 9) A dual frequency test, intermodulation distortion plot, 100 Hz and 1 kHz, of the capacitor shown in figure 8. Made using the same voltage and 1 kHz source impedance. Notice the appearance of new distortion products around 2 kHz and 4 kHz, not present when using the single test frequency. Bad metallised film capacitors exhibit similar distortions.

The level of distortions measured is naturally dependant on capacitor style, construction and capacitor AC and DC voltages.

Measurement equipment.
I have designed a second printed circuit board, similar to that housing my test oscillator. This board provides both the buffer amplifier and notch filter/pre-amplifier needed to complete a measurement system. The buffer amplifier section is designed so it can be easily separated from the notch filter/pre-amplifier if desired. see **Fig.10**

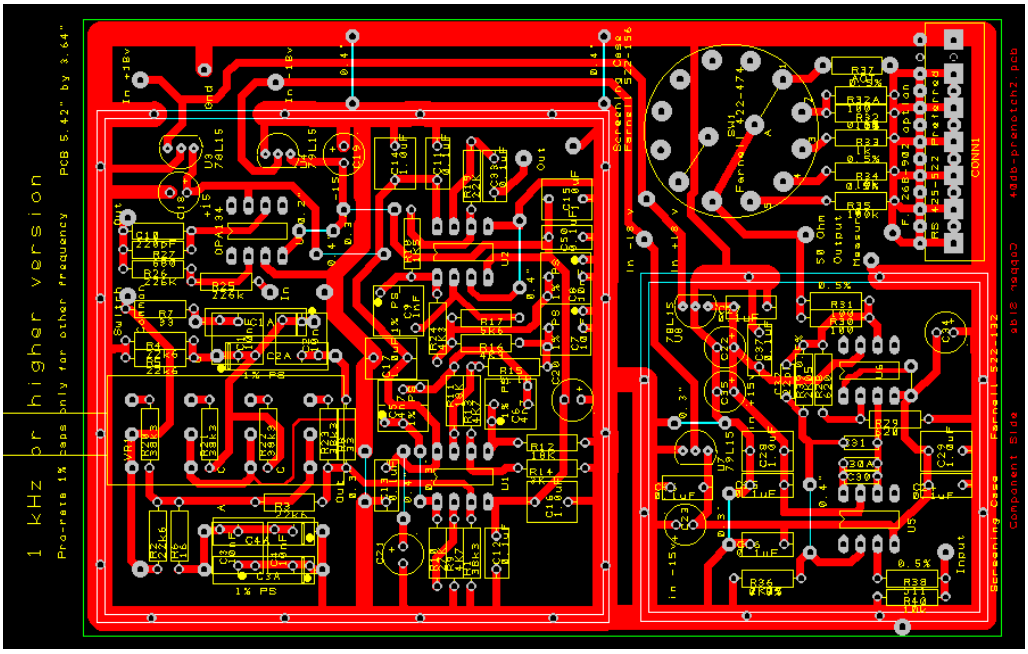


Fig 10) The version II printed board designed for my 1 kHz notch filter/pre-amplifier and low distortion buffer amplifier.

This arrangement was used for all measurement plots in this and my previous article. The board is multi-pierced to allow the widest possible choice of Twin Tee notch and bandpass filter tuning capacitors.

Testing Larger Capacitors.
Above 1 µF it is common practise to change to using electrolytic types, both tantalum and aluminium. To avoid overstressing such capacitors while maintaining similar test voltages, a reduced test frequency must be used. I developed an alternative buffer amplifier, able to drive up to 7 volts and 400 mA at 100 Hz, albeit with slightly greater distortion than for my 1 kHz design. Since electrolytic capacitors distort more than the lower value, better quality film and ceramic types this small increase in distortion is acceptable.

The printed circuit boards for my 100 Hz and 1 kHz generators are identical. The only component differences are the three low loss tuning capacitors, C1, C2, C3 which are 100 nF 1% for 100 Hz. One resistor value, R16 is 1 kΩ for 1 kHz but 0 Ω for 100 Hz. Pads for a wire link have been provided.

The 100 Hz notch and bandpass filters are also based on the 1 kHz design and need ten times capacitance values for 100 Hz. The board layout accepts the Vishay 100 nF 1% MKP capacitors, Farnell 303-8609, also 47 nF Farnell 303-8380. Smaller capacitances were provided using the same capacitor types used for the 1 kHz design. However as can be seen in the photo, the buffer amplifier section of this PCB layout is quite different. see **Fig.11**

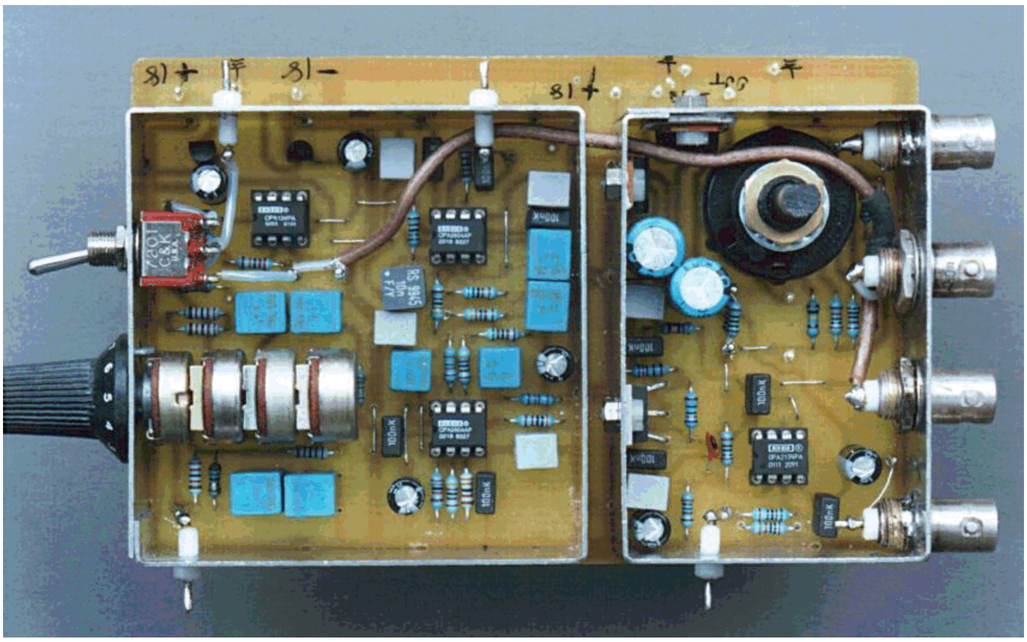


Fig 11) Photograph of the 100 Hz version printed board assembly complete with BNC sockets allowing use with Hewlett Packard test jigs or four separate coax cables.

The board is identical to figures 4 and 10, except for the tuning capacitor values and the higher output current buffer amplifier, designed around an Elantec EL2099C amplifier. The full schematic and PCB layout for this 100 Hz version will be included in a future article.

Constructing the notch filter boards.
To provide a degree of notch filter tuning, a four gang variable resistor is needed, ideally it would be a well matched conductive plastic part. To fit within the screening case it cannot be larger than 18 mm diameter.

I could not find a suitable four gang conductive plastic potentiometer. Alps do list a more modest four gang carbon track design but again I did not find a supplier. Glancing through an old price list from Falcon Electronics. **Ref.2** I found a four gang 4*50 kΩ Alps potentiometer at £1.75, used by Falcon in active crossover filters.

I ordered five potentiometers for evaluation. Apart from being rather old stock needing cleaning and re-tinning of the terminal pins, they worked fine and all were ganged closer than 1 dB. I used these pots in both my 1 kHz and 100 Hz notch filter builds.

With the exception of this variable control, to minimise noise and distortion and for easy replication, all resistors used in the twin tee notch filter signal path up to the first amplifier input, used 0.5% Welwyn RC55C, seen as black in the photo. To save space the four 38k3 series resistors are mounted between the potentiometer and PCB, so are hidden in the photo.

These resistors use plated steel endcaps, which I prefer for reliable long term end contact stability. Many subjectivists claim non-magnetic endcaps are better. I do not subscribe to that belief.

Having emerged from the notch, the fundamental signal has been reduced to a few millivolts, so my usual 1% resistors can be used. Amplified by 40 dB, the maximum output signal is still less than 0.5 volts.

Low distortion, low noise IC's must be used in this amplifier circuit. In my tests I found the OPA134 worked better than the OPA604 for high input levels, but found the reverse when amplifying the tiny voltages output from the notch filter.

For my builds I used OPA134 for the high input impedance, high level, switchable pre-amp U9 and OPA2604 dual IC's for the low level amplifier stages U1, U2.

In each case my preferred IC choice is the first type listed on the schematic drawing.

To facilitate evaluating IC's I used Harwin turned pin sockets for each position.

Similarly for capacitors. Those used in the notch filter must be low distortion, and for the 1 kHz version, 1% COG ceramic or extended foil/Polystyrene types only should be used. At 100 Hz which requires 100 nF, such capacitors are not easily obtained. Foil/Polypropylene then metallised Polypropylene, in order of preference, can be used.

Capacitor Tests.
Having tested one capacitor of a make and type, what guarantee does this give about harmonic distortions generated by other similar capacitors in the same batch.?

In my view that depends totally on the method of manufacture and the particular dielectric used. For the audio perfectionist however, perhaps every signal path capacitor should first be distortion measured.

For example COG ceramic is probably the most stable, and most nearly perfect of all commonly used dielectrics. COG disc and multilayer ceramic capacitors do not rely on pressure contacts or metal spray connections onto their electrodes. One maker's products should measure consistently and with remarkably low distortion. Those from a different maker may measure slightly differently, but again should be consistent from batch to batch.

Polystyrene is another of the best performing capacitor materials. Capacitors made using the extended foil technique and with their lead out wires soldered directly onto the extended foil electrodes, should be consistently nearly perfect.

Distortions in capacitors made using metal spray end contacts to their metallised film dielectric electrodes, for any one film type, will vary more from maker to maker. Worse still, from my measurements, they can also differ considerably even within a small capacitor batch.

Some film capacitor makers however do seem remarkably consistent within a batch and from batch to batch. With other makers I have measured some 20-30 dB different harmonic levels, in quite small batches, even when the capacitors have been supplied taped to card strips.

Having provided a usable, repeatable test method and easily assembled, low cost test equipment, my next articles will explore which capacitor types produce the least harmonic distortion, according to capacitance value.

When possible I shall try to explain how different capacitor constructions can account for the harmonic distortion generated in the capacitor.

With so many capacitor suppliers available, I cannot provide a best buy list. This measurement hardware, which allows repeatable capacitor distortion tests, I feel should be more than sufficient.

My next article will discuss capacitors having values up to 10 nF and soundcard FFT measurement software available on Internet.

References.

1) Capacitor Sounds part 1 C.Bateman — Electronics World July 2002

2) Quad Ganged 50k Linear Alps Pots. — Falcon Electronics. Norfolk. 01508 578272

3) Harmonic testing pinpoints passive component flaws. V.Peterson & Per-Olof Harris. — Electronics July 11, 1966.

4) CLT1 Component Linearity Test Equipment data sheet. — RE Instruments AS. Copenhagen.

5) Understanding capacitors - Aluminium and tantalum C.Bateman — Electronics World June 1998 p.495.

Appendix

Other measuring methods.

In the sixties, engineers at Ericsson believed that non-linearities in capacitors and resistors could be detected. They measured the level of third harmonic distortion generated in a component subject to a very pure sinewave test signal. **Ref.3**

Non-linearities were believed to result from badly ground resistor spirals, poor electrical contacts and non-linear materials. At that time poor contacts, especially in capacitors were commonplace. Fortunately today, with improved techniques, poor contacts in capacitors are now quite rare.

Their original non-linearity detector design produced low distortion test signals at 10 and 50 kHz. Third harmonic distortion generated by the component under test was passed through bandpass filters for measurement. Subsequently the 50 kHz test frequency was dropped and a commercial instrument, the CTL1 component linearity tester, was produced by Radiometer of Denmark. **Ref.4**

To accommodate the range of component impedances and test voltages needed, a low distortion output transformer was used. Having seven adjustable tappings, it was used to tightly couple the instrument to the component under test. Component impedances from 3 Ω to 300 kΩ could be directly measured, using source impedances from 0.05 Ω to 500 Ω respectively.

When testing lower impedance capacitors, the CTL1 datasheet which I still have, claimed to be able to output 0.58 A maximum. Resulting in a maximum test voltage around 100 mVolts at 10 kHz testing a 100 µF capacitor. In my view this is not sufficient to reveal the true characteristics of such an electrolytic.

Today an updated version can be obtained from Danbridge A/S, Denmark, a specialist manufacturer of capacitor test instruments.

Some specialist audio suppliers quote distortion levels for Electrolytic capacitors, measured using the CTL1 meter. Because of the capacitance values measured and the 10 kHz test frequency, usually these results are based on extremely small test voltages, which often seem to be ignored in subsequent distortion claims, especially regarding usable dynamic range attained.

Such small test voltages will not harm the capacitor and will reveal any shortcomings in the metallic connections used in an electrolytic capacitor. However in my experience, today these are at such low level as to be unimportant.

Most important and relevant to audio in my view, are the inherent distortions which result from the electrolytic capacitor's diode characteristics. This diode characteristic is easily measured. **Ref.5**

From my test measurements at 100 Hz and 1 kHz, I find significant and measurable distortions when testing electrolytics, using voltages above 0.5 volts, but less so at very low test voltages.

This is exactly the result to be expected from consideration of the constructions used to manufacture these capacitors.

Extremely tight coupling between the test capacitor and the linearity tester is implicit in the CLT1 equipment design. From my early work measuring capacitors, I found it necessary to loosen this coupling in order to clearly reveal anomalies, now found in many modern capacitors.

By trial and error measuring known good and bad capacitors at 1 kHz, I found that 100 Ω in series with a 1 µF capacitor provided the best compromise between measuring current and capacitor voltage. Adjusting this resistance value according to the capacitors impedance, at the test frequency used.

Soundcard FFT Software.

In this and my earlier article I used my Pico ADC-100 for all measurements, with the latest software downloaded from their site. However many readers will not have this ADC and wish to use a soundcard instead. A modern low cost PCI card with FFT software can provide improved capability, measuring even smaller distortions using my instruments, than is possible using the ADC-100.

The software I choose to use for the remainder of this series, is the 'Spectra 232Plus' FFT software. It can be downloaded from:- http://www.telebyte.com/pioneer

Should you have only an older ISA soundcard, some software may not work. One that will, is FFT.EXE, a DOS program by Henk Thomassen. This can be found on Internet, also the Elektor 96-97 software CD-ROM.

Users having a modern PCI soundcard will find a very large variety of programs, often available as freeware, on Internet. One site which links to some of the better packages is :-

http://www.pcavtech.com/links/index.htm.

Capacitor Sounds 3 - capacitances of 10 nF and smaller.

Updated & expanded March 2003.

Original version Pub. Electronics World October 2002 - C. Bateman.
Readers of my recent articles have seen that many capacitors do introduce distortions onto a pure sinewave test signal. **Ref.1** In some instances this distortion results from the unfavourable loading the capacitor imposes onto its driver circuit, frequently the distortion is generated in the capacitor.

When two or more signals are involved, a distorting capacitor produces a multiplicity of new frequencies. Used in an audio system, this can result in distorted sound. see **Fig. 1**

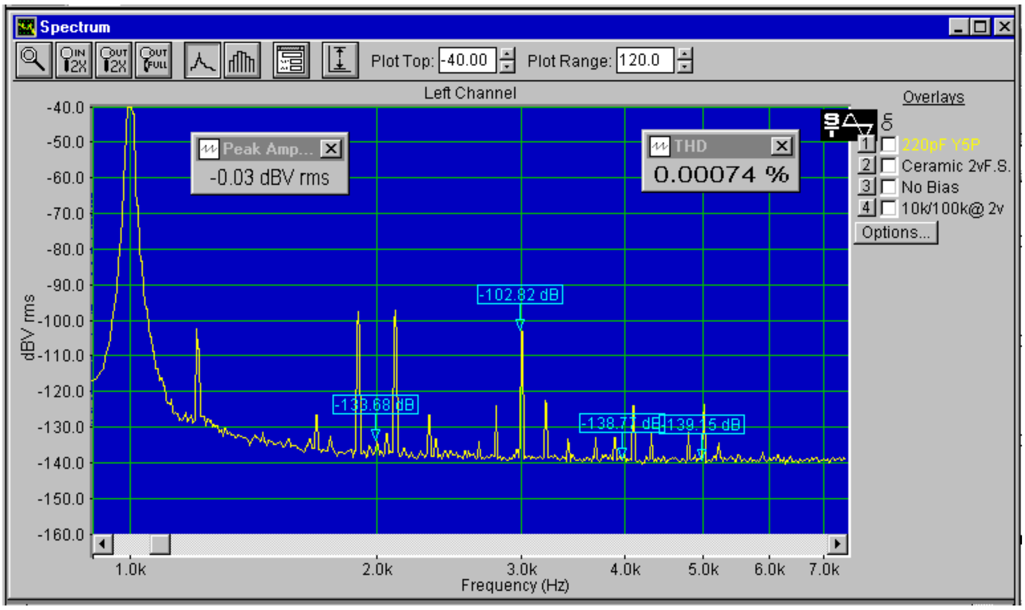


Fig 1) Y5P is a medium 'k' class 2 ceramic. Tested with two signals, 100 Hz and 1 kHz at 2 volts amplitude, with no bias network, the capacitor produces many new intermodulation distortion frequencies.

To better indicate differing distortions found with change of test parameters, measurements are now made using a computer soundcard with FFT software, replacing the Pico ADC-100. The chosen software facilitates analysis, by calculating distortion relative to the voltage across the test capacitor. As can be seen the consequent increase from 12 to 16 bit ADC resolution has improved the measurement noise floor. see Appendix **Soundcard FFT Software**

Many capacitors which distort little when sinewave tested without a DC bias voltage, exhibit much bigger distortions with increasing polarisation. With 18 volt DC bias the second harmonic, of the figure 1 capacitor, increased by 23 dB, but other harmonics hardly change. see **Fig. 2**

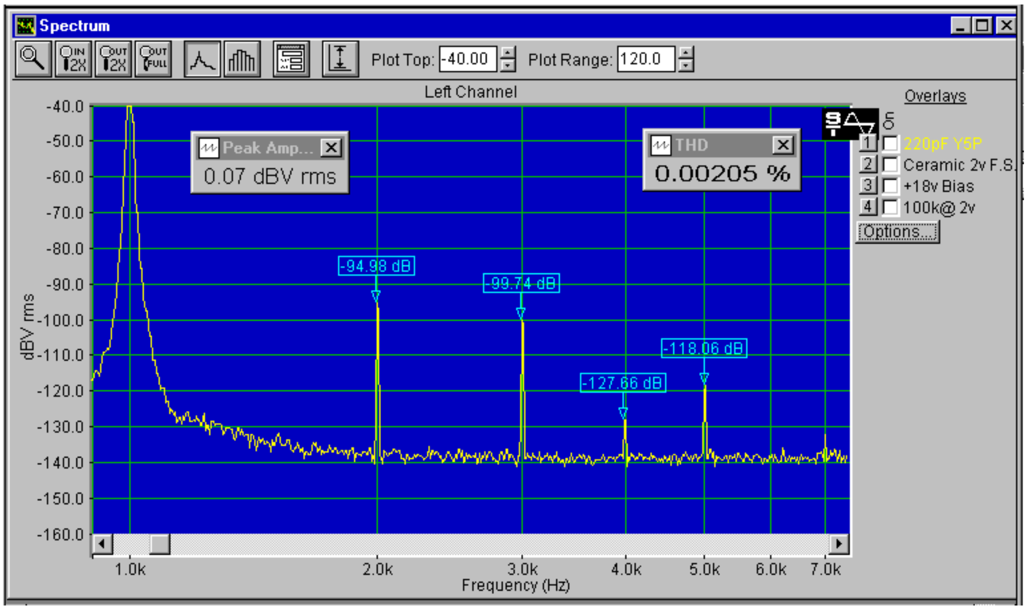


Fig 2) The figure 1 capacitor tested using 1 kHz only with 18 volt DC bias.

Compared to its 0 volt bias test, second harmonic has increased 23 dB, a 14 times distortion increase.

The need to test with and without applying a DC polarising voltage and using two frequencies was not planned. While I was attempting to rationalise the results of a great many single frequency no bias measurements against known differences in capacitor constructions and measured parameters, I slowly realised that single frequency no bias testing would not suffice. My attempts at rationalisation using only single frequency no bias results would fail.

Why should this be ?
As a capacitor design engineer of many years, when I commenced these tests, I believed that capacitor distortions would relate directly to the capacitor's measured tanδ. This belief was based on prior knowledge that high 'k' ceramics distort more than low 'k' and much more than COG, dielectrics which have measurably different tanδ. Dielectric absorption however does not appear to significantly affect these tanδ measurements, so I reasoned it should not greatly affect a capacitor's sound.

I certainly was not alone in this belief, which was shared by my colleagues.

After many weeks trying to analyse a great many single frequency, no bias, capacitor distortion measurements, relating the effects of known construction differences and measurements of capacitance and tanδ with and without DC bias up to 50 volts using my precision bridge, I was not able to understand why many distortion plots did show large differences in second harmonic distortion. I had expected and did find easily reconciled differences in third harmonic distortion.

These second harmonic changes were found even in capacitors having no measurable voltage coefficient of capacitance or tanδ. Lacking any voltage coefficients I had to accept these distortions may in fact be a direct result of dielectric absorption effects.

So began a slow learning process, which from my many years working with and designing capacitors, was quite unexpected.

More than 2000 distortion measurements have been made, using dual frequency 100 Hz and 1 kHz test signals from 0.1 volt to 6 volt AC and DC bias from 0 volt to 30 volt . Using a variety of capacitors, specially purchased for these tests and observing the effect of changing one measurement stimulus at a time, I was then able to reconcile the different distortions.

Starting in January 2002, these measurements together with their analysis, occupied many weeks. With a 30 minute warm up, my test equipment performed consistently throughout, producing exceptionally low distortion.

From analysing these distortion measurements, together with measurements of dielectric absorption, capacitance and tanδ with and without DC bias, I now realise dielectric absorption does influence measured distortions, even if the capacitor measures as a low tanδ using a bridge. see box **Tanδ/ESR.**

As will be seen later in this series, when a capacitor is used with significant DC bias relative to its dielectric thickness, dielectric absorption then becomes the dominant distortion producing mechanism.

Whether these measurable capacitor distortions become audible or not, depends on the capacitor's location in the circuit. The capacitor voltage levels, any subsequent circuit gain and whether the capacitor is located inside or outside a negative feedback loop.

Repetition.
As a result it became necessary to repeat most of my early single frequency tests, but now using two frequencies. Distortion was measured both with and without DC bias voltage applied to the capacitor. To replicate many circuit voltages without over-stressing most capacitors, for this article I standardised on 18 volt DC bias. Apart from Figure 1, the bias network was left in situ, being switched to discharge the capacitor when making no bias measurements.

My 1 kHz notch filter preamplifier was designed to attenuate 100 Hz by some 55 dB. A 100 Hz test signal, similar in amplitude to the 1 kHz signal, can be input without overloading the preamplifier or soundcard. **Ref.1**

To apply a DC bias voltage across the test capacitor, a protective 'DC Bias' network must be used. I already had one, built many years ago, using 100 μF and 1 μF 250 volt rated metallised PET capacitors, which I used to measure capacitance change with applied DC bias, of capacitances up to 10 μF.

A DC bias network comprises capacitors used to block any DC applied to the capacitor under test from entering the measuring equipment, the bias voltage being applied to the test capacitor using current limiting resistors which act to isolate the test signals used from being attenuated by the DC power supply.

A much larger value, higher voltage rated, DC blocking capacitor is used to pass the test voltage/current from the generator into the capacitor under test. A higher voltage but usually smaller value capacitor is used to transfer the test capacitor test voltage together with any distortion, into the measuring system.

When tested with my near perfect 1 μF KP test capacitor **Ref.2**, I found my old metallised PET capacitor bias network, which had no measurable voltage coefficient up to 50 volts DC, introduced its own quite significant distortions.

A new network was required. It was assembled using 11 μF and 1 μF MKP capacitors with a 100kΩ charge/discharge resistor. Another 100kΩ resistor to ground, protects the pre-amplifier/notch filter input from charge/discharge transients, but limits our measurements to using 10kΩ or smaller sense resistors. see **Fig. 3**

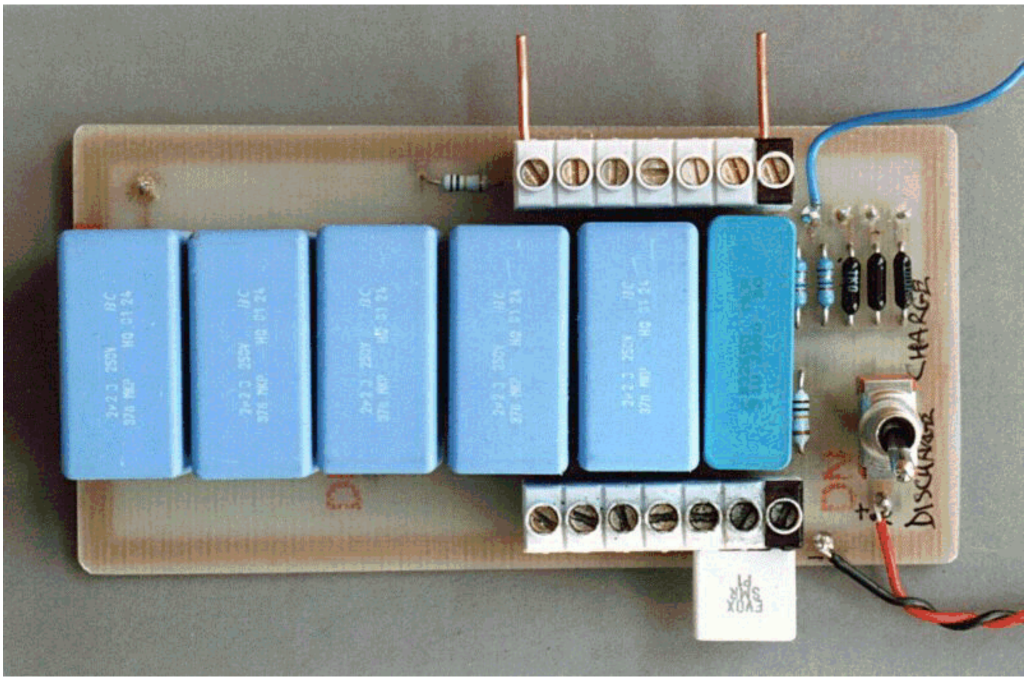


Fig 3) The new DC bias prototype assembly as used for all published tests.
A fly lead connected to the hot AOT resistor terminal, a duplicate set of source resistors and five 2.2 µF MKP blocking capacitors, couple the 1 kHz test signal to the test capacitor.
The test capacitor output is fed to the notch filter via a 1 µF capacitor.
A current limited 100 Hz test signal may be input to the top left terminal, DC bias to bottom right.

This new DC Bias network permits accurate distortion measurements with dual 1 kHz/100 Hz test signals up to six volts AC and with up to 50 volt DC bias. It is quickly attached to or removed from my existing test equipment. **Ref.1** It is designed to mount in place of the test capacitor, shown in the figure. see **Fig. 4** also box **DC Bias Network**

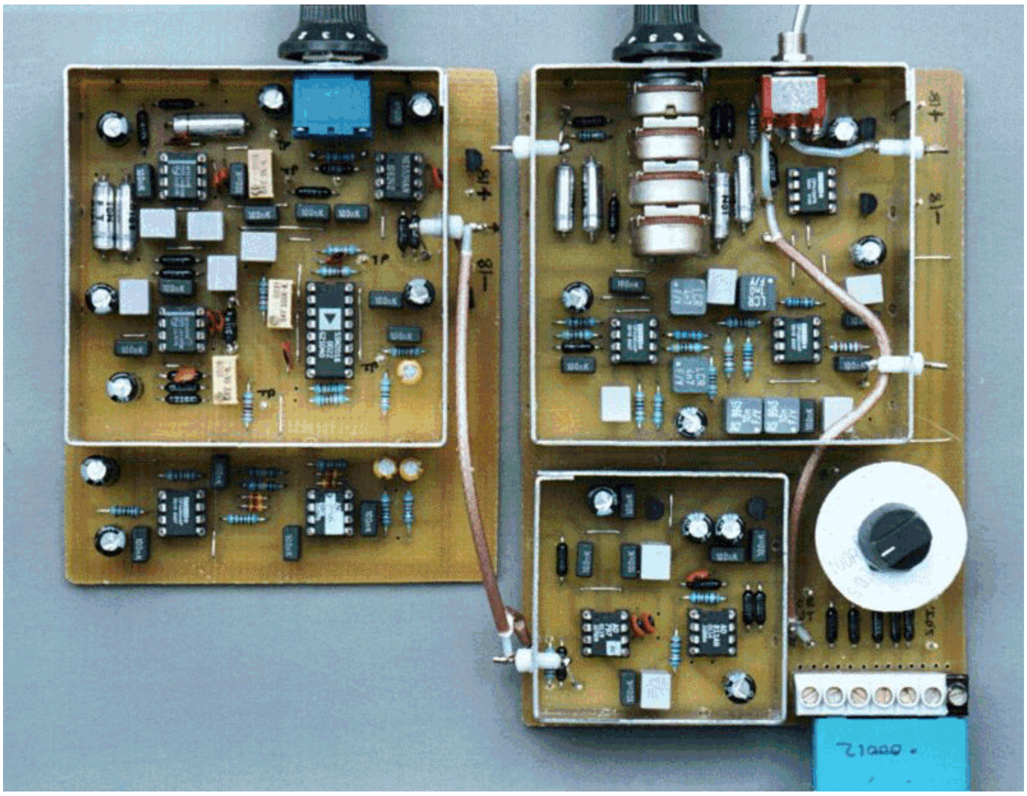


Fig 4) Low distortion test equipment measuring distortion of a capacitor with AC test signal, as described in my last two articles.

To measure capacitors with DC bias, the network of Figure 3 with test capacitor attached, replaces the test capacitor shown bottom right.

Capacitor Myths.
Many articles have been written about capacitor behaviour, mostly by authors having little knowledge of capacitor design and construction. As a result, many popular but false capacitor myths have emerged.

I will try to relate some of these false myths to measurements and capacitor facts:-

a) All ceramic capacitors distort.
b) Dielectric absorption causes smearing and compresses dynamic range.
c) Polypropylene is an inefficient material.
d) Capacitors are highly inductive at audio frequencies.
e) ESR of a capacitor has a fixed value.

Capacitor production tests.
In manufacture every capacitor is measured for capacitance and tanδ, usually at 1 kHz. Capacitance values of 100 pF and smaller are measured at 1 MHz. Capacitors larger than 1 µF are usually measured at 100 Hz. see **ESR / Tanδ.**

Each capacitor is 'voltage proof' tested at higher voltages to ensure reliable operation at rated voltage. Leakage current or insulation resistance, will be measured at the specified time interval or less. This is a time consuming measurement, so to save production time, leakage currents/insulation resistances are always extremely conservatively stated.

Many other tests will be performed on sample capacitors, to ensure compliance with National periodic 'Type Tests', but I know of no company which routinely tests for harmonic distortion, using realistic circuit voltages.

Capacitors are not categorised for distortion, so a distorting capacitor would not be considered defective by its maker. It is the responsibility of the equipment designer to select the correct capacitor for each circuit requirement.

Tanδ measurement reflects both insulation resistance and series resistive losses. Invariably the LCR meters used include a 'tuned' detector, designed to exclude extraneous frequencies. As will be seen later, dielectric absorption affects the second harmonic, so is mostly transparent when measuring tanδ. see **Fig. 2**

ESR / Tanδ.
Tanδ is used to describe capacitor quality. A textbook perfect capacitor has a phase angle of 90°, a phase angle deviation of 0°, a Tanδ of zero. Using a Wayne Kerr 6425 precision LCR meter, Tanδ of a most nearly perfect 10 nF capacitor at 1 kHz measured just 0.00005, a phase angle deviation less than 0.003°. These measurements were made on a Philips 10 nF 1%, axial lead, extended foil and Polystyrene capacitor, exactly as used in my 1 kHz generator circuit. see **Fig. 7**

Some of the resistive losses which contribute to Tanδ are due to leadout wires and metal electrodes, so are relatively constant. Tanδ then increases with frequency. At 10 kHz, Tanδ for this capacitor was measured at 0.00015 and just 0.0005 at 100 kHz.

In past years capacitor quality was sometimes described as a 'Q' value, which is the reciprocal of Tan δ. 'Q' for the above capacitor was 20,000 at 1 kHz, 6,666 at 10 kHz and 2,000 at 100 kHz.

Tanδ is measured using phase sensitive detectors, either by measuring the capacitors impedance and phase angle, or the capacitor's resistive and reactive component vectors.

In which case, Tanδ = resistive vector / reactive vector.

This resistive vector is called ESR thus ESR = Tanδ × reactive vector.

Since Tanδ is frequency dependant, obviously ESR must also vary with frequency. At low frequencies, ESR reduces with frequency, up to the self resonance of the capacitor. At self resonance, the capacitive and inductive reactances have equal and opposite values, so cancel out. The capacitor's ESR is then equal to its measured impedance. For that frequency only, it can be measured using a signal generator and voltmeter.

At higher frequencies, ESR usually increases. The abbreviation TSR, for True Series Resistance, is often used by capacitor engineers to describe this minimal value of ESR.

The LCR meter readings for ESR of the above capacitor, recorded 0.8 Ω for 1 kHz, 0.26 Ω for 10 kHz and 0.08 Ω for 100 kHz.

Self inductance acts to reduce the capacitor's measured reactance value. But capacitive reactance at a frequency is inversely proportional to capacitance value. This means a capacitor's self inductance actually acts to increase, the measured capacitance value of a capacitor. Some writers have suggested inductance acts to reduce measured capacitance, that is incorrect.

This inductance increasing measured capacitance effect, explains why a plot of capacitance v frequency, shows a steep increase in measured capacitance as measuring frequency approaches the capacitors self resonant frequency.

A fuller description of Tanδ together with a proven measurement circuit, was included in my articles describing the construction of an in-circuit meter. **Ref.7** This meter was custom designed to identify good/bad PCB mounted electrolytic capacitors by measuring their Tanδ while in-circuit.

Dielectric characteristics.
In essence two major dielectric characteristics exist, polar and non-polar. By polar I am not referring to an electrolytic capacitor, but how the dielectric responds to voltage stress. This stress relates to the volts per micron gradient across the dielectric, not simply the applied voltage.

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

Under 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. Producing heat in the dielectric with power loss, called dielectric loss, together with second harmonic distortion.

Until recently this 'space charge' remained largely hypothetical, but now, using an acoustic pulse method, it has been measured in practical insulators. Sponsored by an EPSRC grant, professors Fothergill and Alison developed a practical working method enabling 'space charge' to be measured and visually observed within an insulator. see http://www.le.ac.uk

Non-polar dielectrics exhibit very small dielectric loss. Polar dielectrics are more lossy and take longer for the dielectric to return to its original uncharged state. Polar dielectrics produce easily measured 'dielectric absorption' effects, which becomes especially apparent in very thin dielectrics as voltage stress per micron of dielectric thickness increases.

Dielectric absorption is usually measured by fully charging the capacitor for several minutes then briefly discharging into a low value resistor. After a rest period, any 'recovered' voltage is measured. The ratio of recovered voltage to charge voltage, is called dielectric absorption. This method of course only measures dielectric absorption as a DC effect, ignoring AC effects.

Ceramic capacitors.
'Ceramic' covers an extremely wide range of dielectrics. In the seventies the Erie Company produced more than fifty different capacitor ceramic formulations, sub-divided as Class 1 (non-polar) or Class 2 (polar) according to the materials used.

Class 1 ceramics do not contain Barium Titanate, so have a low 'k' value. The best known is C0G. With its controlled temperature coefficient of zero ± 30 ppm, it was originally called NP0 by the Erie Corporation. It is non-polar and has a small dielectric absorption coefficient. From my tests it has almost no measurable harmonic distortion. COG ceramic is more stable with time and temperature than mica capacitors and from my tests COG can produce less distortion. **see Fig. 5**

C0G ceramic provides the most stable capacitance value, over long time periods and temperature excursions, of all easily obtained capacitor dielectrics. It is frequently used as a capacitance transfer standard in calibration laboratories. Yet as a small disc capacitor it costs only pennies. Assembled as a multilayer, it can provide capacitances of 100 nF and above, rated for 100 volts working, and much higher voltages for smaller capacitances.

Other Class 1 ceramics, sometimes called 'low k', provide increased capacitance within a controlled temperature coefficient, e.g. P100, N750 etc. in ppm. These also are non-polar and exhibit little dielectric absorption. I have tested up to N750, sometimes called U2J, and found very low distortion.

Class 2 ceramics do include Barium Titanate. It produces a very high dielectric constant, with 'k' values ranging from a few hundred to several thousands depending on other additives used. Class 2 ceramic is strongly polar, its capacitance varies with applied voltage and temperature. It exhibits an easily measured dielectric absorption, which increases with 'k' value.

Popular Class 2 ceramics include the X7R, W5R, BX capacitor grades and the exceptionally high 'k' Z5U. These do produce extremely large measured distortions, so are not suited for use in the signal path of an audio system. see **Fig. 6**

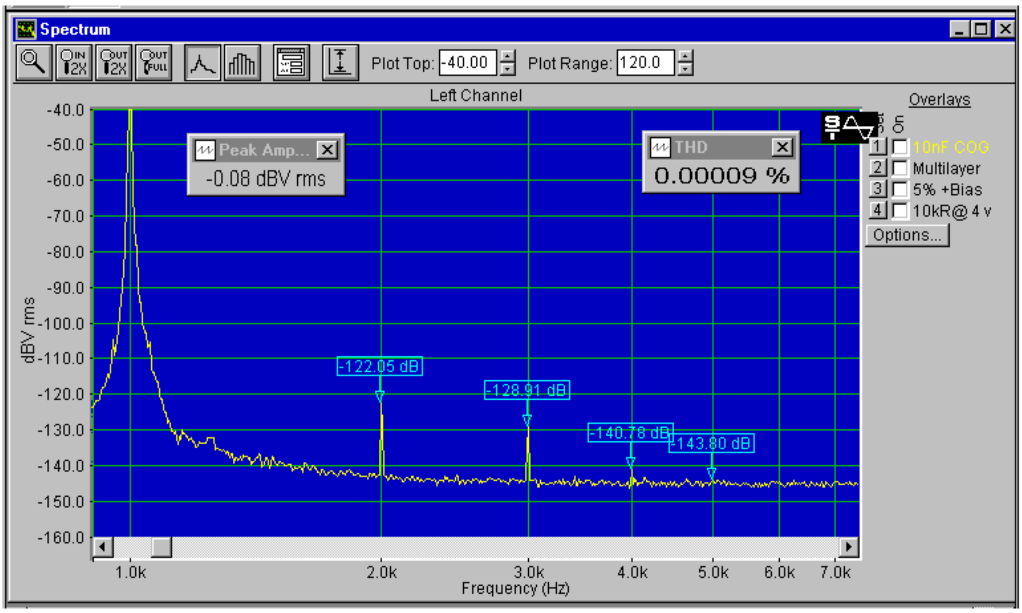


Fig 5) Distortion measurement of a 10 nF Class 1 COG ceramic using 100 Hz and 1 kHz signals at 4 volts and with 18 volt DC bias.

With no bias this tiny COG 10 nF 50 volt multilayer capacitor measured just 0.00006%. Second harmonic was -128.5 dB, the other levels remained as shown.

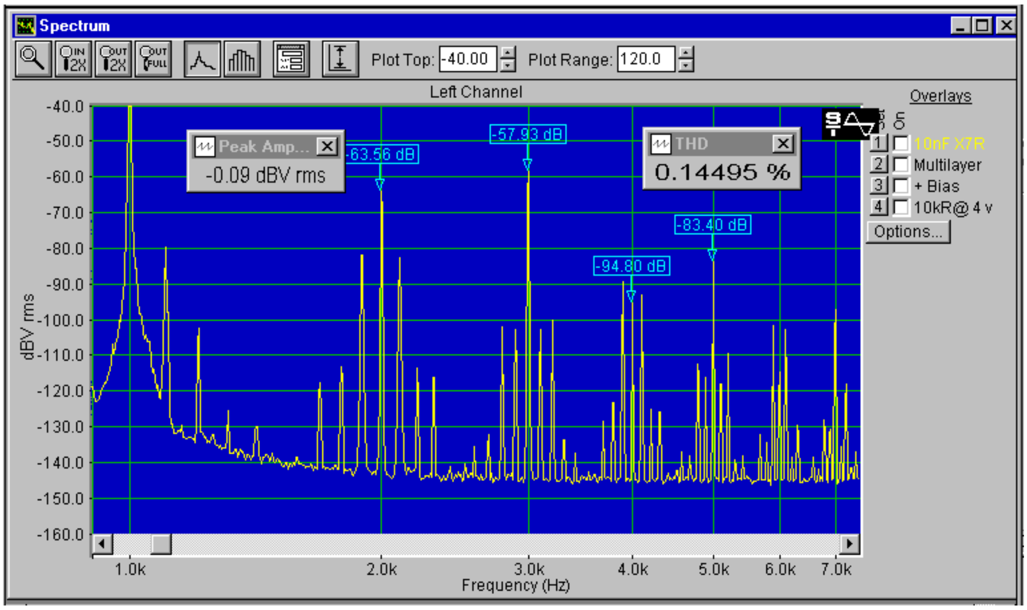


Fig 6) A Class 2 X7R ceramic 10 nF capacitor from the same European maker as figure 5 and tested exactly the same.

This test dramatically shows the impact an increase in both tanδ, voltage coefficient and dielectric absorption have on capacitor distortions.

Film capacitors.
Film dielectrics have smaller 'k' values, ranging from 2.2 for Polypropylene (PP) to 3.3 for Polyethylene Terephthalate (PET). **Ref.3** More significant than 'k' value is just how thin the film can be produced and used to assemble capacitors.

Perhaps the best performing of the easily obtained plastic film dielectrics, Polystyrene is now becoming less popular. It has an N150 temperature coefficient, a very small tanδ and the smallest dielectric absorption coefficient of all film materials. It softens around 85°C and cannot be metallised or used thinner than 4 microns, to manufacture capacitors. see **Fig. 7**

Some makers of foil/Polystyrene capacitors wind the elements using two metal 'inserted tabs' to connect to the external leadwires. The best performing foil/Polystyrene capacitor are wound using the 'extended foil technique'. Wound together with solderable soft metal electrodes, this dielectric was used for many years, to produce vast quantities of 1% tolerance, high quality very low distortion capacitors, with values up to several µF.

Foil and film capacitors cannot self-heal. They must be made using film of sufficient thickness to with stand the required voltage without self-healing and the stress of being wound together with metal foil electrodes.

All other popular film dielectrics can be metallised. They can be used to produce small, low cost, metallised film capacitors having a limited current handling ability. Alternately, using the superior foil and film assembly to produce larger and higher cost capacitors for the same value and voltage. Foil and film capacitors survive larger AC currents, than metallised film types.

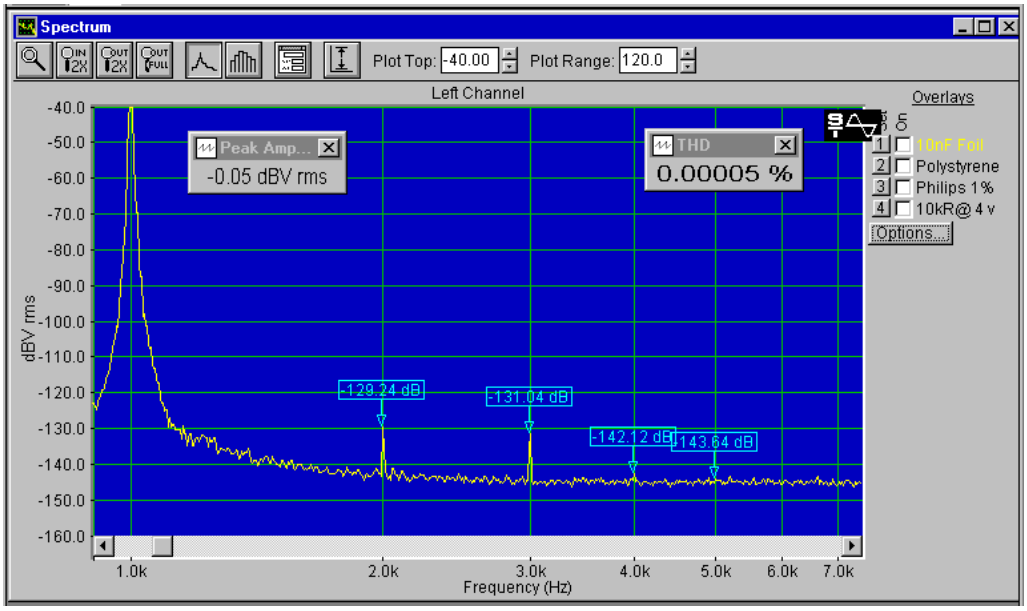


Fig 7) This now discontinued Philips extended foil/Polystyrene 1% axial lead capacitor, with 4 volt signals and 18 volt DC bias, shows negligible distortion.

With test signals increased to 6 volt and DC bias to 30 volt second harmonic increased less than 4 dB and distortion to 0.00007%. No visible intermodulation.

Metallised film capacitors.
Metallised film capacitors rely on 'self-healing' to 'clear' minor insulation faults, so can be assembled using very thin films, their metallised electrodes adding almost no thickness. Capacitance is inversely proportional to dielectric thickness so they provide large capacitance and small size.

PET has very high tensile and voltage strengths and is easily metallised. Film thinner than 1 micron can be used in 50 volt capacitors. It is polar with 0.5% dielectric absorption and a relatively high 0.5% tanδ. Capacitance and tanδ are strongly temperature and frequency dependant. With up to 3% capacitance change in two years, it has poor long term stability.

A metallised PET capacitor rated for 100 volt may use film perhaps 1 micron thick. A foil and film PET capacitor might be made using 5 micron thick film. With 5 times the volts/micron stress, we measure more distortion with the metallised film type.

In contrast, non-polar PP, has a very small dielectric absorption of 0.01% and low tanδ of 0.03%. It has notably less tensile strength and is very much more difficult to metallise. Assembling capacitors using PP film thinner than 4 micron is difficult, so PP is best suited to producing higher voltage capacitors.

With dielectric losses only slighter higher than C0G ceramic or Polystyrene and usable to 105°C, PP can provide large capacitance high voltage capacitors, suited for use on AC or DC. Since its introduction more than 30 years ago, it has produced the most reliable capacitors used in the high stress line-scan circuits of domestic TV receivers. PP is one of the most efficient, and low loss dielectrics.

Capacitor connections.
For the best undistorted sound, dielectric choice is obviously all important. But using the best dielectric materials does not guarantee a non-distorting capacitor.

A poor dielectric principally influences the levels of the second and even harmonics produced by the capacitor.

An internal non-ohmic connection in the capacitor however, introduces significant levels of odd harmonics, the third having the biggest amplitude. **Ref.4**

Disc ceramics use solder connections to a sintered, usually silver, electrode. Multilayer ceramics mostly use precious metal sintered end termination, with soldered wire leads. I have not found ceramic capacitors with non-ohmic end connections. All class 1 ceramics I measured, have produced negligible and mostly second harmonic, distortions.

From research carried out in Sweden by the Ericsson Company a non-ohmic connection can exist in film capacitors. All metallised film and many foil and film capacitors use a 'Schoop' metal spray end connection to connect the capacitor electrodes to the lead-out wires.

I have measured many metallised film capacitors having very large third harmonic levels, frequently as much as +20 dB higher than others in the same batch.

I have not found this problem when foil electrodes are used with the same dielectric.

To avoid any possibility of a non-ohmic end connection we could use a solderable, soft metal foil electrode and solder it directly to the lead out wires. This is exactly the time proven assembly used by a large maker of extended foil/Polystyrene (PS) capacitors. It produces a near perfect, non-distorting, capacitor. see **Fig. 7**

Unfortunately few manufacturers still make PS capacitors. Many have changed their production over to extended foil/PP, retaining the soldered end connections.

Polystyrene dielectric has almost unequalled electrical properties but softens at low temperatures, so cannot be flow soldered into a circuit board. It is attacked by many solvents so boards with unprotected capacitors are not easily cleaned.

Self Inductance.
Each electrode turn of an extended foil or metallised film capacitor, is short circuited to every other turn, so contributes almost no self inductance. Self inductance of a capacitor body is then less than its equivalent length of leadwire. These capacitors have almost no self inductance, apart from the 7 nH per cm of the leadwires used to connect them into circuit.

By way of interest I measured the resonant frequency of a 10 nF 'Tombstone' capacitor. **Ref.5** A vertical mounting, extended foil, axial wound capacitor. This construction has a small footprint but increased inductance due to its one extended leadout wire. The self resonance frequency was above 10 MHz. At audio frequencies, such small self inductances are clearly unimportant.

Low distortion choice.

For the lowest distortion I still prefer PS, however from my measurements, it proved almost impossible to distinguish between an extended foil/PS and a similarly made foil/PP capacitor, apart from small increases in second harmonic, measured for the PP versions. Both types are easily available from mainstream distributors in values up to 10 nF. see **Fig. 7, 8, 9.**

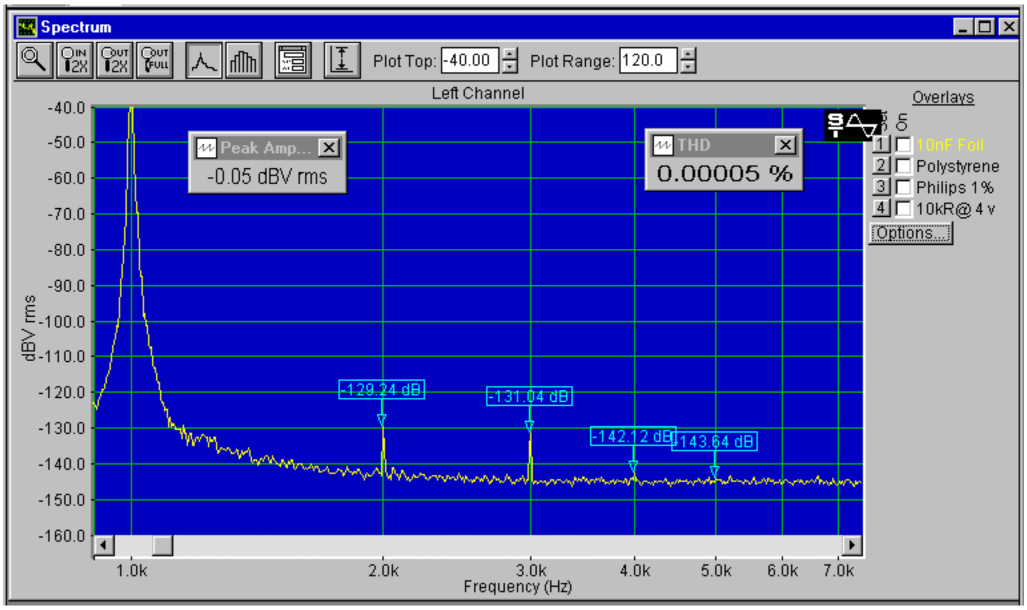


Fig 7) Repeated for reference.
This now discontinued Philips extended foil/Polystyrene 1% axial lead capacitor, with 4 volt signals and 18 volt DC bias, shows negligible distortion.

With test signals increased to 6 volt and DC bias to 30 volt second harmonic increased less than 4 dB and distortion to 0.00007%. No visible intermodulation.

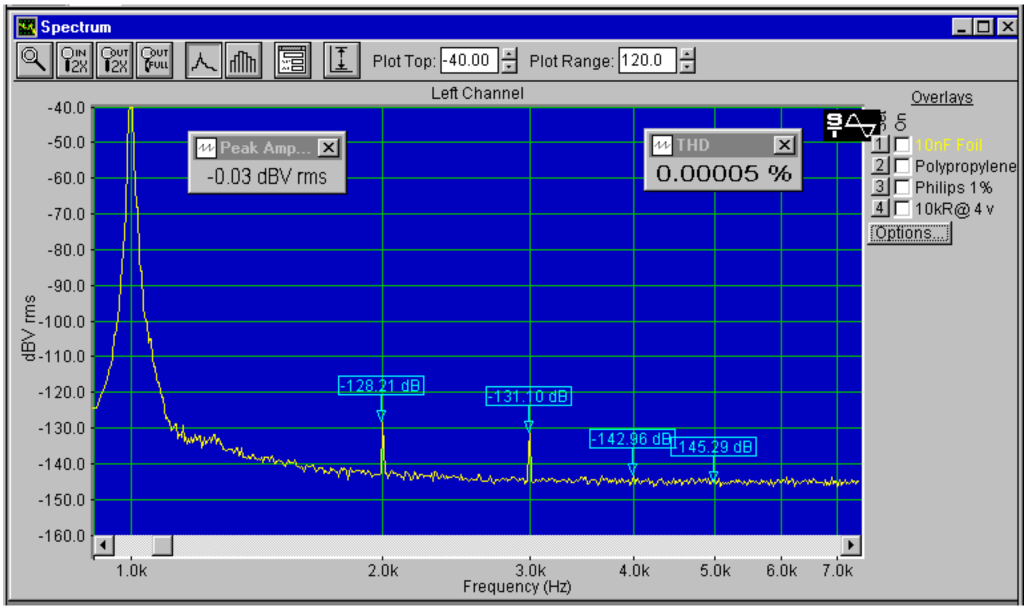


Fig 8) The makers replacement extended foil/Polypropylene shows the same 0.00005% distortion but second harmonic is 1 dB worse.

With test signals increased to 6 volt and DC bias to 30 volt second harmonic increased just over 5 dB, distortion to 0.00008%. Again no visible intermodulation .

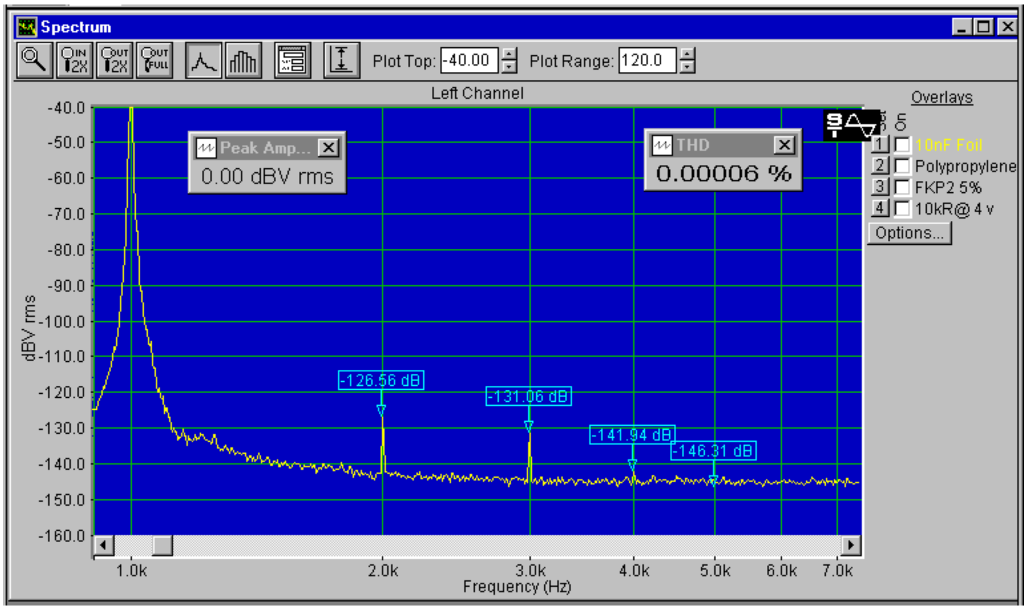


Fig 9) The tiny Wima FKP2 foil/Polypropylene capacitor shows similar performance except for 2 dB increased second harmonic.

Distortion just 0.00008% with 6 volts stimulus and 30 volt DC bias.

For small, low distortion capacitors up to 10 nF, my personal choices would be C0G ceramic, perhaps also including discs up to N750, extended foil/PS or extended foil/PP, with the leadout wires soldered to the electrodes.   see **Figs. 5, 7, 8 and 9.**

Alternative capacitors.

Perhaps because of size, price, temperature range or voltage the above small selection is not suitable. Stacked Mica is still available, but from my tests can be variable. I have some which are at least thirty years old with almost no measurable distortion. However a small batch of 1 nF, purchased specially for these measurements, distorted badly. One sample was even unstable, showing significant and variable third harmonic.   see **Fig. 10**

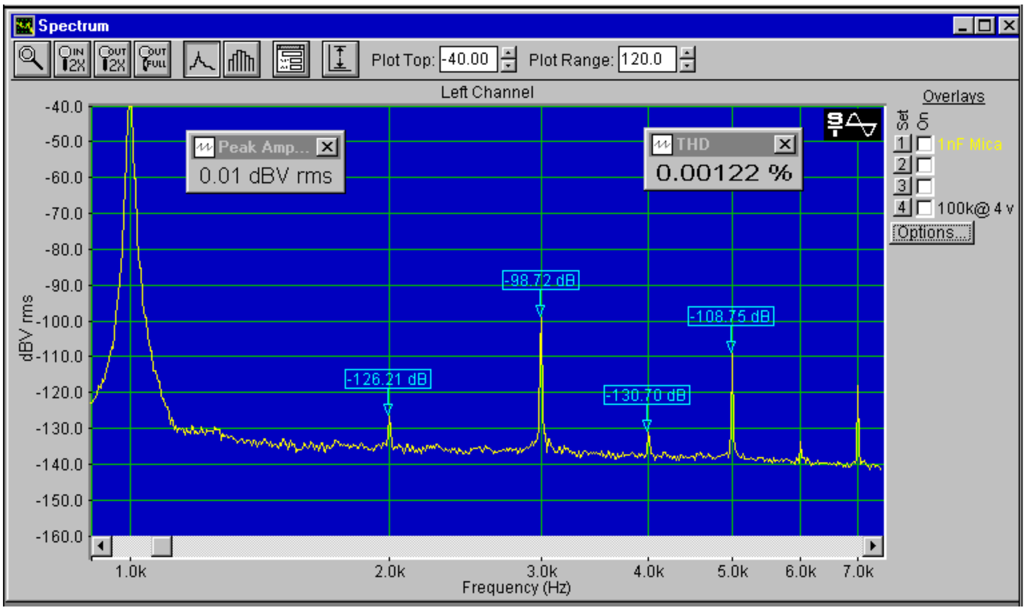


Fig 10) Despite cleaning and re-tinning its oxidised leadout wires, this 1 nF Mica capacitor, single frequency tested at 4 volts 1 kHz and no bias, clearly has an internal non-ohmic connection problem.

I have measured very low distortions with Wima FKC2 foil and Polycarbonate capacitors. Bayer has discontinued production of Makrolon Polycarbonate film, so FKC2 capacitor production may cease.

No doubt because of the thicker PET film used, I have measured surprisingly low distortion when testing Wima 10 nF 100 volt FKS2 foil and PET capacitors. Results were almost as good as the FKP2 foil and PP of Figure 8. Tested with 30 volt DC bias, second harmonic distortion was only 2 dB worse than for the PP capacitor. Unfortunately this FKS2 style is not available in larger values

Having measured several hundred metallised PET capacitors, I have found many with extremely low distortions when measured without DC bias. I have also found far too many showing very bad distortions, with and without DC bias.   see **Fig. 11**

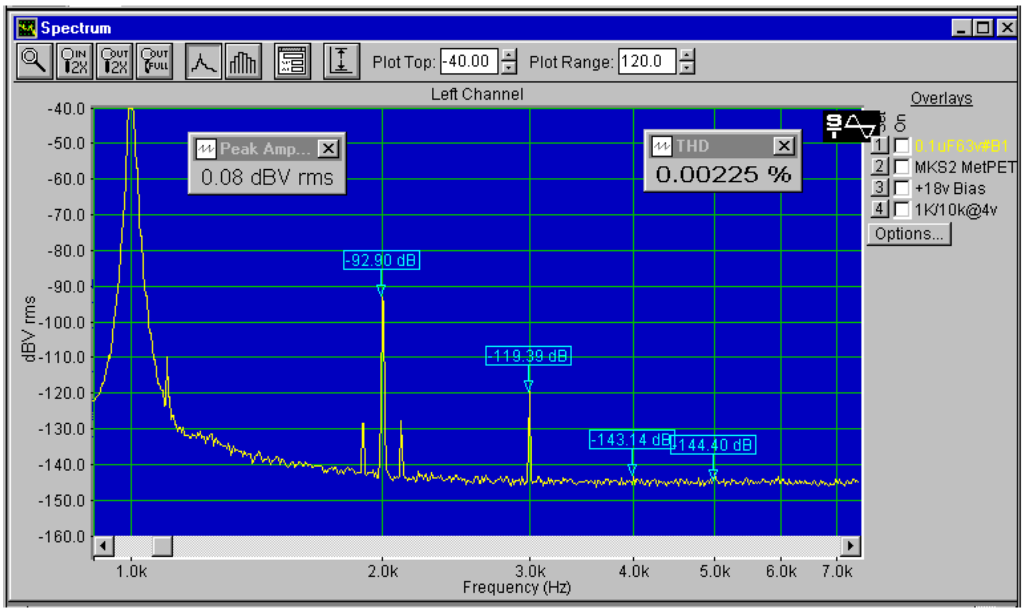


Fig 11) Tested with no bias, this 0.1 µF MKS2 metallised PET capacitor measured 0.00016% with clearly visible intermodulation products.

With 18 volt DC bias, the second harmonic increased from -119.0 dB to -92.9 dB, harmonic distortion to 0.00225%.

Capacitor Choice.
For capacitances up to 10 nF, low distortion, small, low cost capacitors are easily available, so I would avoid using metallised PET capacitors for such values.

For capacitance values above 10 nF the near perfect C0G, foil/PS and foil/PP types are not easily available. Our best options for capacitance values from 10 nF to 1µF, will form the subject of my next article.

Two further articles will then extend our distortion measurements to 100 µF electrolytic, exploring our best options for these values.

END.

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3) Film Capacitors 2000. — Evox Rifa AB. Kalmar. Sweden.

4) Harmonic testing pinpoints passive component flaws. V.Peterson & Per-Olof Harris. — Electronics July 11, 1966.

5) High-frequency impedance meter. C.Bateman. — Electronics World January 2001.

6) Spectra 232Plus FFT software. — http://www.telebyte.com/pioneer

7) Check C's in situ. C.Bateman. — Electronics World May/June 1999

Appendix-1 **DC Bias Network**.
Two DC blocking capacitors are needed. One to couple the signal to the test capacitor, the second to couple the test capacitor voltage into the pre-amplifier input.

To minimise test signal loss, that capacitor should be ten times the value of the capacitor being tested. To not introduce distortion it should be of much higher voltage rating than the DC bias and the same or better quality, as the best capacitor to be tested. I used five 2.2 µF 250 volt MKP from BC Components (Philips), type 378 capacitors connected in parallel.

To couple the test capacitor voltage to the high impedance preamplifier input, a smaller value can be used. For this a 1 µF 250 volt version of the MKP capacitor would be fine. I already had a distortion tested sample of the Epcos (Siemens) equivalent, so I used that instead.

Source impedance resistors, as used in the buffer amplifier, are selected and connected to the AOT 'hot' pin using a short fly lead. Two 100kΩ charge/discharge resistors and a toggle switch, completed the bias network. see **Fig. 3**

All were mounted on a single sided PCB size 110 * 55 mm. For convenient interconnections, I mounted two lengths of the terminal strip, one on either side of the buffer. see **Fig. 12**

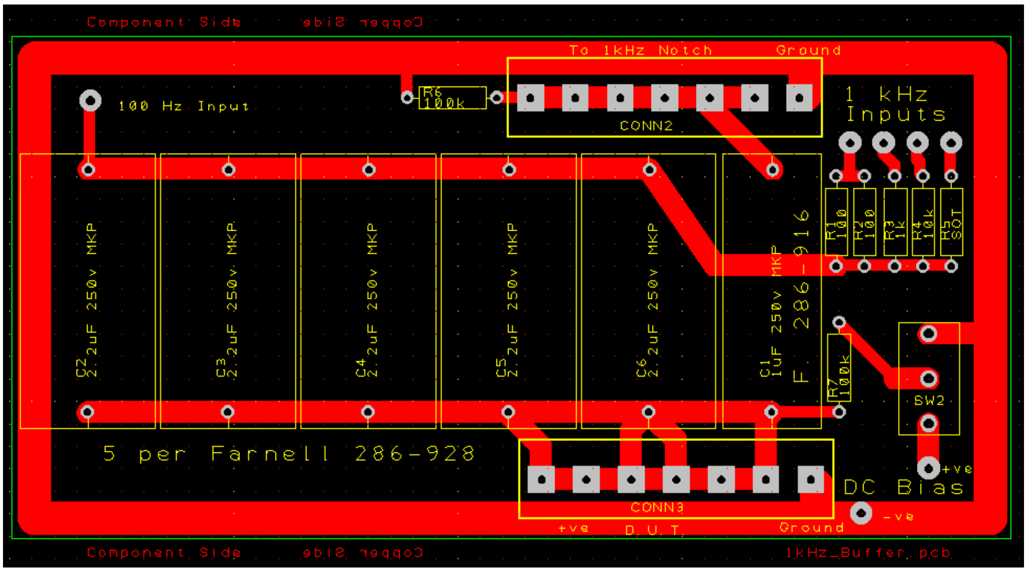

Fig 12) The 110 * 55 mm single sided PCB used to assemble Figure 3, the 1 kHz DC blocking buffer network.

To avoid overloading the soundcard input, the 100 Hz/1 kHz connections to the bias network should be completed before connecting the pre-amp output to the sound card.

Appendix2 **Soundcard FFT Software**.

Measurements for my earlier articles used a Pico ADC-100. Many readers may wish to use a soundcard instead. A modern low cost PCI card with FFT software can provide increased dynamic range, measuring smaller distortions using my instruments, than is possible with the ADC-100.

I now use the Spectra 'Plus232' software under Windows98SE with a Soundblaster Live 1024 card, for all measurements.

With 'CoolEdit', the audio manipulation software, already on my hard disc, I did try using it to measure capacitor distortions. Both 'CoolEdit' and the Pico ADC-100 software display distortion spectra but don't calculate percentage distortion. Tired of making a great many repetitive calculations, I searched Internet for a better solution.

I downloaded some twenty FFT packages for evaluation. On reading their help files, many were obviously of little use. A small number looked promising, because they provided a dB scaled display and calculated distortion percentages. However few packages promised any facility to calibrate and control the soundcard gain settings.

I decided the best choice was the Spectra 'Plus232' software. **Ref.6** I calibrated its input level using a known 1 volt signal. This calibration was accurately maintained from day to day. Having established a measurement set-up, it was saved as a 'config file' for re-use.

It also accepts a correction file, intended to compensate for microphone errors. Having carefully measured the output of my notch filter/pre-amp by frequency using a 1 volt test signal, I wrote a correction file to restore the much attenuated test fundamental back to level and correct for pre-amplifier gain errors.

The software then automatically displays percent harmonic distortion, on screen. see **Fig. 13**

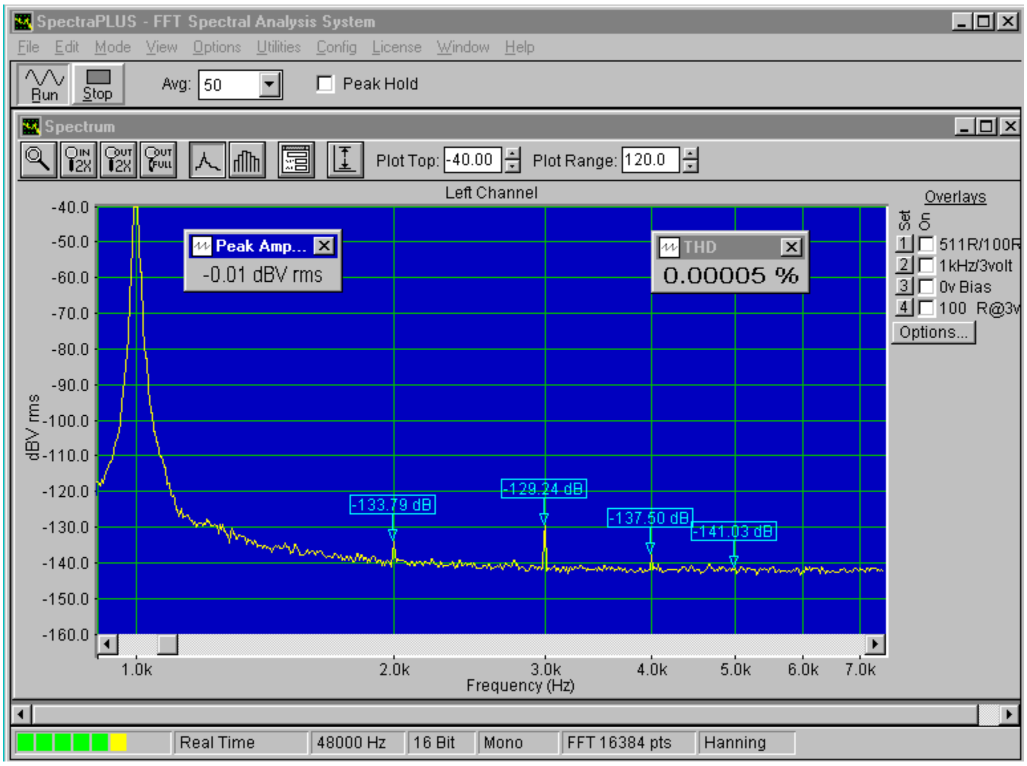

Fig 13) The Plus232 software shows a green then yellow signal strength meter, bottom left, changing dramatically to red at the soundcard overload level.

My 'standard' settings can be seen.

Loaded with a 511 Ω resistor, all harmonics from my test equipment are well below 0.5 ppm distortion.

I quickly produced other files, from 0.1 volt test level to 6 volts, by simply adding or subtracting the appropriate dB levels to the 1 volt file values. see **see Table**

Spectra 'Plus232' can measure in real time, without first saving to disc. It can be used to cover the maximum frequency span of your soundcard, or as shown to measure over your selected frequency band.

Spectra 'Plus232' software was used for all my repeat dual frequency with DC bias, capacitor distortion measurements, more than 2000 in all taken over several weeks, commencing with those for this article.

Should you have only an older ISA soundcard, some software may not work. One that will, is FFT.EXE, a very simple, no-frills, DOS program by Henk Thomassen. This can be found on Internet, also the Elektor 96-97 software CD-ROM.

Users having a modern PCI soundcard will find a very large variety of programs, often available as freeware, on Internet. One site which links to some of the better packages is :-

http://www.pcavtech.com/links/index.htm.

Table 1 **Correction Table for 1 volt at 1 kHz distortion measurements.**

Frequency.	**Value dB**	**Frequency.**	**Value dB**	**Frequency.**	**Value dB**
100	-14.0	1005	-24.45	2100	40.0
200	-3.2	1010	-24.0	2200	40.0
300	3.3	1050	-10.0	2500	39.8
400	6.0	1100	8.2	3000	39.65
500	8.0	1200	16.2	4000	39.9
600	9.0	1300	21.4	5000	40.2
700	9.0	1400	25.6	6000	40.3
800	7.6	1500	29.2	7000	40.2
900	3.5	1600	32.4	8000	39.6
950	-10.0	1700	35.2	9000	38.7
990	-24.0	1800	37.25	10000	37.2
995	-24.45	1900	38.8	11000	36.0
1000	-24.45	2000	39.6		

Capacitor Sounds 4 - capacitances from 100 nF to 1 µF.

Updated & extended March 2003

Original version Pub. Electronics World November 2002 - C. Bateman.

Readers of my previous articles will have seen that many capacitors do introduce distortions onto a pure sinewave test signal. In some instances distortion results from the loading the capacitor imposes onto its driver. In others, the capacitor generates the distortion within itself. **Ref.1**

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, capacitor distortions can now be measured, surpassing speculation. Equipment designers can now easily test and select capacitors for each circuit requirement.

For capacitances of 10 nF and smaller, the safe solution is to use C0G ceramic or extended foil/film capacitors. Made with Polystyrene or Polypropylene dielectrics and with leadwires soldered or welded directly to the extended foil electrodes. Avoiding altogether capacitors made with metallised film dielectrics or using 'Schoop' metal spray end connections.

These idealised choices minimise all measurable distortion products. While this presents a counsel of perfection, as an engineer I believe prior knowledge of the best and worst extremes should form part of any compromise.

Problem area.

Such near ideal capacitors are not easily available in acceptable sizes or costs for higher capacitance values. Finding suitable low distortion 0.1 µF and 1 µF capacitors proved almost impossible.

High 'k' BX, X7R, W5R and Z5U capacitors produce far too much distortion for our needs. **Ref.1**

Multilayer ceramics of 100 nF 50 volt manufactured in C0G, produce little distortion, with and without DC bias, but are not easily available in small quantities. COG can provide very low distortion, comparable with the best film capacitors. see **Fig. 1**

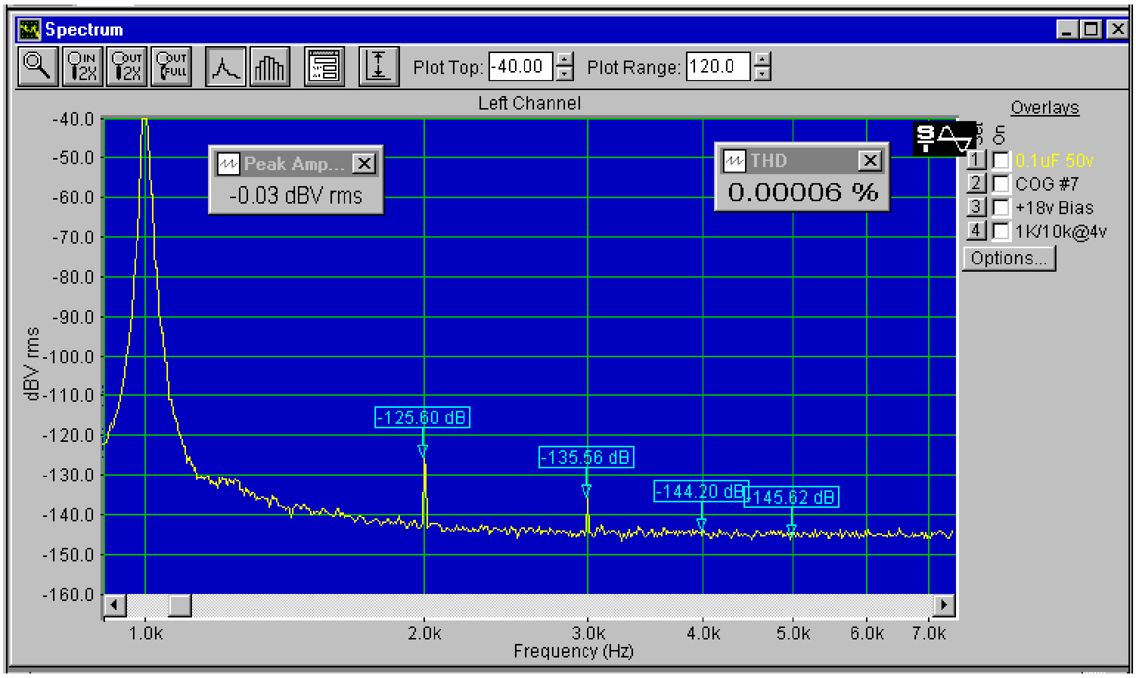

Fig 1) Distortion measurement of a 100 nF 50 volt C0G ceramic, using 100 Hz and 1 kHz signals at 4 volts and 18 volt DC bias. With no DC bias this multilayer capacitor measured just 0.00004%. Second harmonic was -131.7 dB, other harmonics remained as shown.

The worst capacitor?

A 100 nF ceramic disc capacitor is still available. Having the thinnest possible high-k dielectric it provides the worst possible distortion. Despite this, a number of papers found on Internet, choose to use this style on which to base their ceramic capacitor measurements and opinions. This mistake resulted in a totally biased prejudice against using COG capacitors for audio. **Ref.2**

Originally called a 'transcap', it pre-dated all low cost 0.1 µF film capacitors by many years. It was developed as the smallest, lowest possible cost decoupling capacitor, used in transistor pocketable AM radios.

A conventional high 'k' ceramic, re-sintered in a reducing atmosphere, becomes a semi-conducting disc measuring a few Ohms resistance. The outer few surface molecules are re-oxidised when the electrode silver is fired in air, to become the dielectric of this 'Barrier Layer' disc capacitor. If sectioned, you will find a black disc, apparently made from charcoal. Using a high power microscope, you may just see an extremely thin, much lighter coloured dielectric layer covering the outer surfaces. Performance of a 'Barrier Layer' capacitor bears no resemblance to that of any other ceramic capacitor so must not be taken as representing other styles of capacitor. This barrier layer construction does produce a uniquely bad, exceptionally high distortion. **Ref.3**

Such devices have no place in any audio system. So take care if offered a small ceramic disc, having significantly greater capacitance than the few hundred pF found in conventional 'Type 1' ceramic disc capacitors. **Ref.4** see **Fig. 2**

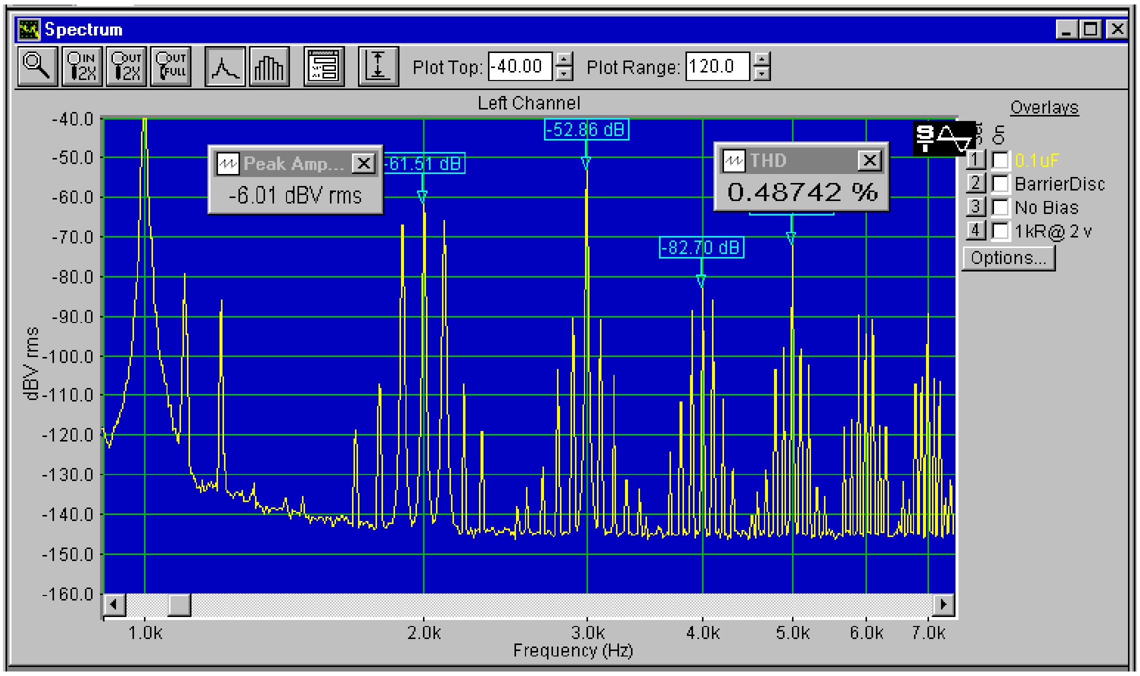

Fig 2) The worst distortion of more than 2000 capacitor measurements. The test voltage had to be reduced to two volts AC with no DC bias, to avoid harmonics overloading my soundcard.

This test was made using only 1 kHz, even worse intermodulation is produced using two or more test signals.

With the exception of figure 2, all distortion plots in this article used two test frequencies, 1 kHz and 100 Hz both set to 4 volts. To ensure all test plots also resulted from applying similar test currents, source impedances for 100nF types used 1k for 1 kHz 10k for 100 Hz, while 1.0 µF used 100R for 1 kHz, 1k for 100 Hz. These test stimuli can be read upper right on each plot.

Electrolytics.
Tantalum or Aluminium electrolytic capacitors are available in these values and form the subject of my next article. Meanwhile we will investigate the options available in film capacitors. Very low distortion foil and film, Polypropylene (PP) and Polyethylene Terephthalate (PET) capacitors are available but are large and usually expensive. The lowest cost, smallest size capacitors, are made with metallised PET.

Metallised PET.
In the drive, some thirty years ago, to size and cost reduce the 0.1 µF capacitor, two problems had to be addressed:-

> 1) First was to produce satisfactory quality, extremely thin metallised PET. In 1978, the Dupont 'Mylar'® capacitor film became available 1.5 microns thick, some 20 times thinner than human hair.
> 2) Second was to develop low labour cost methods to wind small capacitor elements. For the makers this was difficult because of the high cost and large numbers of automatic winding machines needed to produce capacitors in volume.

The major German capacitor makers were leading these developments. Wima with others, worked to develop intricate machines capable of automatically winding individual small capacitors. The Siemens company, now Epcos, sought a different solution, their so called 'stacked' capacitor.

Despite their name, stacked film capacitors are first wound onto a large diameter wheel, to make a 'mother' capacitor. When all possible processing stages are complete, this 'mother' is sawn into short lengths, each a discrete capacitor element. **Ref.5.**

During my initial distortion measurements on metallised PET capacitors, I was curious whether these two processes would result in different distortion characteristics.

Concentrating my measurements on known wound, BC Components type 470 and known stacked Epcos capacitors, I did find differences. The stacked film capacitors usually exhibited increased third harmonic, compared to this wound type. My initial stocks were too small to be statistically valid, so more capacitors were purchased.

Wound v Stacked metallised PET.
At this time I measured distortion using only a single pure 1 kHz tone and no DC bias. With 4 volts dropped across the capacitor, my equipment noise floor was below -140 dB. Loaded with a 0.5% metal film resistor, distortion measured 0.00005%.

Similarly the best capacitors typically measured 0.00006%, with second harmonic better than -125 dB, third and higher harmonics better than -130 dB.

Measuring 25 type 470 capacitors I found three having more than ten times higher distortion. Even harmonics were little changed, but third harmonic increased to -100 dB, fifth to -115 dB. Measuring another 25 capacitors I found another two with high distortion.

I set an arbitrary good/bad limit at -120 dB, any harmonic exceeding this level being viewed as bad.

Measuring 25 stacked capacitors, using this criteria, I found most measured as bad. Distortions varied from 0.00034% to 0.0018% and many displayed -90 dB third harmonics.

Was this difference genuine or was my sample still not statistically significant ? Measuring more capacitors, I found some also having increased second harmonic distortions. I had anticipated finding third harmonic variations, which can result from non-linear connections in the capacitor, but did not understand these second harmonic problems.

PET of course has significant dielectric absorption, typically 0.5%, when tested at the rated voltage of the capacitor. **Ref.6** Several capacitors, pre-selected as good and very bad distortion, were accurately measured for capacitance and tanδ at 1 kHz using my precision bridge, initially unbiased then with 30 volts DC bias. The biggest capacitance change found was less than 0.01% and with tanδ values remaining constant regardless of bias voltage, seemed to rule out any dielectric absorption effects.

Somewhat puzzled, I decided to expand my distortion measurements, changing the measurement stimulus in small steps and varying one test parameter only at a time. I would also look for intermodulation using two test frequencies and explore the affects of change of DC bias voltage. I would measure more capacitors for voltage coefficient and dielectric absorption.

I had no choice but start again, repeating almost 1000 single frequency distortion measurements already saved to disk, but this time using two test frequencies, with no DC bias and using various DC bias voltages, both of film and electrolytic capacitors.

Revised measurements.
To prove my DC bias buffer contributed no distortion, I measured my near perfect 1 μF KP capacitor. Using 6 volt test signals at 100 Hz and 1 kHz, with and without 50 volts DC bias, its distortion measured 0.00006%. This DC bias buffer was then used for all these new measurements including all those made with 0 volt DC bias. see **Fig. 3**

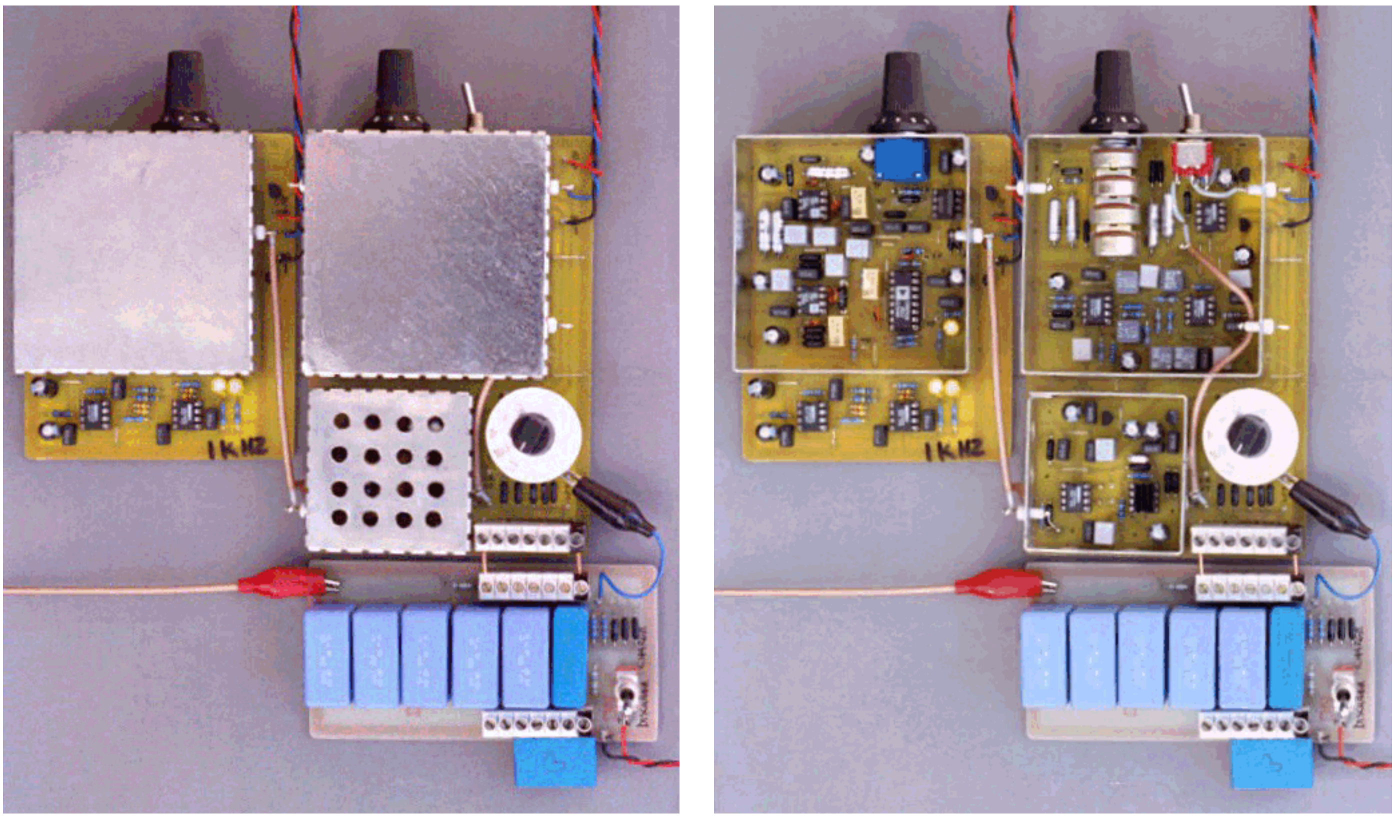

Fig 3) Finalised prototype measurement system using two test signals, 100 Hz and 1 kHz to measure capacitor intermodulation and harmonic distortion, with and without DC bias voltage. The capacitor under test is mounted directly onto the DC bias buffer network. The Red crock clip and screened cable supply the 100 Hz signal. All screening case lids must be fitted while measuring distortion.

A ‘good’ 0.1 µF 63 volt type 470 wound capacitor, tanδ 0.00337, measured similar distortion when tested with no DC bias. Intermodulation was just visible either side of the second harmonic. With 18 volt DC bias, second harmonic increased by 22dB and distortion to 0.00027%. Voltage coefficient measured 0.0% up to 30 volt bias, DA measured 0.107% see **Fig. 4**

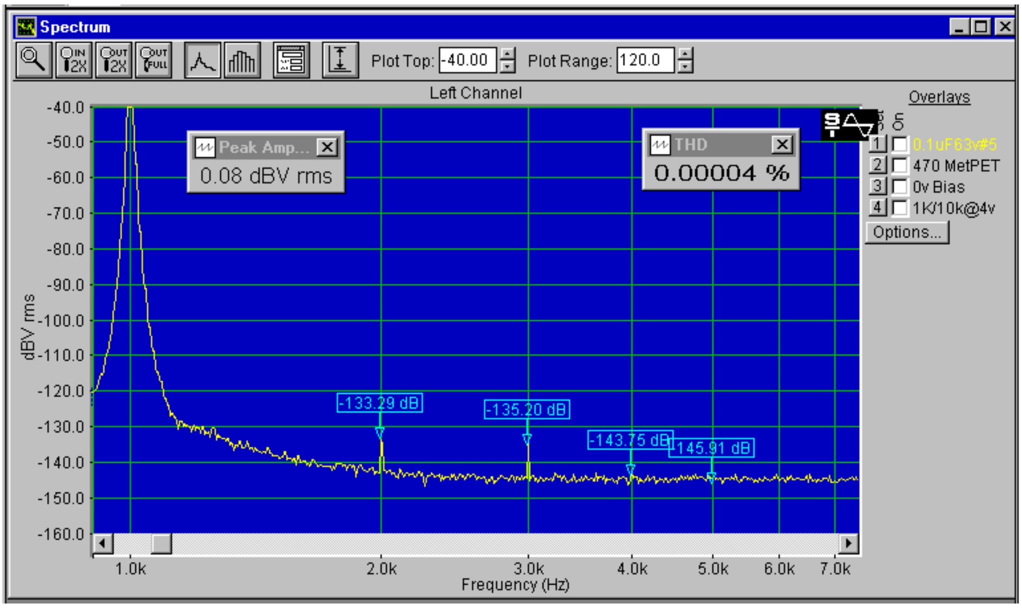

Fig 4A) With no bias, this exceptionally good 0.1µF 63 volt type 470 metallised PET capacitor, from BC Components, made with magnetic leadwires, tested at 4 volts 1 kHz/100 Hz measured 0.00004% distortion. Intermodulation is just visible either side of the second harmonic.

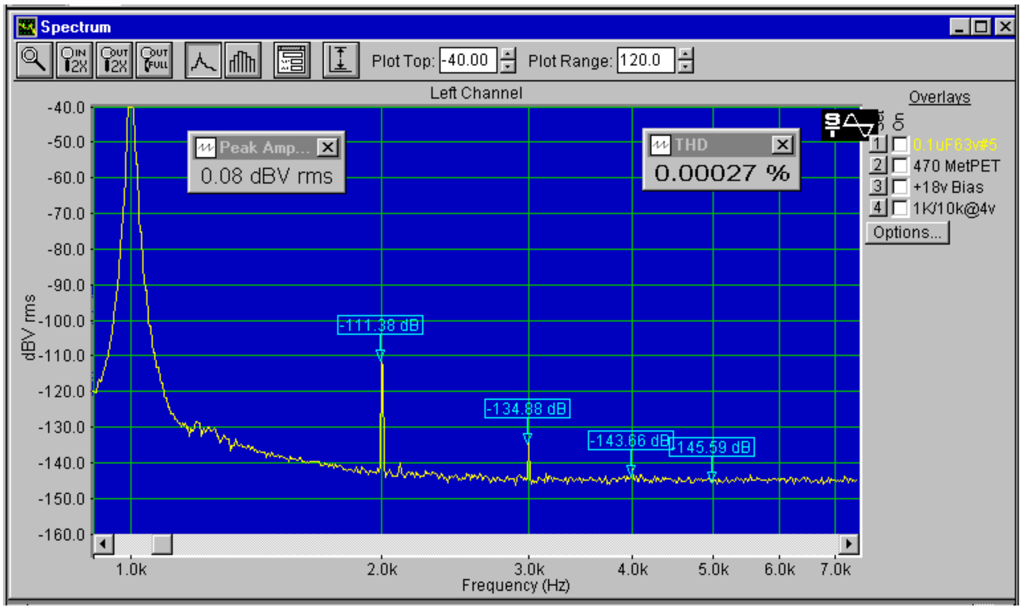

Fig 4) With 18 volts DC bias, the second harmonic increased 22 dB from -133.3 dB to -111.4 dB, distortion increased six fold, but third harmonic has not changed. Intermodulation products also are unchanged, just visible, either side of 2 kHz.

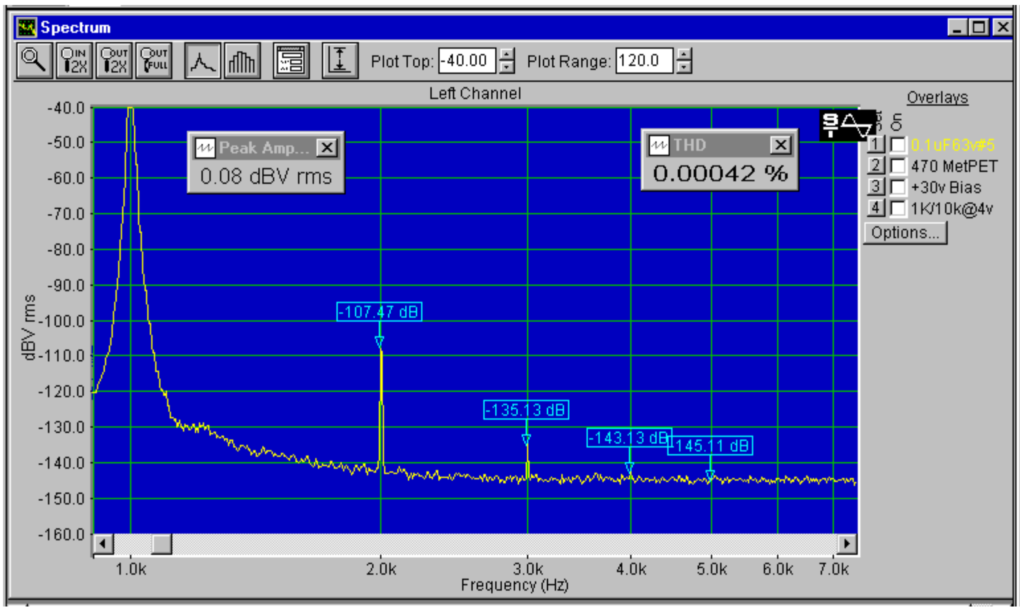

Fig 4B). When bias was increased to 30 volt DC second harmonic became -107dB and distortion increased to 0.00042%. However as can be seen, increase of DC bias, has little or no effect on the level of third harmonic or the intermodulation distortions, which remain almost invisible.

A batch of Wima MKS2 wound capacitors consistently show increased intermodulation products and third and fifth harmonics. Typical no bias distortions measured around 0.0001%. With 18 volt DC bias the second harmonic increased 32 dB and distortion measured 0.00151%. Voltage coefficient was less than 0.01%, DA measured 0.147%. see **Fig. 5**

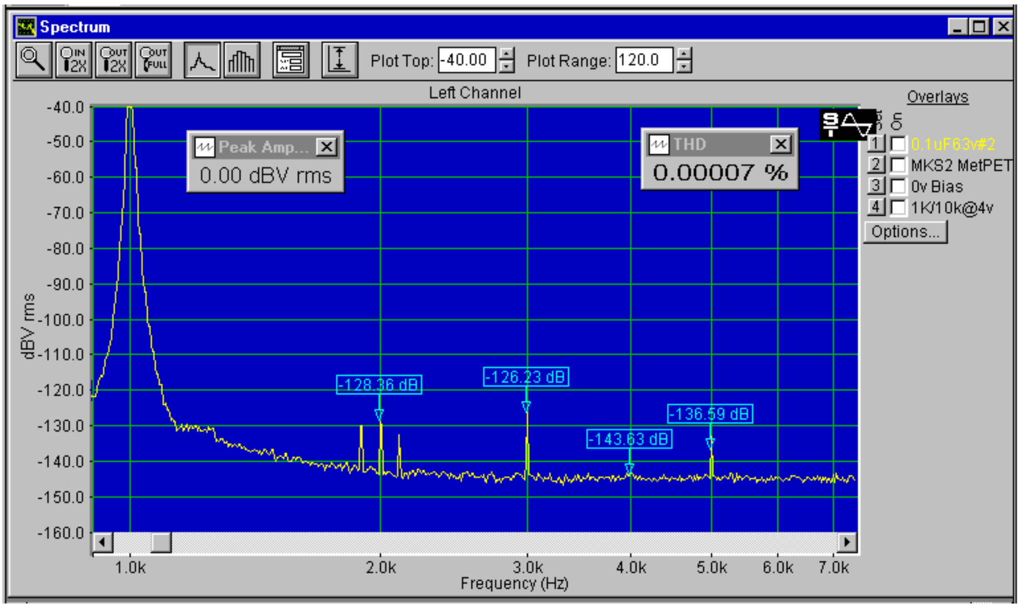

Fig 5A) Distortion measurement of a typical 0.1 µF 63 volt MKS2 with no DC bias measured just 0.00007%. All other samples measured, consistently show similar increased intermodulation products and third and fifth harmonics when compared to the B C Components style 470 of figure 4.

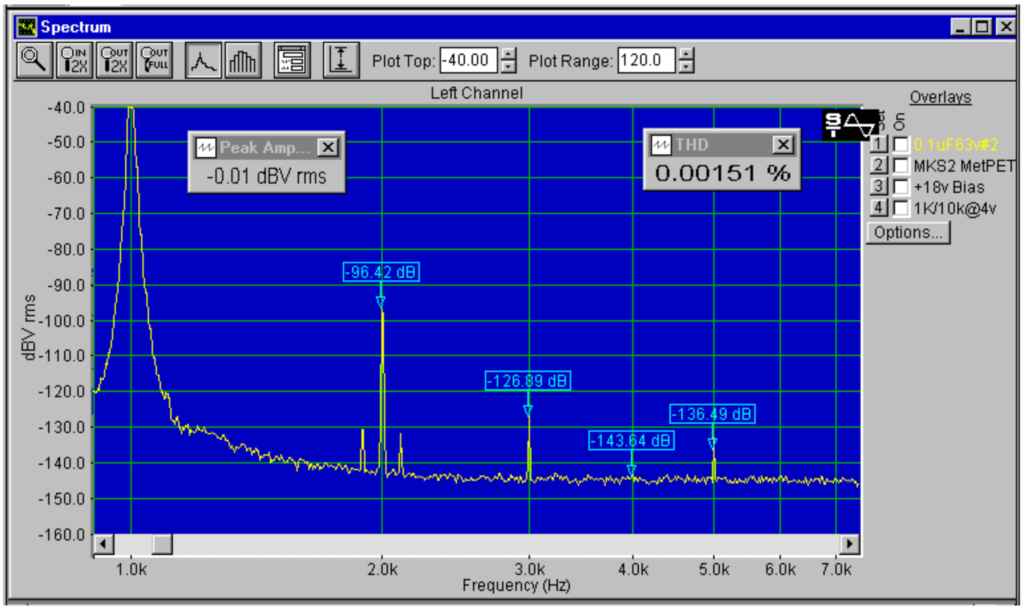

Fig 5) With 18 volts DC bias, second harmonic increased 32 dB from -128.3 dB to -96.4 dB, distortion increased to 0.00151%.

Intermodulation products and other harmonic levels did not change.

With a tanδ of 0.00272, this capacitor was dismantled to confirm it was wound construction.

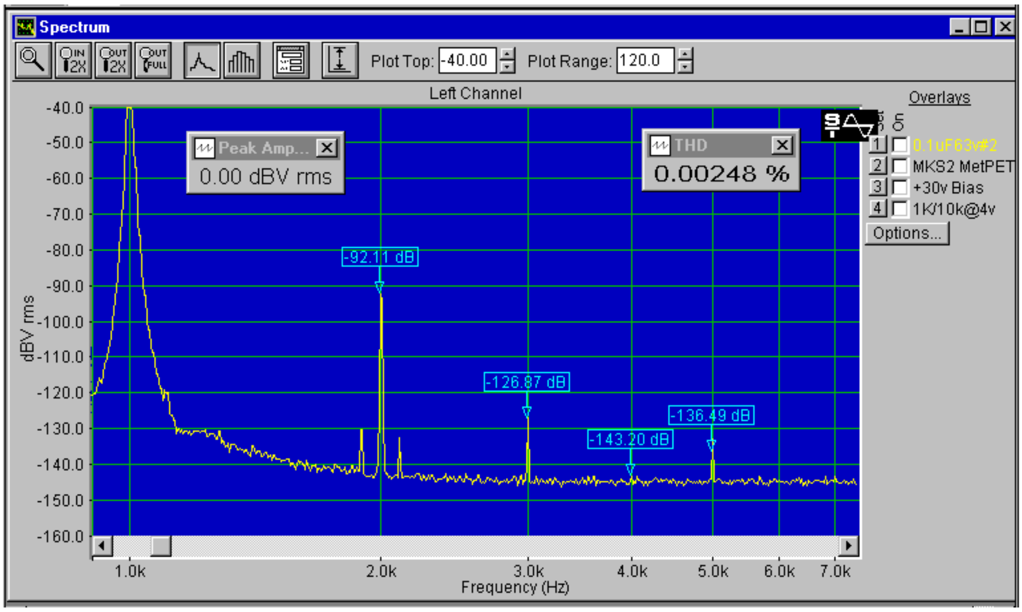

Fig 5B) When bias was increased to 30 volt DC second harmonic became -92.1dB and distortion increased to 0.00248%. However as can be seen, increase of DC bias to 30 volt again has little or no effect on the level of third or fifth harmonics which remain notably higher than with the 470 style.
Intermodulation distortions remain clearly visible around -130dB.

A much bigger, 100 volt rated, un-cased stacked capacitor with tanδ 0.00352, shows a very high third harmonic level and increased intermodulation products, typical of the construction. Made using thicker dielectric, its second harmonic increased by 16 dB when biased to 18 volts. Due to its third harmonic, high distortions were measured with and without bias. see **Fig. 6**

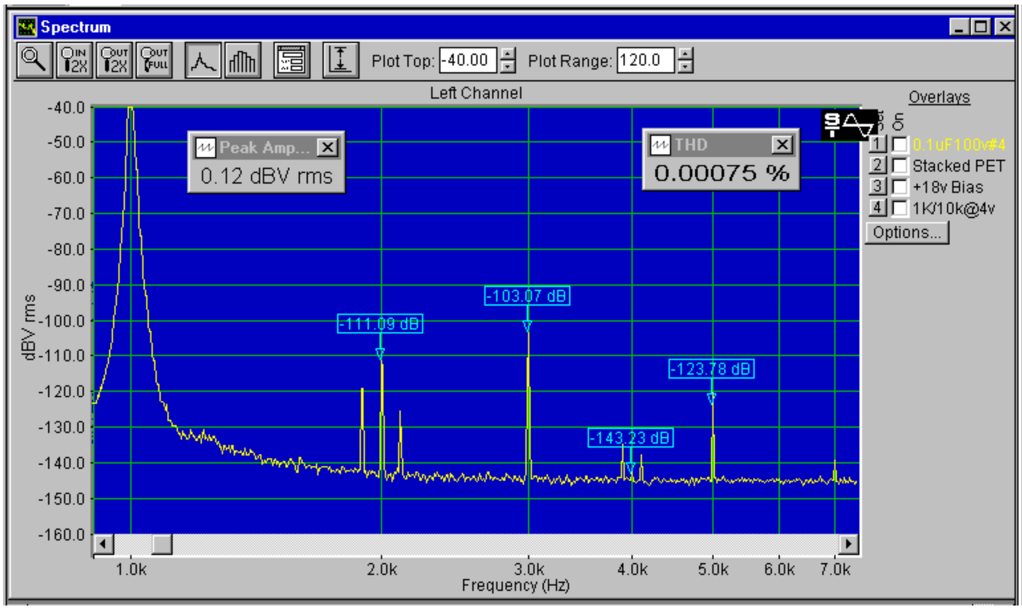

Fig 6) A 0.1 µF 100 volt stacked metallised PET, with magnetic leadwires, displays much increased odd harmonics and intermodulation components. Second harmonic of this much larger capacitor made with thicker PET, increased less with DC bias, compared to figures 4 and 5.
Third and odd harmonics do vary with AC test signal, but DC bias from 0 volts to 30 volts, has almost no affect.

These enormous changes in second harmonic found in metallised PET capacitors tested with and without DC bias, clearly result from bias voltage, dielectric thickness and dielectric absorption, not from their negligible, less than 0.01% voltage coefficient.

Box **Dielectric Absorption.**

Two major dielectric characteristics exist, polar and non-polar. By polar I am not referring to an electrolytic capacitor, but to the way the dielectric responds when subject to voltage stress. This stress relates to the voltage gradient across the dielectric, and not just the applied voltage. In other words it is stress in volts per micron, which matters.

Non-polar dielectrics, for example vacuum and air, are little affected by voltage stress. Solid dielectrics which behave in a similar fashion are termed 'non-polar'. Most solid dielectrics and insulators however are affected to some extent, increasing roughly in line with their dielectric constant or 'k' value. This 'k' value is the increase in measured capacitance when the chosen dielectric is used to replace a vacuum or more usually, air.

When a dielectric is subject to voltage stress, electrons are attracted towards the positive electrode. The electron spin orbits become distorted creating mechanical stress and a so-called 'space charge' within the dielectric. This mechanical stress produces some heat rise in the dielectric and a power loss, called dielectric loss. Non-polar dielectrics exhibit very small power or dielectric losses. Polar dielectrics are much more lossy. Having been charged to a voltage, it takes much longer for the electron spin orbits in a polar dielectric to return to their original uncharged state. Polar dielectrics produce easily measured 'dielectric absorption' effects.

Dielectric behaviour with voltage, depends on the voltage gradient, in terms of volts/micron as well as on the characteristics of the dielectric. It's effects are more readily apparent with very thin dielectric. The lowest voltage, 50 and 63 volt rated metallised PET film capacitors, are often made using 1 micron or thinner film.

Foil and film capacitors cannot 'self heal' so must be made using relatively thick dielectric films. As a consequence we find that foil and film PET capacitors can provide low distortion, even when subject to DC bias voltages.

Dielectric absorption is usually measured by fully charging the capacitor for several minutes to a DC voltage, 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' DC 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 descriptions can found in magazines and on Internet, describing smearing, time delays and compression. My AC capacitance and distortion measurement results, simply do not support these claims.

The main characteristic I have found, which clearly relates to dielectric absorption, is the magnitude of the second harmonic. This does increase with applied AC or DC voltage stress and especially so with thin materials, having known higher dielectric absorption. For example the PET (Polyethylene Terephthalate)and PEN (Polyethylene Naphthalate) dielectric films have almost identical characteristics except for dielectric absorption. Comparative distortion measurements with and without DC bias, made on metallised PEN and metallised PET capacitors, show that PEN capacitors do produce much larger second harmonics. The PEN material at 1.2%, has almost three times greater dielectric absorption than PET. **Ref.6 End of Box.**

Uncertain of their construction, I ordered just ten MKT capacitors (Farnell 814-192), all behaved similarly. Exceptionally high distortion with and without bias, dominated by the near -90 dB third and -113 dB fifth harmonics. Voltage coefficient measured less than 0.01%, DA measured as 0.173%. see **Fig. 7**

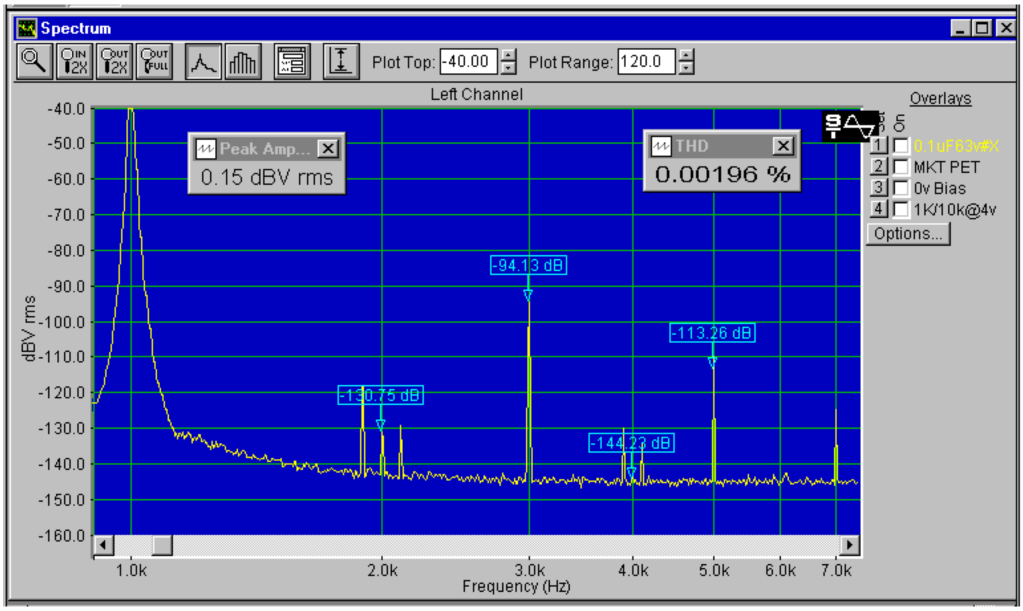

Fig 7A) A different makers very much smaller, 0.1 µF 63 volt stacked metallised PET capacitor, made with copper lead wires, tested with no DC bias, exhibits worse distortions than those shown in figure 6.

Notice however a family likeness of distortion components, similar to figure 6 but quite different from figure 4.

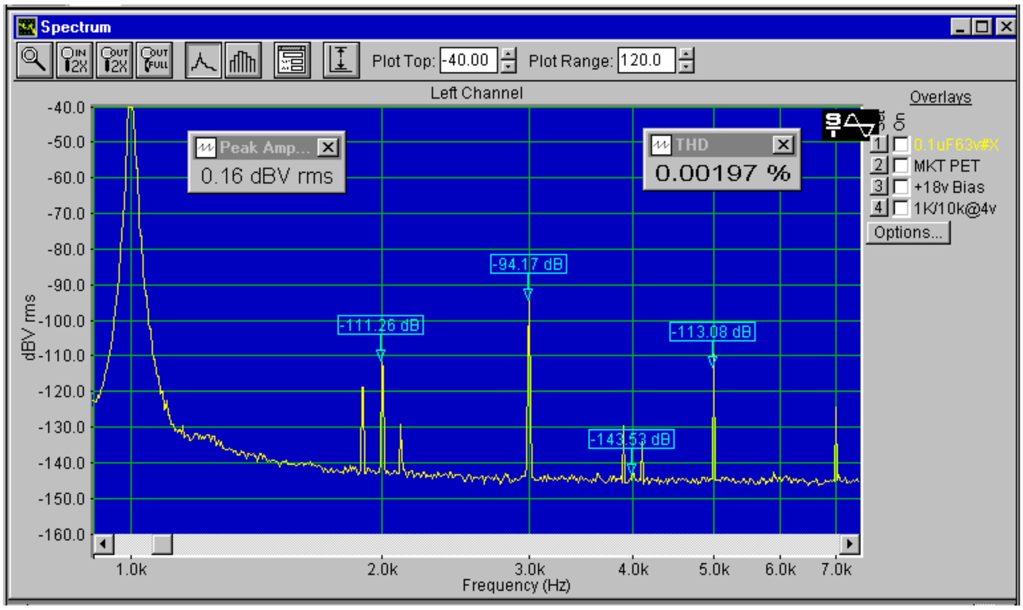

Fig 7) Measured with 18 volt DC bias the second harmonic increases by 20 dB to -111dB.

Harmonic distortion remains high regardless of test voltage. Dominated by the unusually high level of third harmonic it changes little.

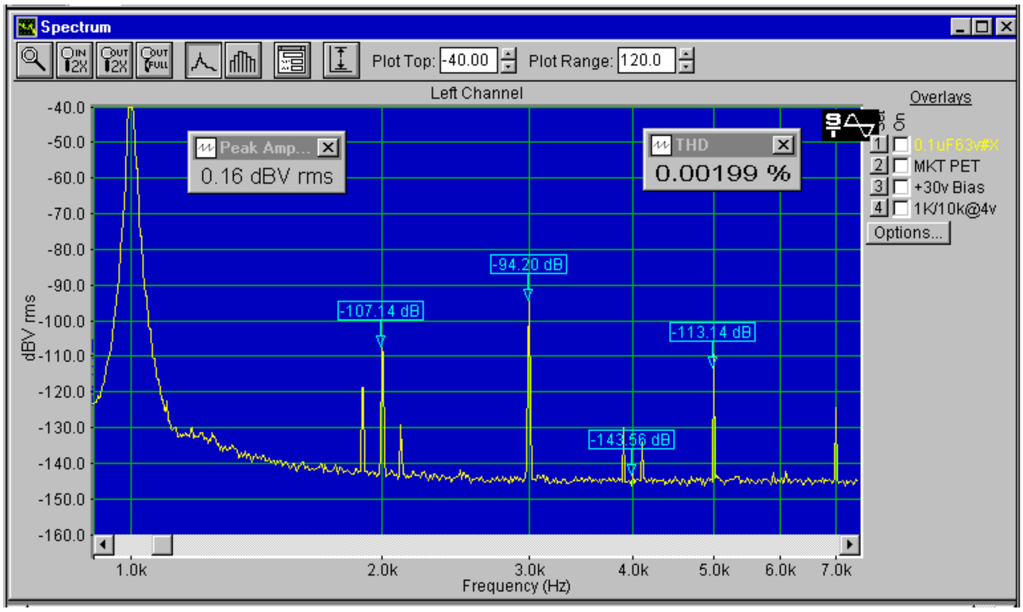

Fig 7B) Remeasured using 30 volt DC bias, second harmonic distortion increases to -107dB.

With tanδ 0.00371, this capacitor was dismantled to confirm it was stacked construction.

With such large variations in harmonic distortion, it seemed all small metallised PET capacitors should be distortion tested, to avoid building obviously 'bad' capacitors into the signal paths of audio equipment

Box **Metallised film dielectrics.**

All common film capacitor dielectrics, other than Polystyrene, can be metallised, to produce a negligibly thick electrode. This metallised coating, usually aluminium, is produced by evaporating metal ingots inside a vacuum chamber. The film is stretched taut and passed through the chamber at controlled speed. To prevent overheating, the film passes over refrigerated rollers.

To produce exceptionally thin plastic films, the material is stretched almost to breaking along its length and across its width then 'fixed' by heating, changing the orientation of the long polymer chains. Initially 'tangled' these chains become straightened, re-oriented and cross-linked with consequent change in material characteristics, see Wima web site for details.

The metallised coating is so thin it is transparent. Thickness is monitored by measuring resistance, typically a few Ohms per square, of the metallised surface.

PET and PPS films are easily metallised and provide good adhesion to an evaporated aluminium coating. Untreated Polypropylene (PP) has a smooth, waxy surface which inhibits adhesion.

Various pre-treatments have been applied to PP to improve electrode adhesion. These include mechanical roughening and exposure to high voltage ionisation fields. However metallised electrode is often applied to a higher resistance value, i.e. thinner, onto PP than other films.

Contact to the metallised electrode is made by spraying minute metal particles, evaporated inside a high temperature spray gun, onto each end of the capacitor winding. This is known as a 'Schoop' connection. The volume of air needed to propel the metal particles ensures the film surface is only exposed to relatively cool metal, so is not melted.

This 'schoop' metal spray end connection is also used to manufacture some makes of foil and film capacitors and those with double-sided metallised carrier film electrodes. The conductive end spray, short circuits together all turns of a wound capacitor, ensuring minimal self inductance.

When sufficient 'end spray' thickness has been applied, the capacitor leadwires are attached, usually by soldering or electrical resistance 'welding.' Properly applied this 'schoop' end spray then provides the connection to the metallised electrodes.

The extremely thin metallised film electrodes obviously cannot handle high currents. When overloaded, visible electrode 'edge burning' occurs, ultimately leading to an open circuit capacitor. The resistance of the metallised electrode (a few Ohms per square) combined with aluminium's temperature coefficient of 0.0039, results in a non-linear resistance. This may at least partially explain some of the larger third harmonic distortions.

One simple indicator of the current carrying ability of the 'schoop' end connection into the electrodes used, can be seen in the peak current ratings claimed for the capacitor. For example a 10 nF metallised PET capacitor might be rated for 30 v/µsec, foil and PET has a much higher current carrying ability, being rated as high as 1000 v/µsec. **End of Box.**

The 1 µF problem.

To approach our idealised capacitor we need the small size provided by metallised PET, the low distortions found using Polypropylene and low cost.

These qualities could be approached using metallised Polycarbonate, but Polycarbonate capacitors have become extremely expensive. Production of Bayer Makrofol Polycarbonate film having ceased, metallised Polycarbonate capacitors may disappear.

A great many 0.1 µF metallised PET capacitors having been measured, without finding clear reasons for their widely differing distortions. Would measurements at 1 µF help ?

1 µF measurements.

I decided to measure the same make and style, rated at both 63 volt and 100 volt, to explore the D. Self comment that 63 volt capacitors exhibit ten times more distortion than 100 volt. **Ref.7**

Provided the maximum capacitance possible at these voltages in both case sizes is obtained, dielectric absorption effects related in volts per micron to the differing film thickness used should be observed. It seemed probable that the 63 volt capacitor would exhibit increased second harmonic compared to the 100 volt version. I choose to measure the 470 style capacitors, because 0.47 µF at 100 volt and 1.0 µF at 63 volt, were the maximum capacitances available in the case size.

I soldered together several pairs of 0.47 µF to produce near 1 µF 100 volt capacitors.

Measured within a few minutes of each other, with no bias voltage, the 63 volt and 100 volt capacitors measured almost identically, with distortion at 0.00007% and 0.00006% respectively.

Re-measured with 18 volt DC bias, the third and higher harmonics were unchanged but second harmonic levels increased for both capacitor voltage ratings. Second harmonic for the 63 volt capacitors increased by +12.5 dB, the 100 volt capacitors by +7 dB, giving measured distortions of 0.00024% and 0.00011% respectively. see **Figs. 8 & 9**

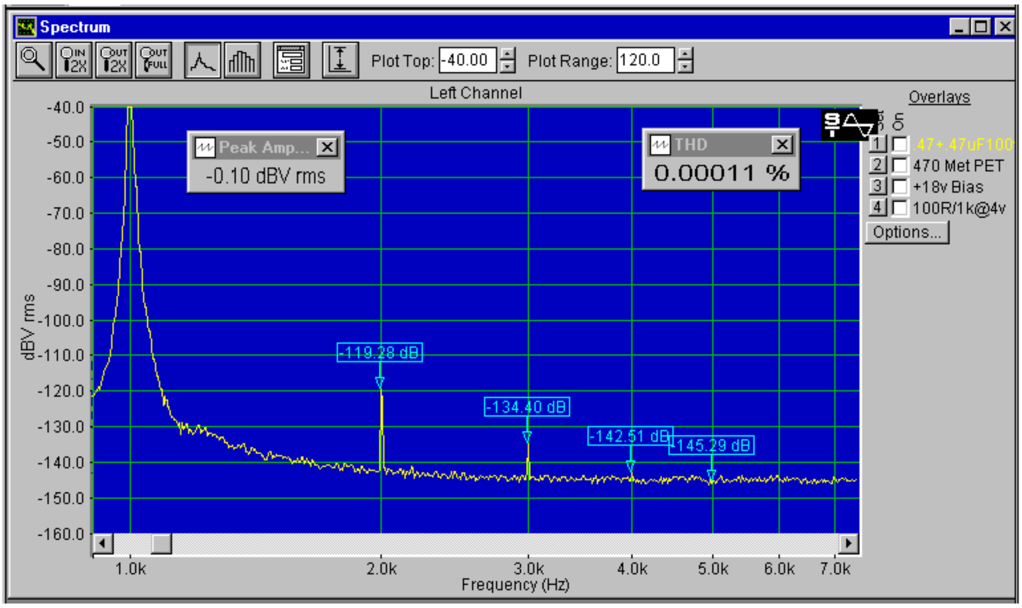

Fig 8) The first of two plots which explore the effect an increase in metallised PET film thickness might have on distortions. With no bias, distortion of this 100 volt capacitor measured 0.00006%, second harmonic -126.2 dB. With DC bias, second harmonic increased by 7 dB and distortion to 0.00011%

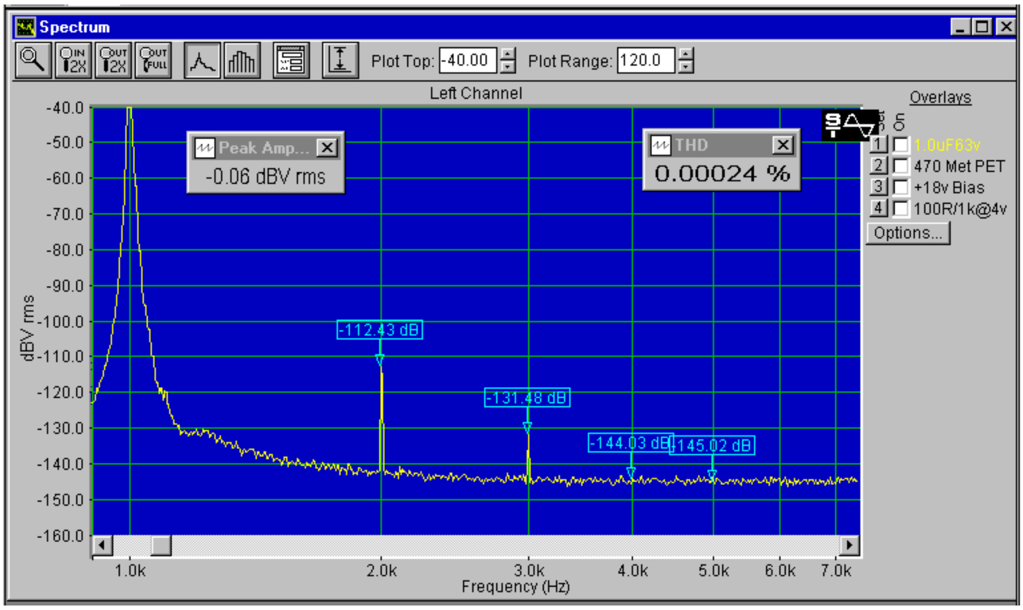

Fig 9) Distortion of the 63 volt capacitor, same make comparison with figure 8. With no bias, distortion measured just 0.00007% with second harmonic at -124.9 dB. With DC bias, second harmonic increased by 12.5 dB. At 0.00024% distortion is double that of the 100 volt capacitors.

These figures equate well with the expected differences in film thickness and confirmed the effect stress in volts/micron and dielectric absorption has on second harmonic distortion.

Some factor other than rated voltage, must account for Douglas's reported observation.

Further measurements on 1 µF metallised PET capacitors, using 25 pieces of the wound type 470, and a similar quantity of stacked film capacitors, revealed nothing new. Distortion patterns established by the smaller capacitors, being repeated.

I also had 10 pieces wound capacitors type 370, dated 1995. These produced harmonic levels with and without bias remarkably similar to those measured on the MKS2 types.

Possible mechanisms.
These tests clearly illustrate how audible problems can exist using metallised PET capacitors in low distortion audio. I now sympathise with listeners who complain about amplifier sounds, when using metallised PET capacitors.

Lacking the facility to assemble test capacitors using known differences in materials and processes, I can only speculate as to possible reasons for the different third harmonic distortion levels I found. These may result from differences in manufacture of the basic film or the vacuum deposition of the metallised electrodes. Processes which vary from maker to maker.

It might even be as simple as the electrode metallisation thickness used. Perhaps thickness gives the wrong impression, this aluminium coating is so thin, like mirror sunglass lenses it is quite transparent. Its thickness is measured in Ohms/square, typically some 2 to 4 Ohms.

One convenient explanation for these differences might be the use of copper v magnetic leadwires. Not so, the lowest distortion, type 470, metallised PET capacitors tested, use magnetic leads, the worst distortion stacked types used copper.

More likely are differences in the metal compositions and spray application methods used, to produce the 'schoop' end connections. **Ref.5** Aluminium metallised electrode has an electro-chemical potential of +1.66 volt, magnetic leads +0.44 volt, copper wires -0.337 volt. For the 'schoop' connection, a variety of other metals are also used, having intermediate, mostly positive potentials. Possible 'Seebeck' effects should not be ignored.

Intermodulation distortion.
From many measurements using AC voltages from 0.5 to 6 volts, intermodulation products are produced in metallised PET capacitors according to the level of third harmonic the capacitor produces.

For example a 'bad' capacitor exhibits intermodulation when subject to much less than 1 volt AC. A capacitor developing smaller third harmonic, shows no visible intermodulation until its AC voltage exceeds 3 volts. see **Fig. 4**

The best metallised PET capacitors produced almost no distortion with no DC bias, but when used to block DC, second harmonic distortion increased rapidly with increasing DC bias voltage.

Depending on circuit arrangements, many capacitors could produce audible distortions. Perhaps this should not surprise us. Audiophiles have claimed to be able to 'hear' PET capacitors for many years.

I believe that for 0.1 µF to 1 µF values, metallised PET capacitors should first be distortion tested. Because of their rapid increase in second harmonic with DC bias, they should not be used with significant DC bias, relative to their rated voltage, in high quality audio equipment.

Having so far failed to find a physically small, economic, low distortion solution, is one possible ?

Polyphenylene Sulphide.
A much better but little used, slightly more expensive dielectric has been available for many years. **Ref.8** It is available metallised down to 1.2 microns and with a 'k' of 3, it provides capacitors slightly larger than metallised PET. **Ref.6**

It has many other benefits. Usable to 125°C, it provides a near flat temperature coefficient and tanδ slightly higher than metallised Polypropylene. It has a small dielectric absorption of 0.05%, considerably better than Polycarbonate and ten times better than PET.

Like Polycarbonate, Polystyrene and C0G ceramic, it provides superb long term capacitance stability, changing 0.3% maximum in 2 years.

It seems Polyphenylene Sulphide (PPS) should provide acceptable size, low distortion capacitors.

I used 0.1 µF 50 volt, 5 mm centres Evox Rifa SMR metallised PPS capacitors, in my tanδ meter assemblies. Measurements of 25 pieces I had left, displayed extremely low distortion. This stock was purchased from RS, who has since dropped the product from its catalogues, so I sought another stockist.

The Farnell web site recently listed a small selection of Evox Rifa Polyphenylene Sulphide capacitors. Maximum stock value in 5 mm lead spacing is 10 nF, with up to 1 µF at 63 volt in 10 mm centres and at 100 volt in 15 mm. The largest value, 3.3 µF at 63 volt, has 15 mm centres.

The 0.1 µF 100 volt SMR produced superb results with and without DC bias voltage. see **Fig. 10/10A/10B**

The 1 µF 63 volt produced superb results if biased to less than 10 volts but with increasing bias, second harmonic distortion increases. The larger 1µF 100 volt capacitor made with much thicker film should be less sensitive. see **Fig. 11/11A/11B**

Both SMR types tested have small case size and 10 mm lead spacing.

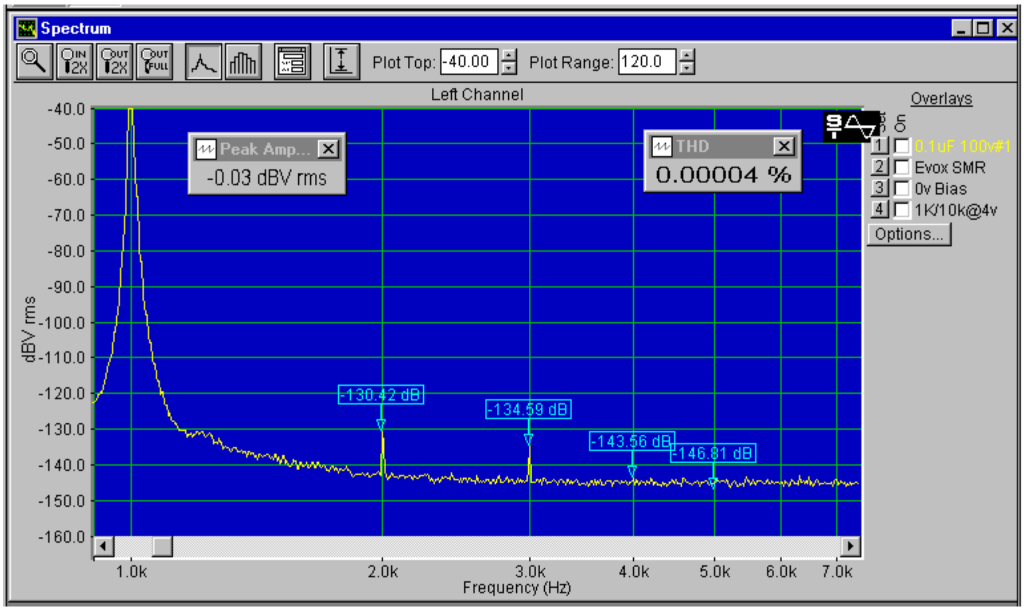

Fig 10A) All 0.1 µF 100 volt Evox Rifa SMR capacitors, made using metallised Polyphenylene Sulphide film, produced superb results when measured with or without DC bias voltage.

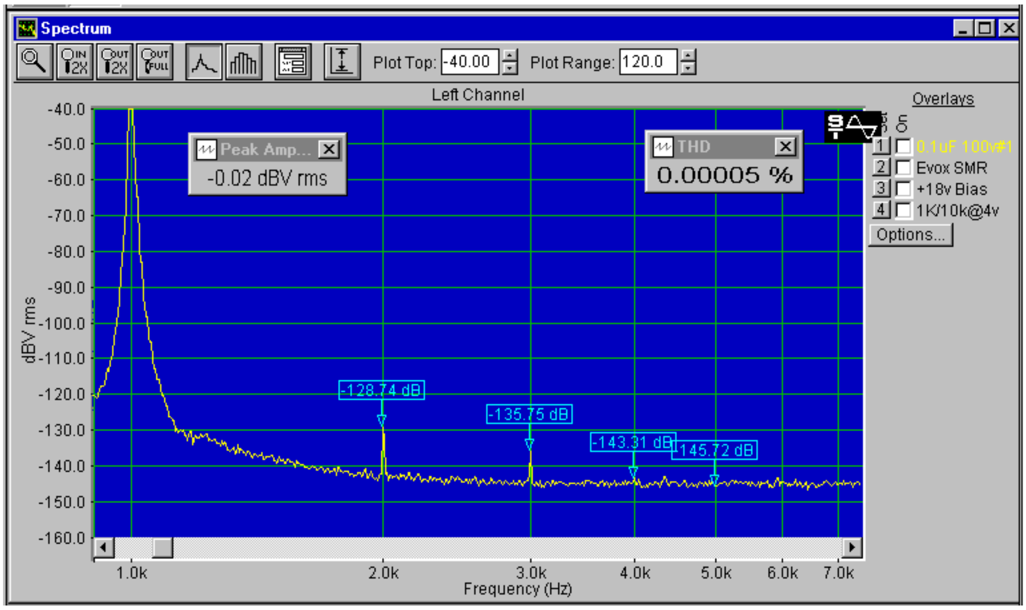

Fig 10) Second harmonic of the 0.1 µF 100 volt Evox Rifa SMR, increased by less than 2dB with 18volt DC bias.

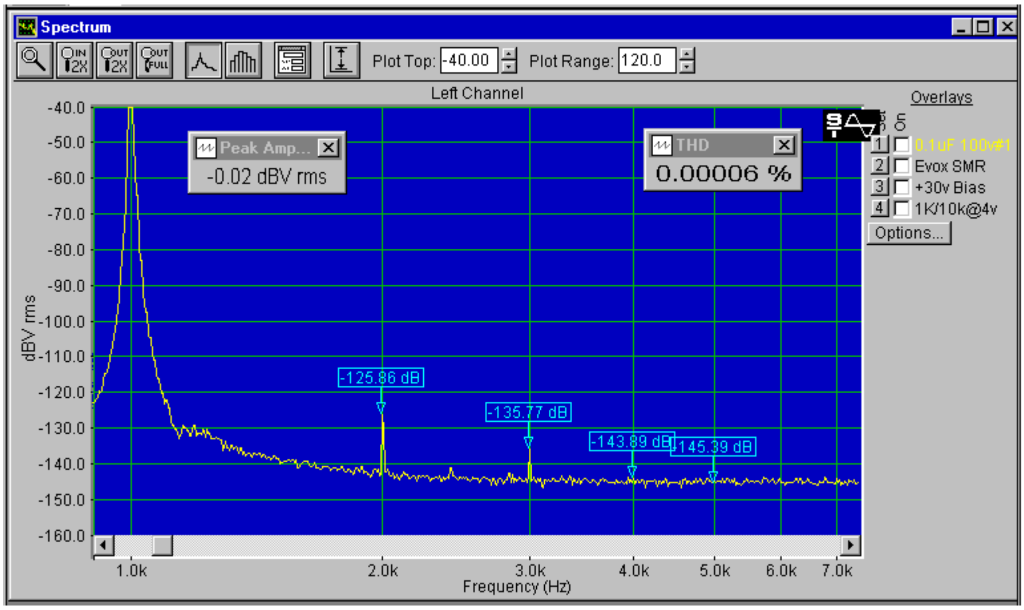

Fig 10B) Second harmonic of the 0.1 µF 100 volt Evox Rifa SMR increased to -125.8dB with 30 volt DC bias.

This small change, less than 5dB with 30 volt DC bias, directly results from the small DA of PPS film, which is considerably smaller than found for Polycarbonate .

Capacitors made using metallised Polyphenylene Sulphide are a little bigger and slightly more expensive than metallised PET types, but comparing distortions they do test consistently better. Altogether a superior capacitor for use in audio systems.

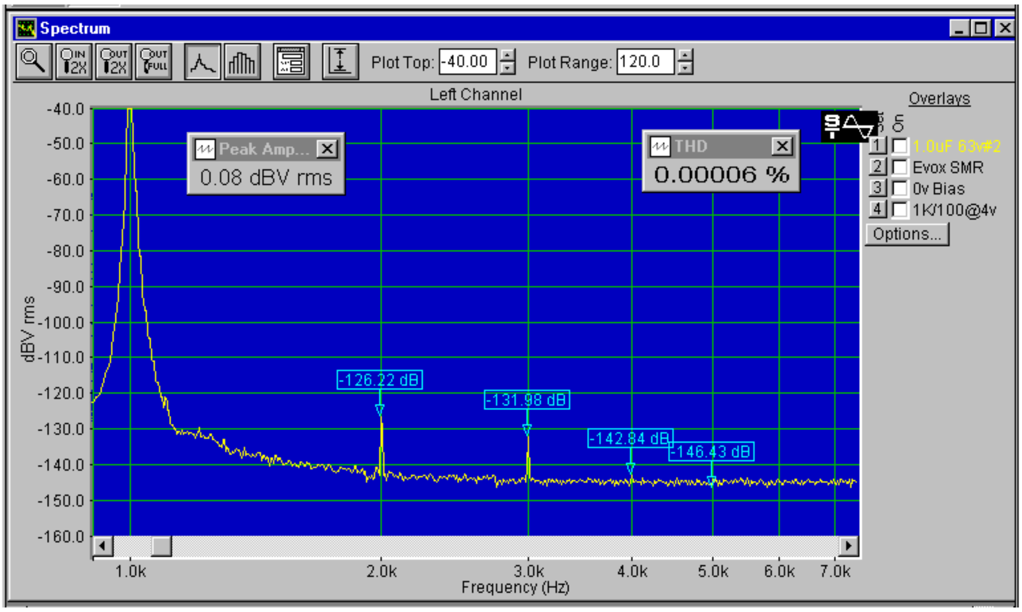

Fig 11A) The Evox SMR 1.0 µF 63 volt metallised Polyphenylene Sulphide film capacitor with 10mm lead centres, produced superb results unbiased and when biased to less than 10 volts.

With increasing bias however, second harmonic distortion does increase, but much less than for a similar voltage metallised PET capacitor.

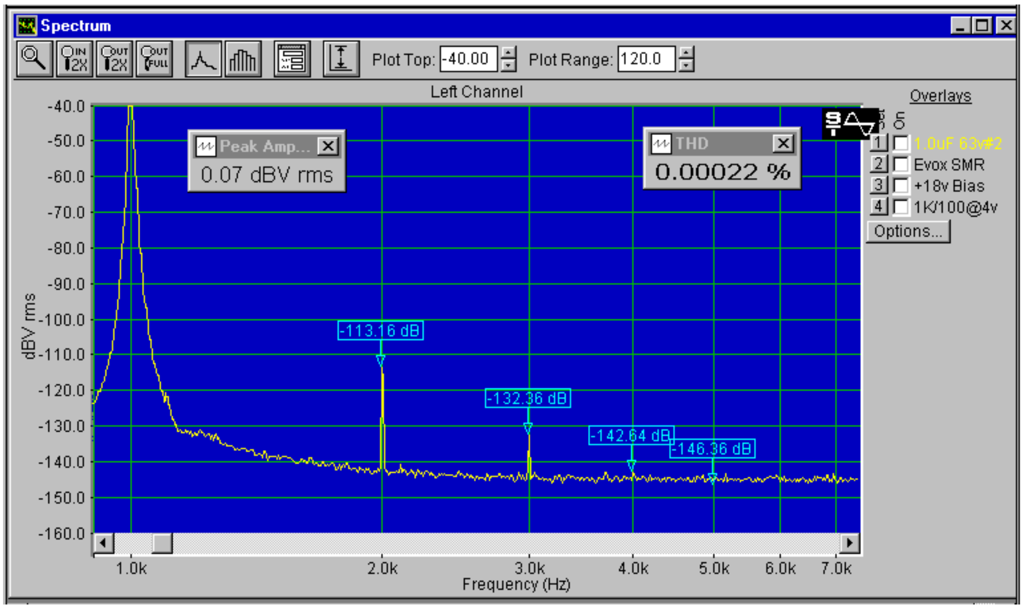

Fig 11) Second harmonic of the 1.0 µF 63 volt Evox Rifa SMR met PPS capacitor increased by 13dB to -113.2dB with 18volt DC bias. Almost 10dB better than the best met PET tested which increased by 22dB.

The larger 1µF 100 volt made with thicker film, has not been tested, but should be much less sensitive to DC bias voltage.

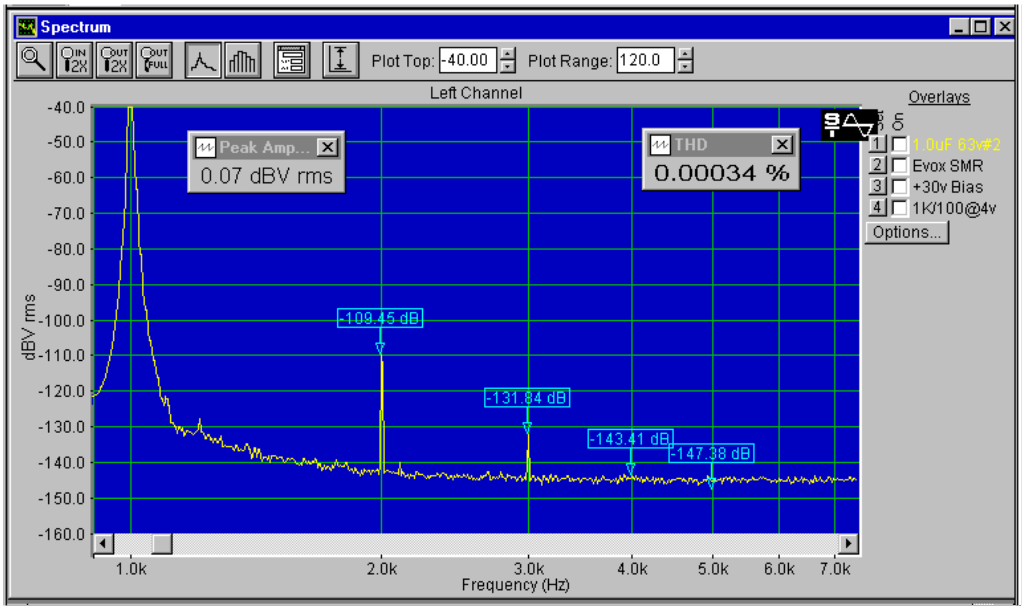

Fig 11B) Second harmonic of the 1.0 µF 63 volt Evox Rifa SMR met PPS capacitor has increased to -109.5dB with 30 volt DC bias.

This small change, less than 17dB with 30 volt DC bias, maintains nearly 10dB improvement over the best met PET tested. Made using very thin film, this improvement directly results from the smaller DA of PPS film, considerably better than Polycarbonate, very much better than met PET.

Bigger is best ?

Another new Farnell line is Polypropylene capacitors from Epcos (Siemens). The second harmonic of the 1µF 5% 250 volt B32653, 22 mm centres, changes little with DC bias up to 30 volts, distortion is then 0.00008%, a superb performance. **Fig. 12**

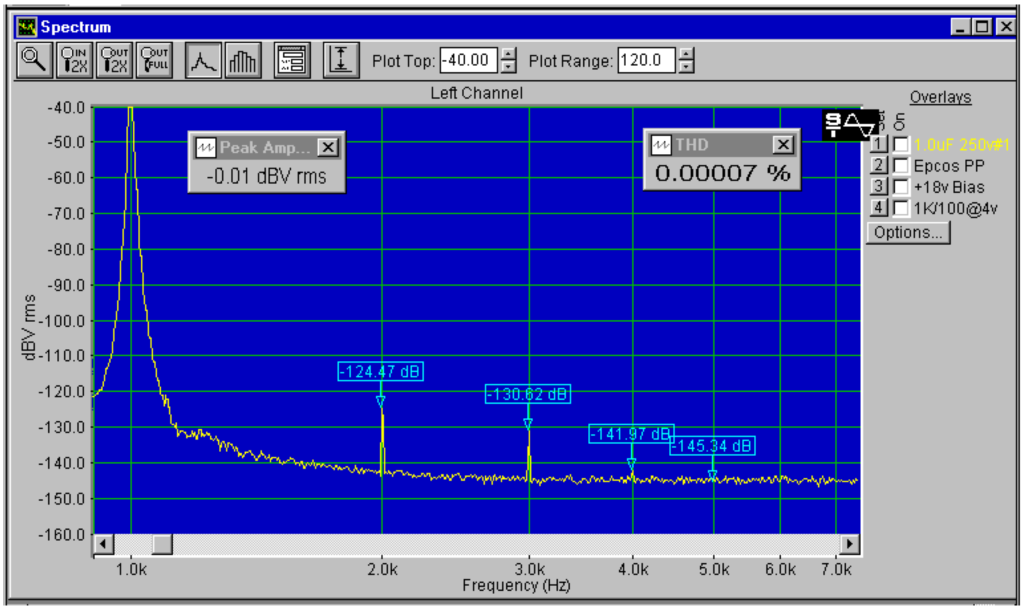

Fig 12) If you have room for a capacitor with 22mm lead spacing, this 1.0 µF 5% 250 volt B32653 capacitor from Epcos distorts less with 18 volts DC bias than did most capacitors when tested without DC bias.

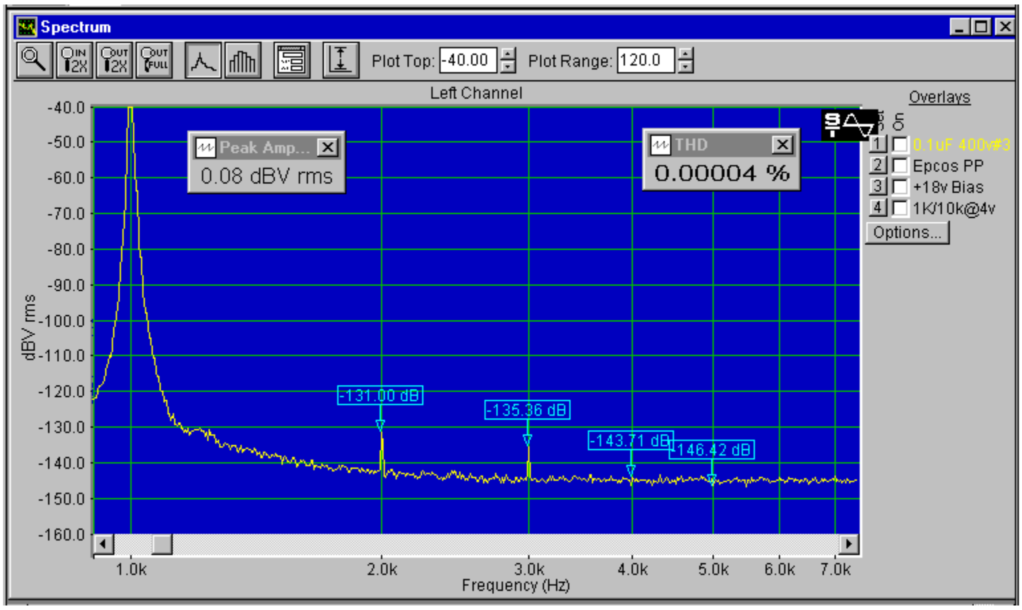

Fig. 13) As good as Polystyrene ? Distortions from this 0.1 µF 5% 400 volt 15 mm centres B32652, also from Epcos, measured just 0.00005% even tested with 30 volts DC bias.

Distortions from these 0.1µF and 1µF Epcos Polypropylene capacitors were not bettered by any similar sized capacitor I tested. With double the PCB footprint of the SMR types, however, they may not fit your available space.

No doubt these new lines will also appear in the Farnell catalogue.

Maintaining designed performance.

Having measured several hundred metallised PET capacitors, I found many with extremely low distortions if measured without DC bias. I also found far too many showing very bad distortions, both DC biased and unbiased, yet metallised PET capacitors continue to be used in the signal paths of high quality audio amplifier designs.

To ensure the claimed performance of a published audio circuit can be repeated, the designer should declare the make, model and rated voltages of the capacitors. Simply stating ceramic, film etc. is totally unacceptable.

These tests illustrate how a capacitor with an acceptable single frequency distortion test, can produce significant intermodulation on audio when presented with multiple frequencies.

Many years ago Ivor Brown presented the case that amplifier tests should comprise three test signals. This seems to have been completely ignored, at least in Electronics World amplifier design articles. **Ref.9**

Single tone 1 kHz amplifier harmonic distortion tests ignore distortions caused by the rising impedance of capacitors at low frequency. It is now clear that large amplitude bass notes and drum beats in music can result in peculiar intermodulation distortions, in an otherwise apparently good amplifier.

For my part I shall disregard any published audio designs which do not report low frequency intermodulation distortion claims or low frequency harmonic distortion results, especially if the capacitors used are not properly chosen and adequately defined.

In my next article we introduce that most complex of capacitors, the electrolytic, then explore which produces the least distortion at 1 µF, a metallised film or an electrolytic capacitor.

END.

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

Updated & expanded March 2003

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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**

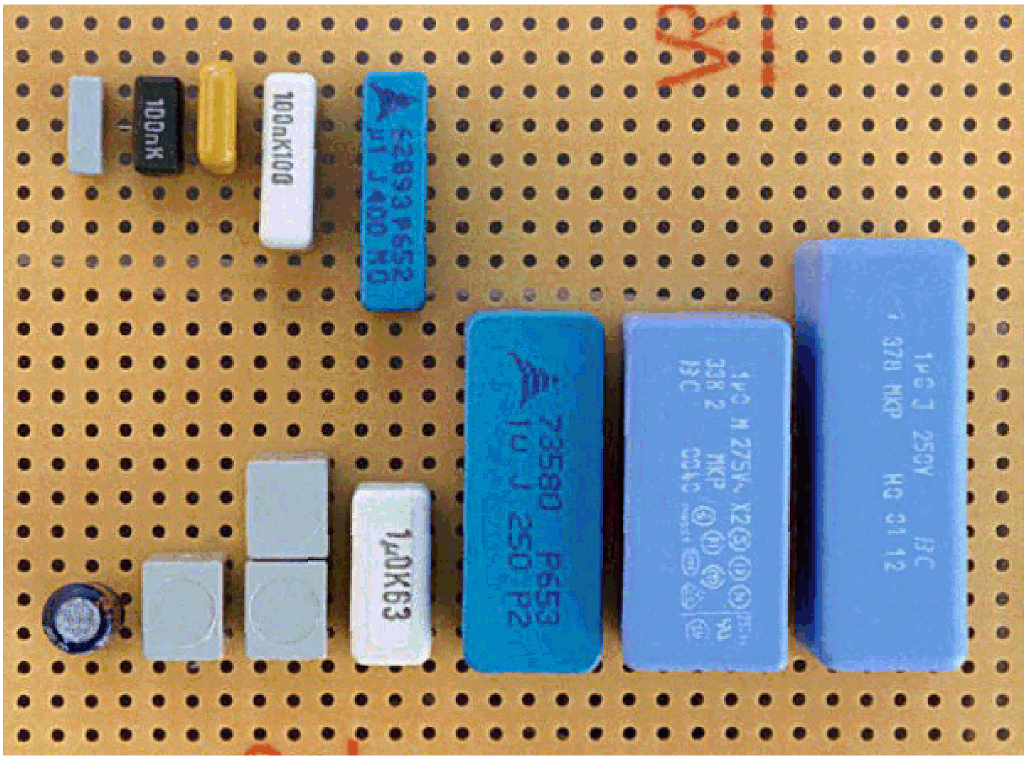


Fig. 1) Top row 0.1µF, the 50v and 100v SMR capacitors second and fourth, the B32652 fifth from left. Far left is the BC Components type 470 met PET, third from left is the 100 nF COG multilayer ceramic.

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**

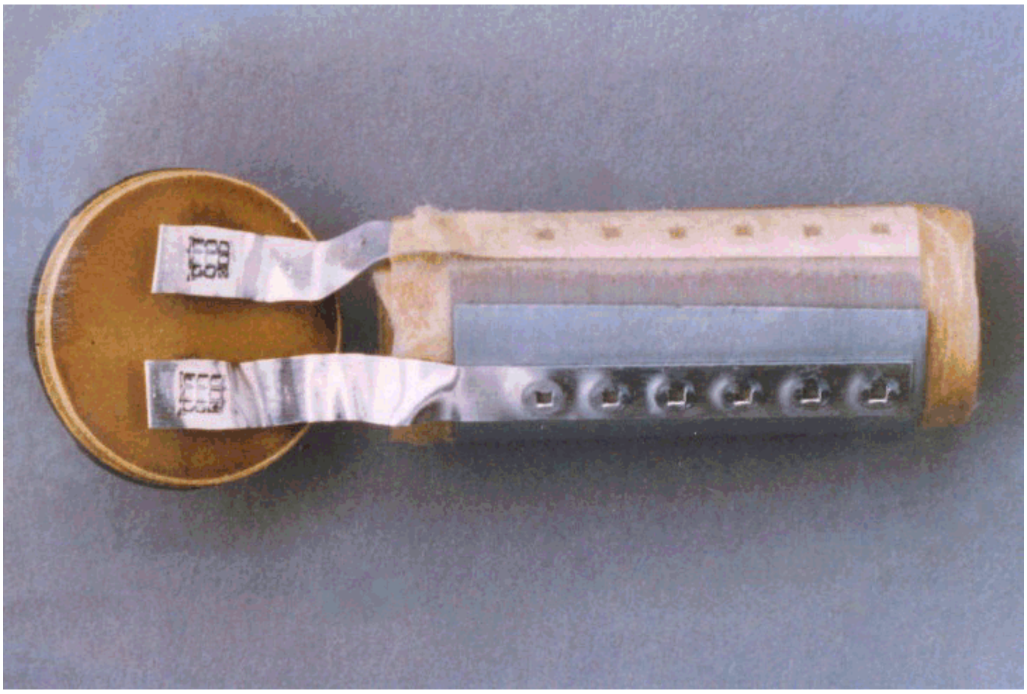


Fig 2) The 'eyeletting' type connections most often used to connect aluminium lead out tabs to the centres of both cathode and anode foils.
In this case because the winding was central tabbed, for clarity the outermost, almost half the wound turns, of both anode and cathode foils, have been removed.

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**

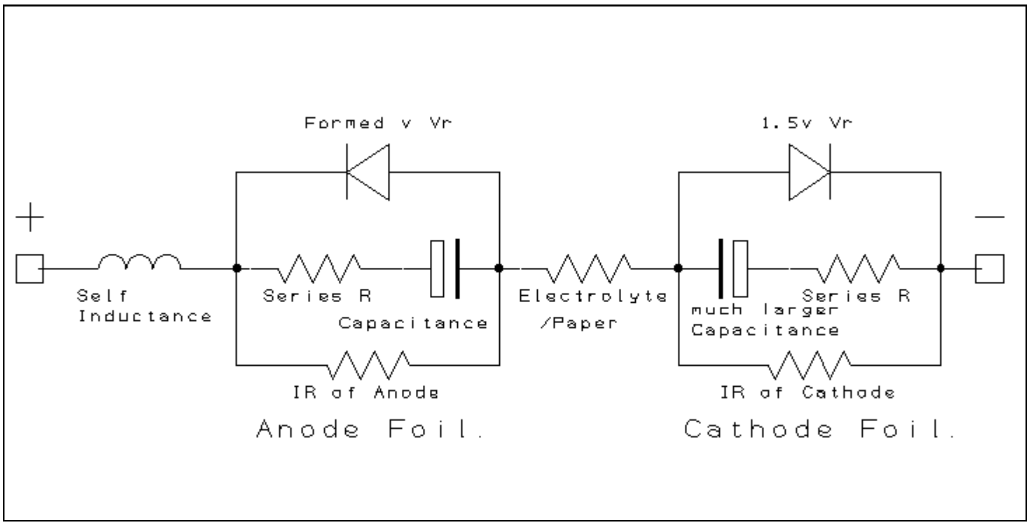


Fig 3) This simplified equivalent schematic illustrates how a polar electrolytic capacitor behaves. For clarity, components needed to account for dielectric absorption, have been omitted.

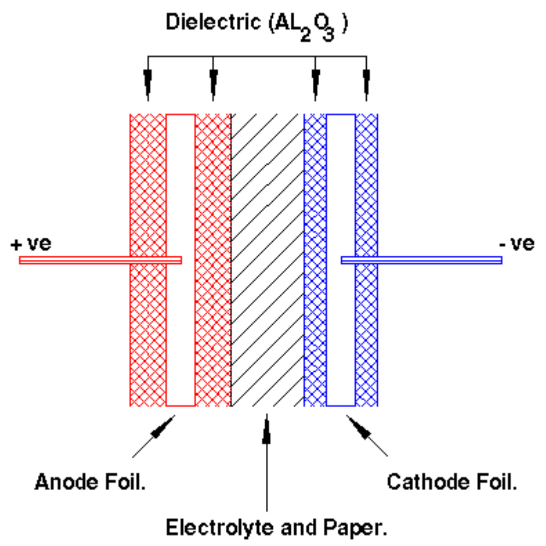


Fig 3A) Sectional view of anode and cathode foils showing their dielectric oxide layers and how the 'electrolyte/paper' function acts to provide a good electrical connection between the aluminium oxide dielectric capacitances of both foils.

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**.

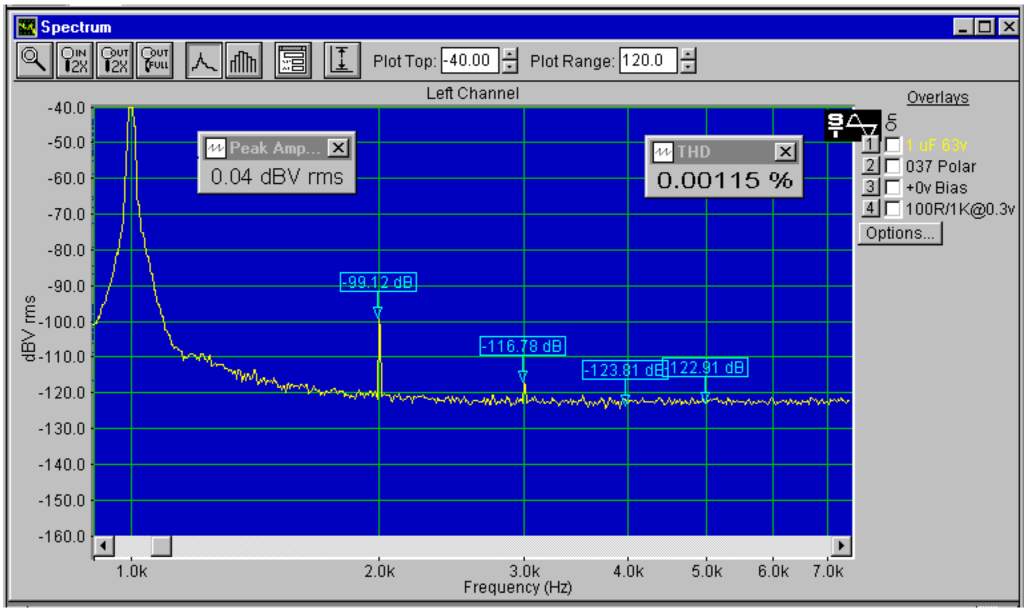


Fig 4) Distortions measured on our 1 µF 63 volt polar capacitor, using a 0.3 volt test signal without DC bias.

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**

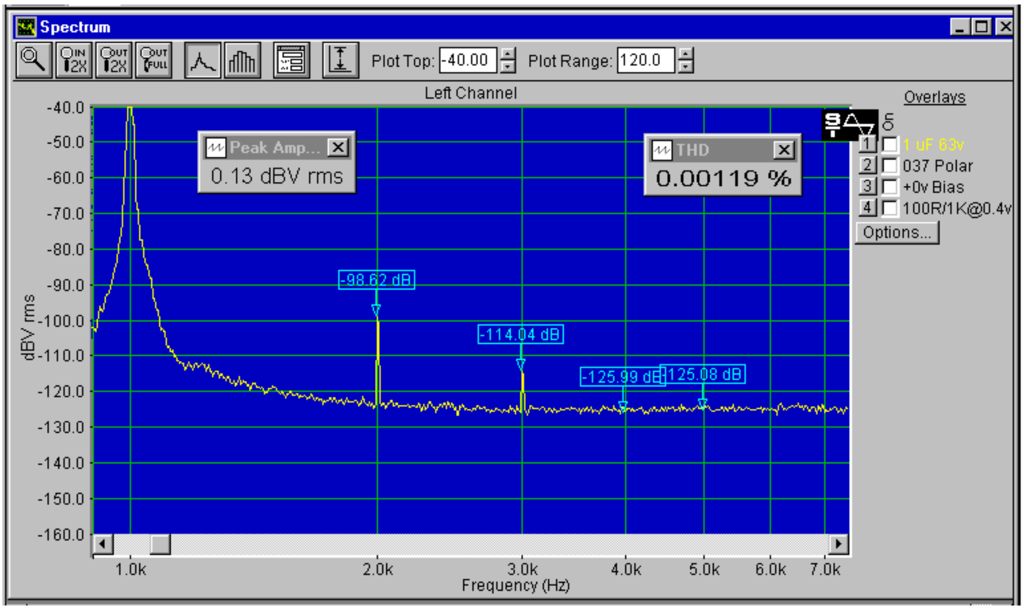


Fig 5) Both second and third harmonics have increased relative to the 0.4 volt test signal. The second has increased much more than the third. Intermodulation components remain buried in the noise floor.

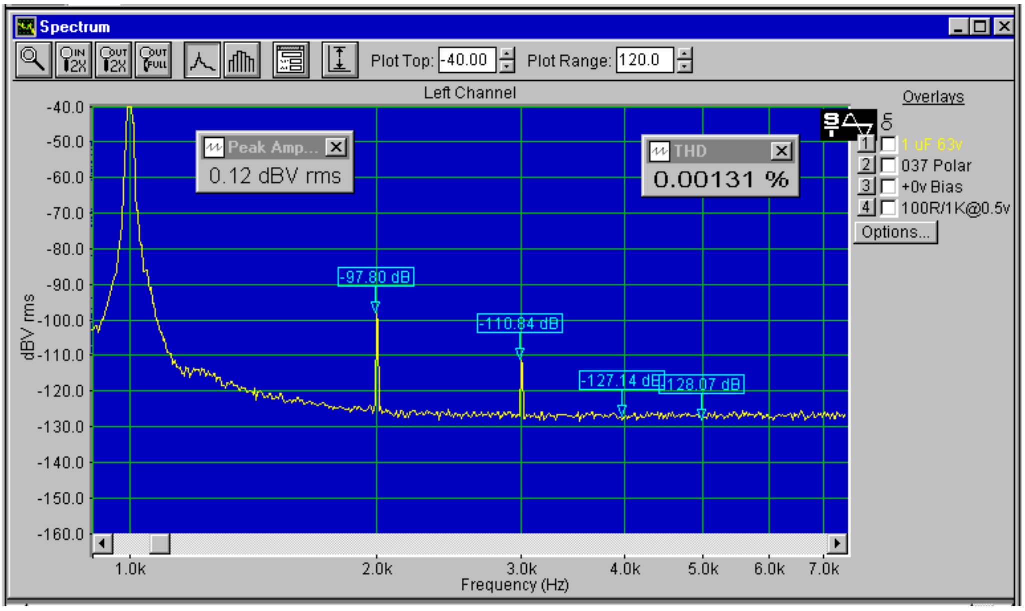


Fig 5A) Both second and third harmonics have again increased relative to the 0.5 volt test signal. The second very much more than the third. Intermodulation components remain buried in the noise floor.

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.

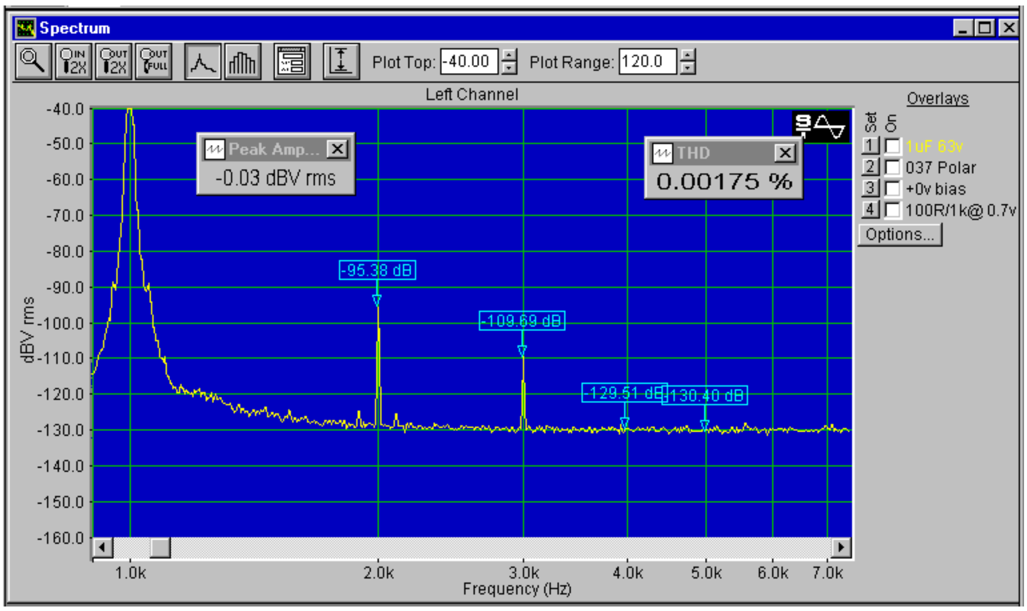


Fig 5B) At 0.7 volt RMS, with the third harmonic some -110 dB below the 0.7 volt test signal, intermodulation products can be seen either side of the second harmonic.

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**

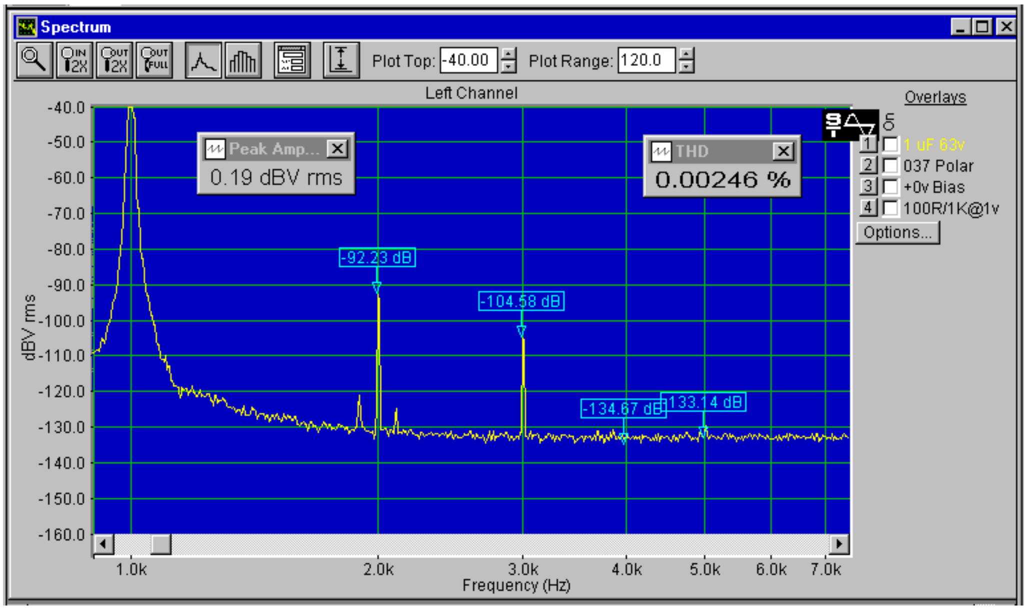


Fig 6) With a 1 volt test signal and no bias, the capacitor is producing 22.4 times more distortion than found with the film reference capacitor.
Second and third harmonic components continue to increase out of all proportion to the test signal.

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

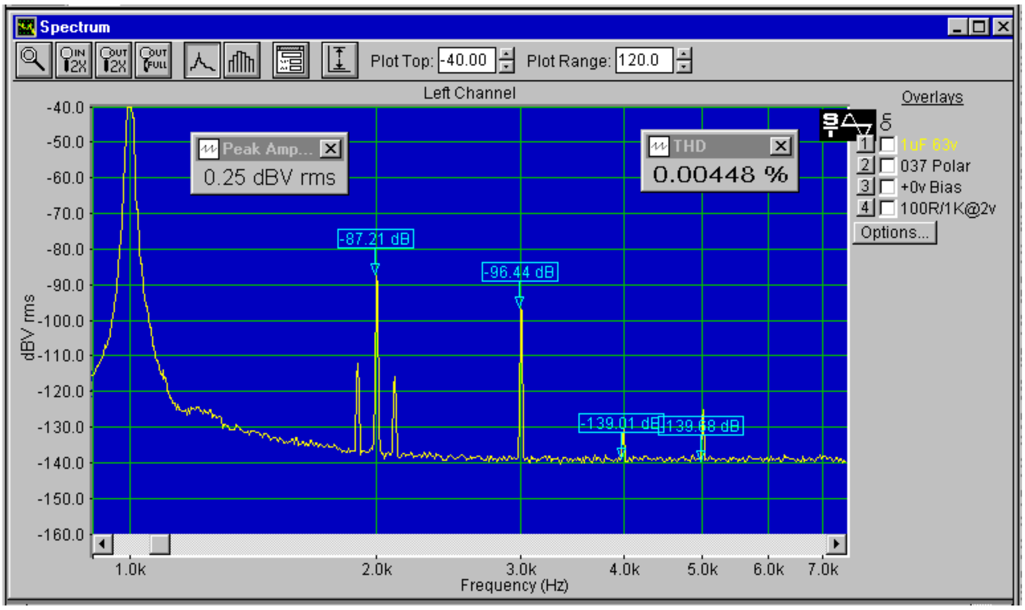


Fig 7) This 2 volt RMS test illustrates how both second and third harmonics together with intermodulation distortion continue to develop when an unbiased polar capacitor is subject to significantly more than 0.7 volts RMS across its terminals.

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**

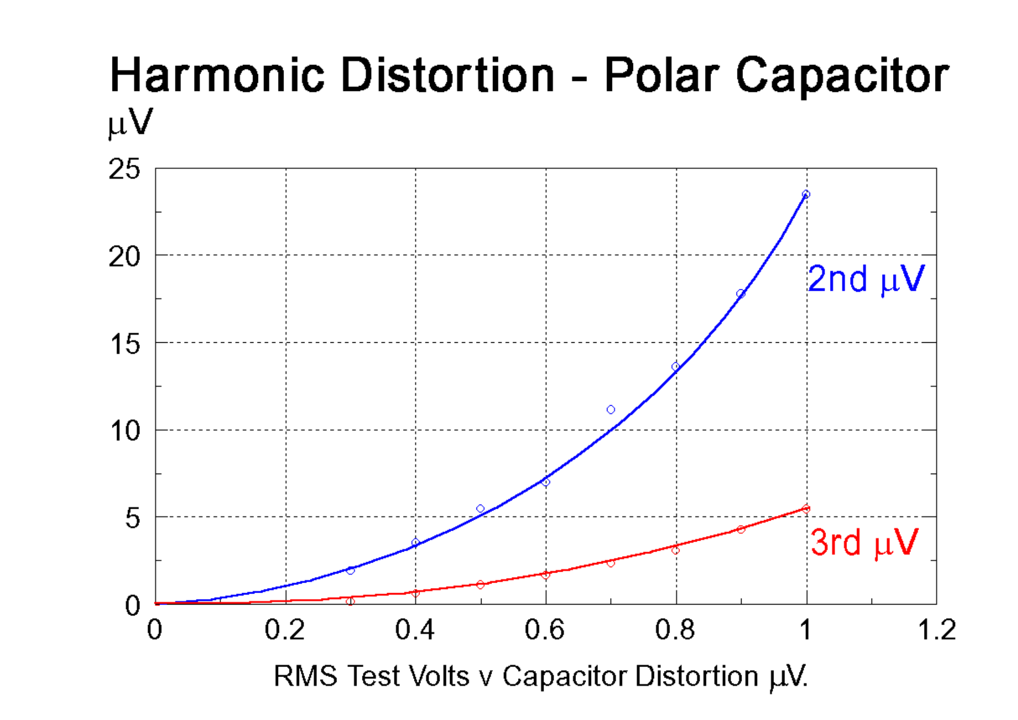


Fig 8) The dB levels in the above plots tend to disguise distortion increase with test voltage.
Translating measured dB values into µV, this plot of distortion versus test signal but with no DC bias voltage, provides a much clearer picture of how non-linearly our unbiased polar capacitor behaves, with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

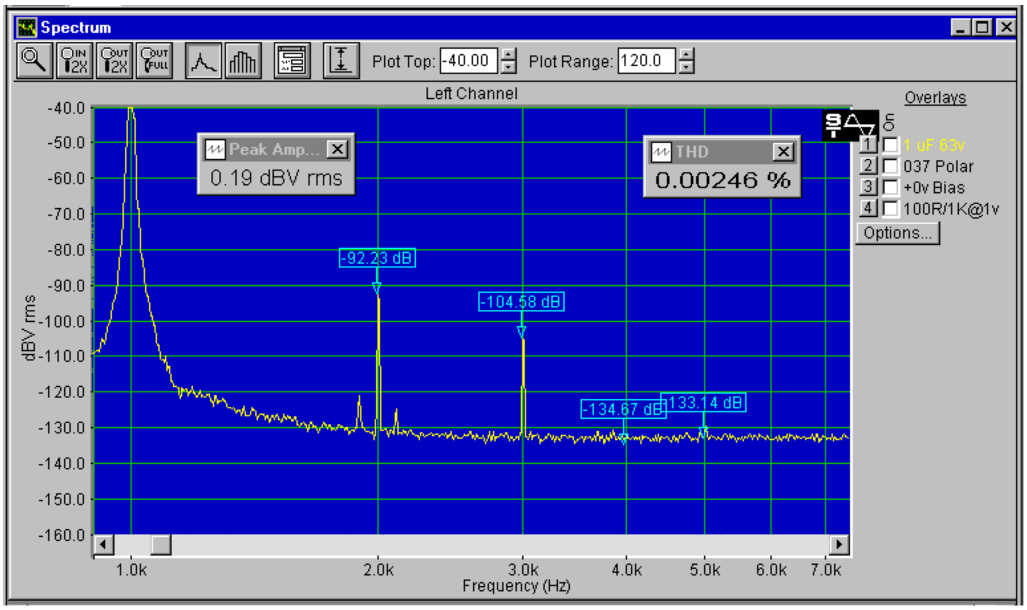
With DC bias.

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.



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**

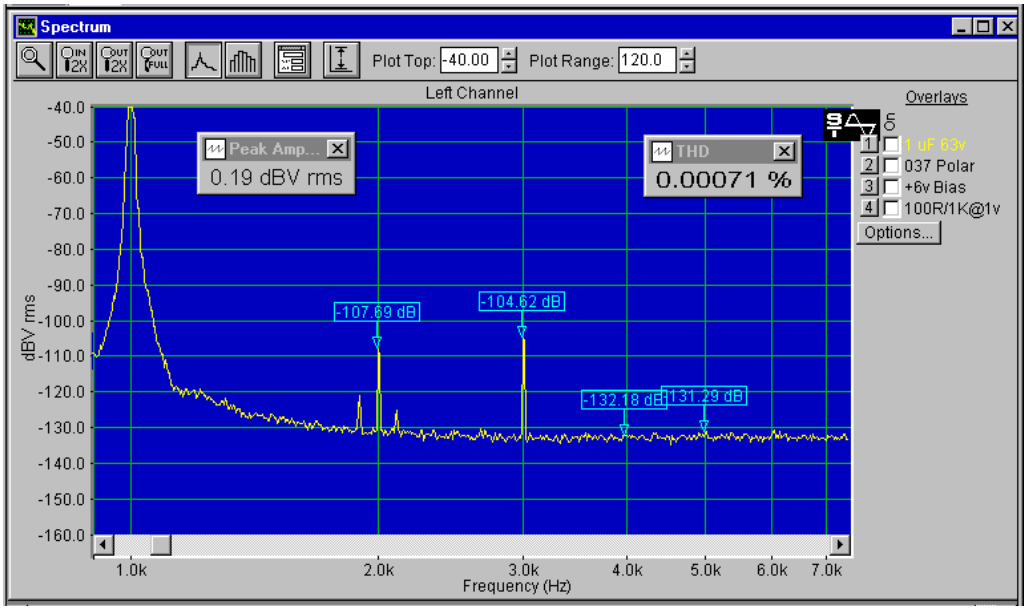


Fig 9) Measured as for figure 6, but now using a 6 volt DC bias. This capacitor is biased close to optimum, minimising its second harmonic distortion at this 1 volt AC with 1 kHz / 100 Hz test frequencies. Now just 6.5 times more distortion than found for our reference capacitor. Notice how the third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

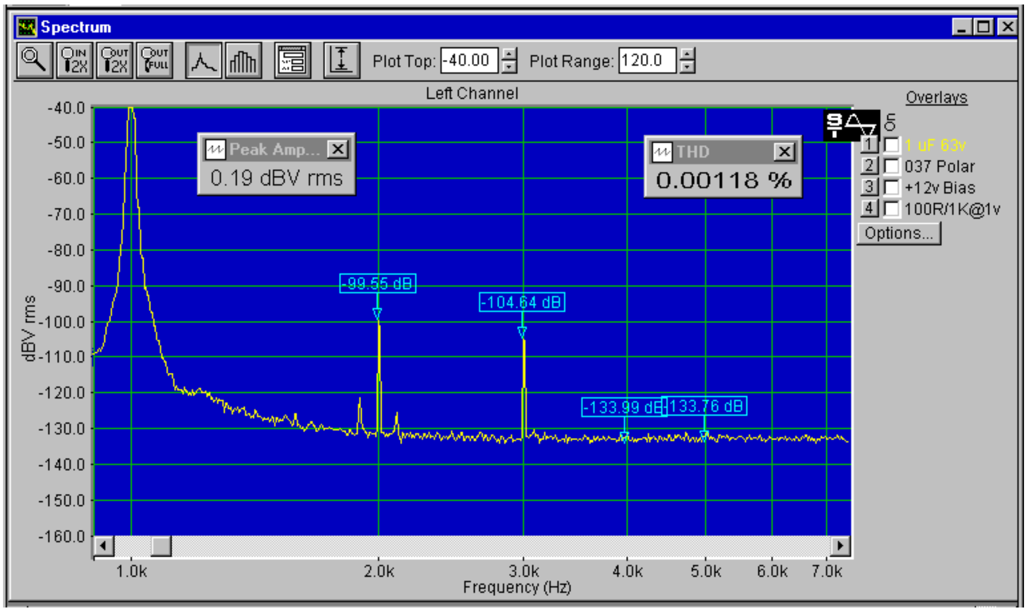


Fig 9A) Using the same AC test signals but with DC bias voltage increased to 12 volts, the second harmonic increased by 8 dB to become dominant over the unchanging third harmonic. Intermodulation distortions also remain constant.

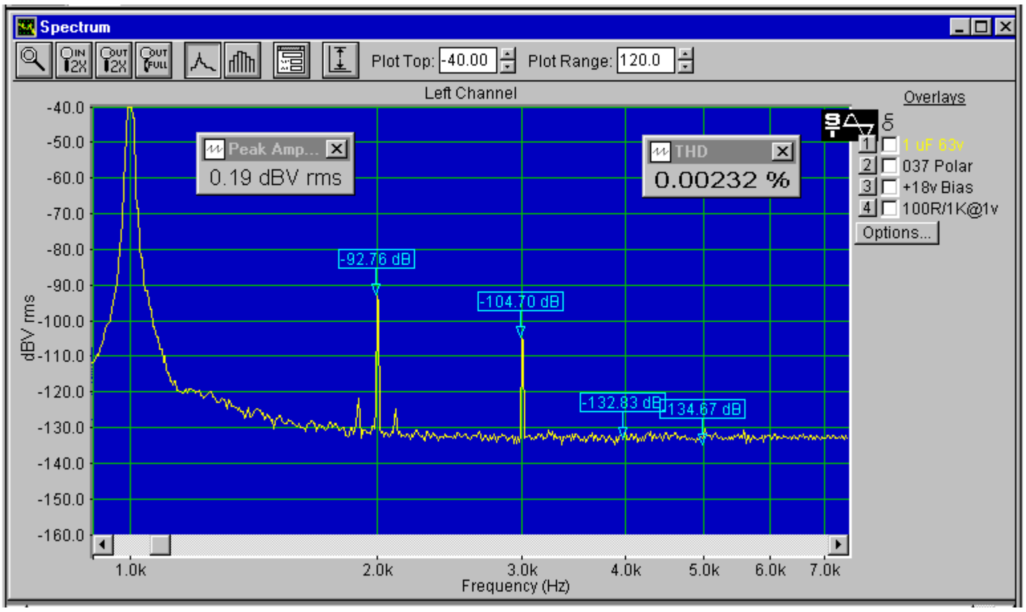


Fig 9B) Increasing DC bias to 18 volts and using the same AC test levels second harmonic has increased again by almost 7 dB, doubling the overall measured distortion.
Third harmonic and intermodulation levels remain unchanged.

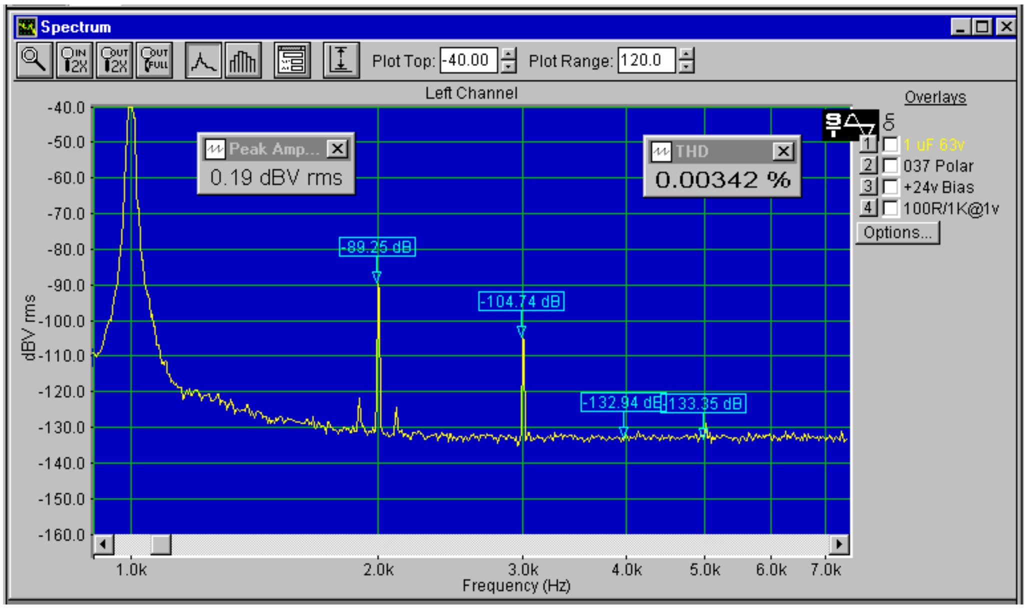


Fig 9C) Increasing DC bias to 24 volts we find second harmonic increasing by 3.5 dB, rather faster than suggested by the 2.5 dB increase in voltage stress.

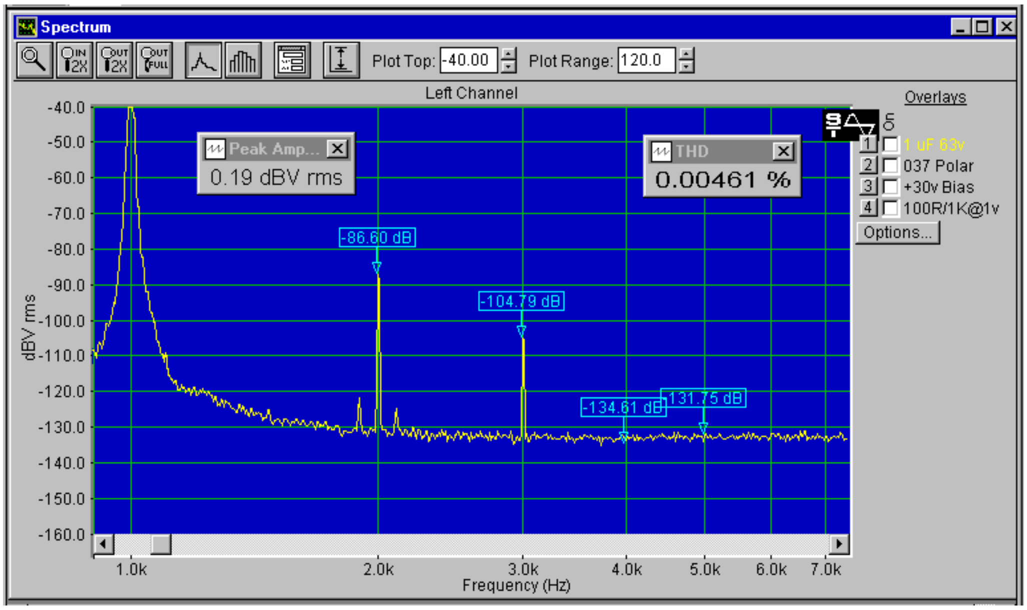


Fig 10) Measured as for figure 6 but now with 30 volt DC bias.
The capacitor is polarised to one half its rated voltage, the 'Myth' value.
Second harmonic has increased dramatically and distortion doubled compared to no bias figure 6.
Compared with its optimum bias distortion, we find a 16 dB, more than 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.

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?.

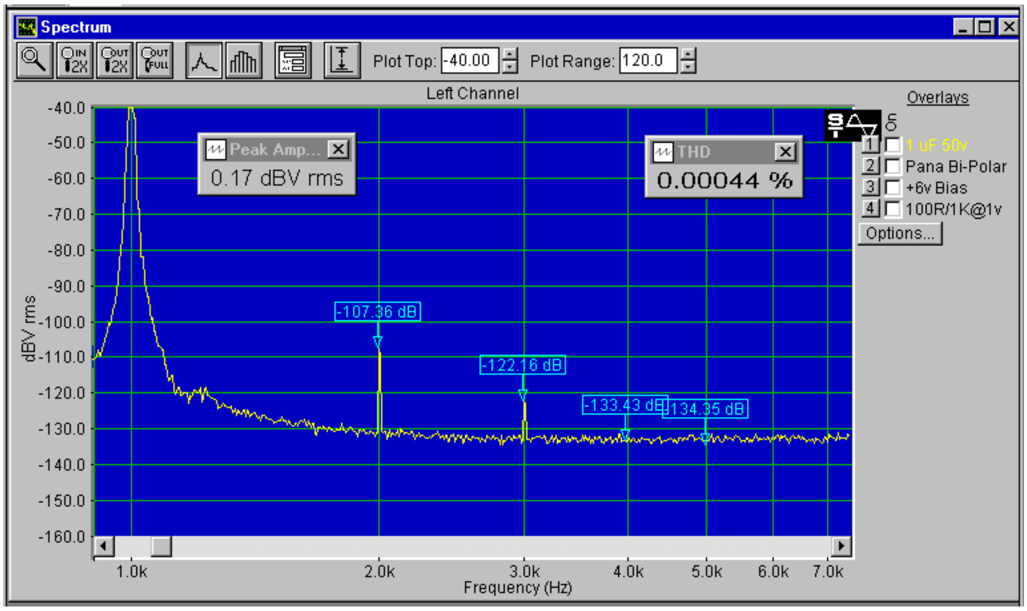


Fig 11A) Re-measured as figure 6 but now using 6 volts DC bias, we find an increase in second harmonic of some 10 dB over its no bias value, but this distortion is only 60% of that measured for the polar capacitor at these voltages..

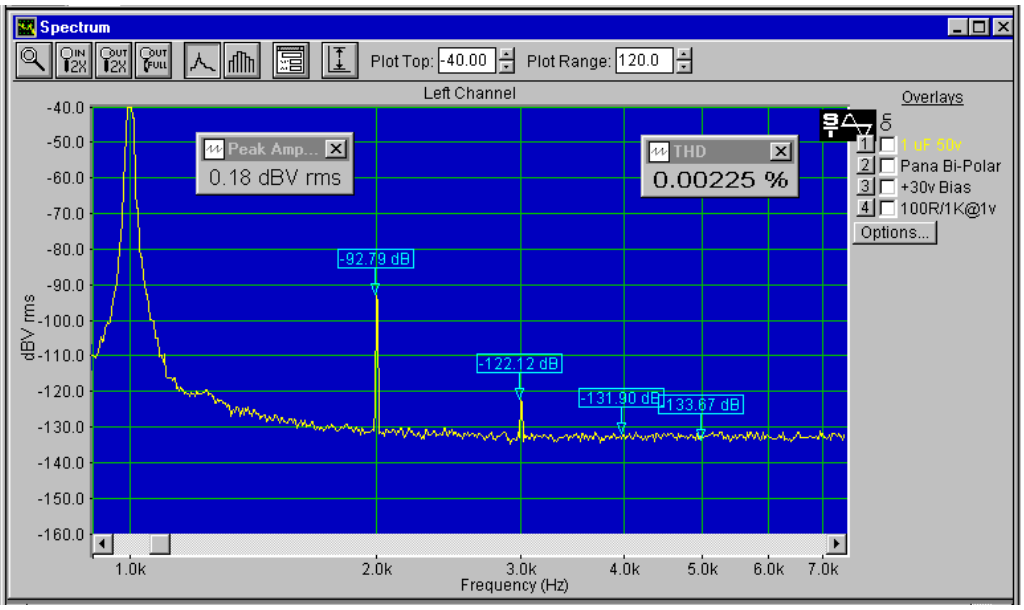


Fig 11B) With 30 volts DC bias this Bi-polar type produces less than half the distortion measured on the polar capacitor.

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**

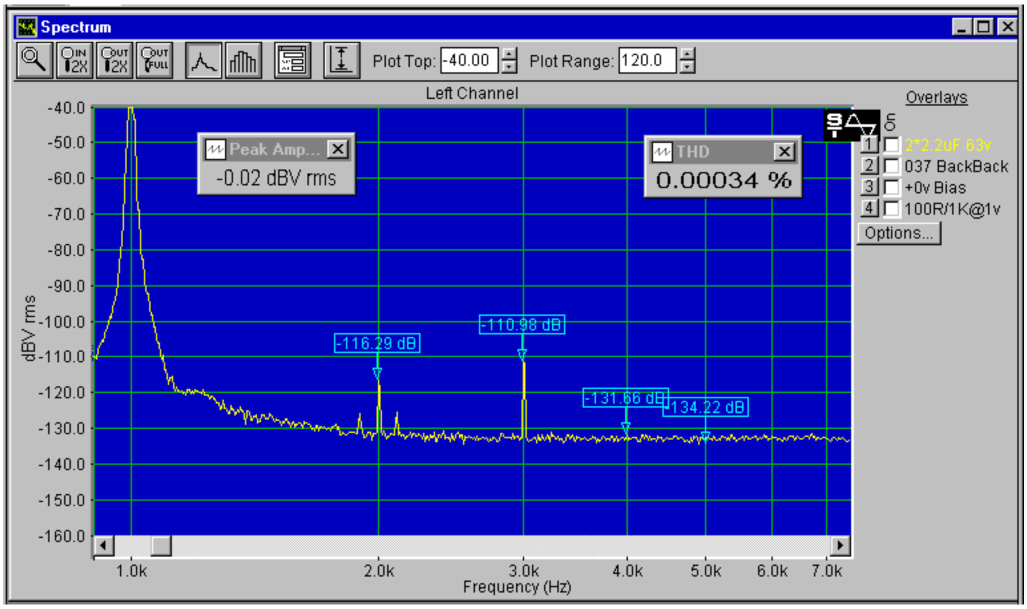


Fig 12) Two 2.2 µF 63 volt polar capacitors connected back to back and measured unbiased as figure 6, produce less distortion than the polar capacitor. However with intermodulation products and double the distortion of the Bi-polar capacitor, why use two polar capacitors, when one Bi-polar (see figure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

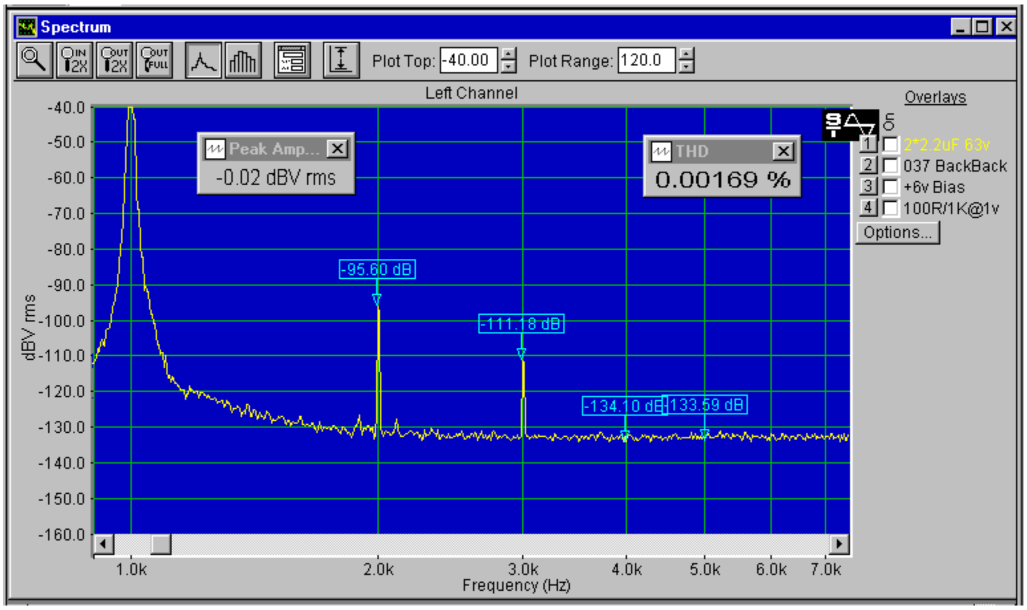


Fig 12A) Measured exactly as figure 6 but now with 6 volt DC bias, the back to back connection produces more than double the distortion of our single polar capacitor.

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.

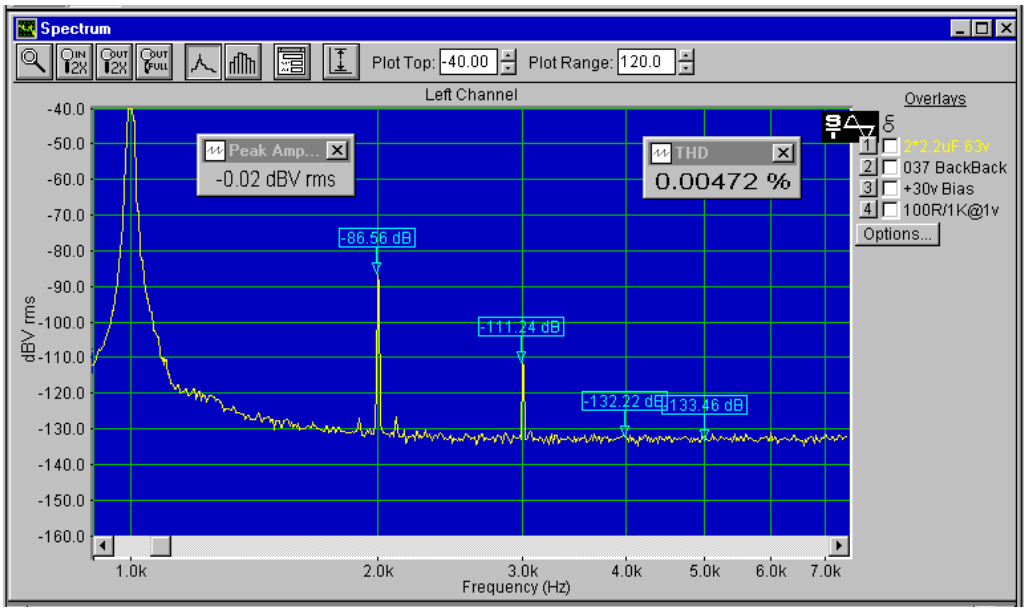


Fig 12B) Measured exactly as figure 6 but with 30 volt DC bias, the back to back connection produces slightly more distortion than did our single polar capacitor.

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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Capacitor Sounds 6 - 10 to 100 µF capacitors and 100 Hz measurements.

Updated & expanded March 2003

Original version Pub. Electronics World Jan 2003 - C. Bateman

Readers of my articles have now seen that many capacitors introduce distortions onto a pure sinewave. In some instances this distortion results from the unfavourable loading the capacitor imposes onto its valve or semiconductor driver. More often, the capacitor generates the distortion within itself.

For 1 µF, the lowest distortions are generated by choosing a film capacitor or a Bi-polar electrolytic. Polar aluminium electrolytics produced considerably larger distortions, even when tested with small AC signals. **Ref. 1**

While high capacitance, low cost, electrolytic capacitors, can be obtained from distributors. Low cost metallised film capacitors are restricted typically to 10 µF at 100 volt and 22 µF at 63 volt.

In this final article, which completes last months discussion on electrolytic capacitors, we explore whether a metallised film capacitor or an electrolytic is our economic, low distortion choice, for capacitors at 10 µF to 100 µF values.

Test frequency.

To avoid overstressing large value electrolytic capacitors, we should reduce our test signal frequency towards 100 Hz. But sufficiently above or below this frequency, to discriminate between harmonics of the supply mains and the test capacitor.

With minor changes in capacitance values, the PCB used for our 1 kHz oscillator can provide an exceptionally low distortion 100 Hz test signal. **Ref. 2** In similar fashion the PCB used for our 1 kHz notch filter and pre-amplifier can also be used at this frequency. **Ref. 3**

The AD811 low distortion buffer can output 40 mA. At 100 Hz using a 100Ω series resistor, it can develop a 5 volt test signal across a 10 µF capacitor. Using a 10Ω resistor, 0.5 volts could be developed across a 100 µF capacitor.

These test voltages are more than sufficient to distortion test any electrolytic capacitor up to 100 µF. However when I designed the test instruments I decided to provide the ability to measure both values of film capacitors to 5 volts. To produce a larger test signal with 100 µF capacitors, a more powerful buffer must be used. A low distortion circuit able to drive up to 400 mA has been designed but needs a different PCB. see **Fig. 1**

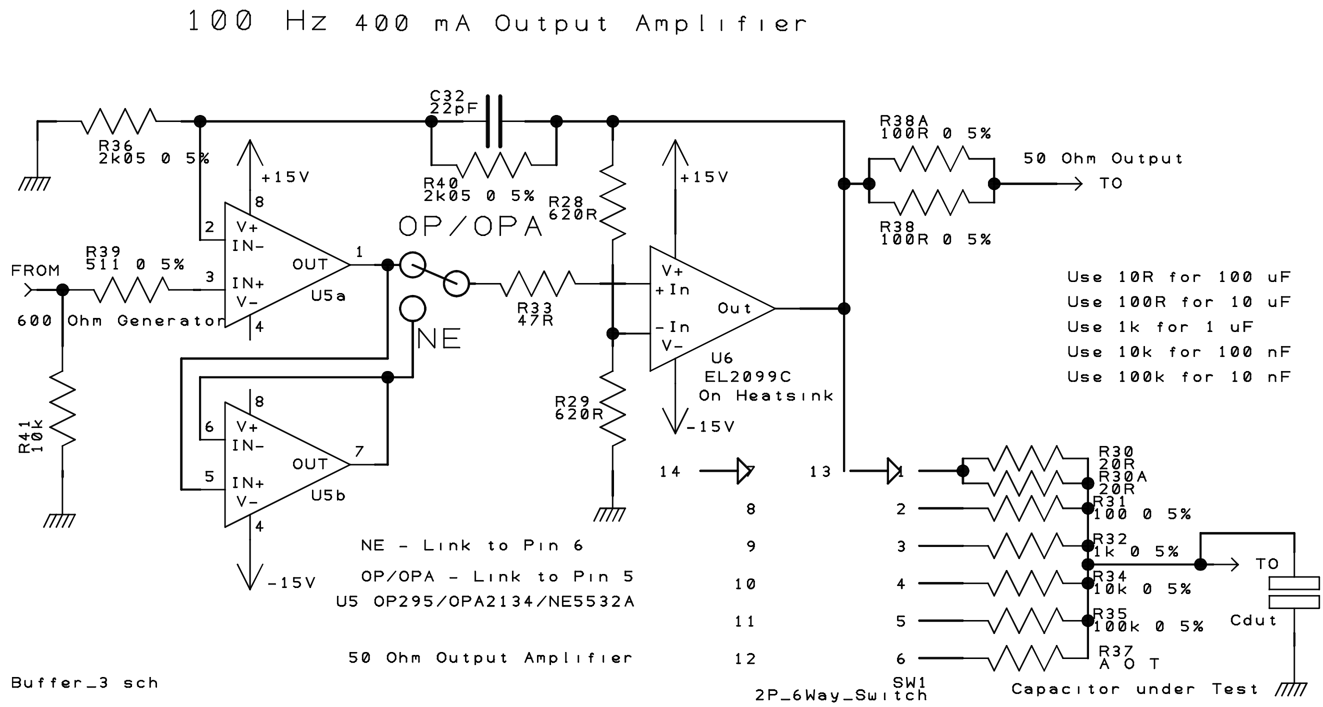

Fig. 1) High power buffer provides low distortion, a gain of two and a 400 mA output. It can develop more than five volts across a 100 µF capacitor via a 10 Ω current limiting resistor.

When testing large value capacitors, a four terminal test system is preferred. Four BNC connectors are provided. which accept either Hewlett Packard capacitor test jigs or four discrete cables and crock clips.   see **Fig. 2**

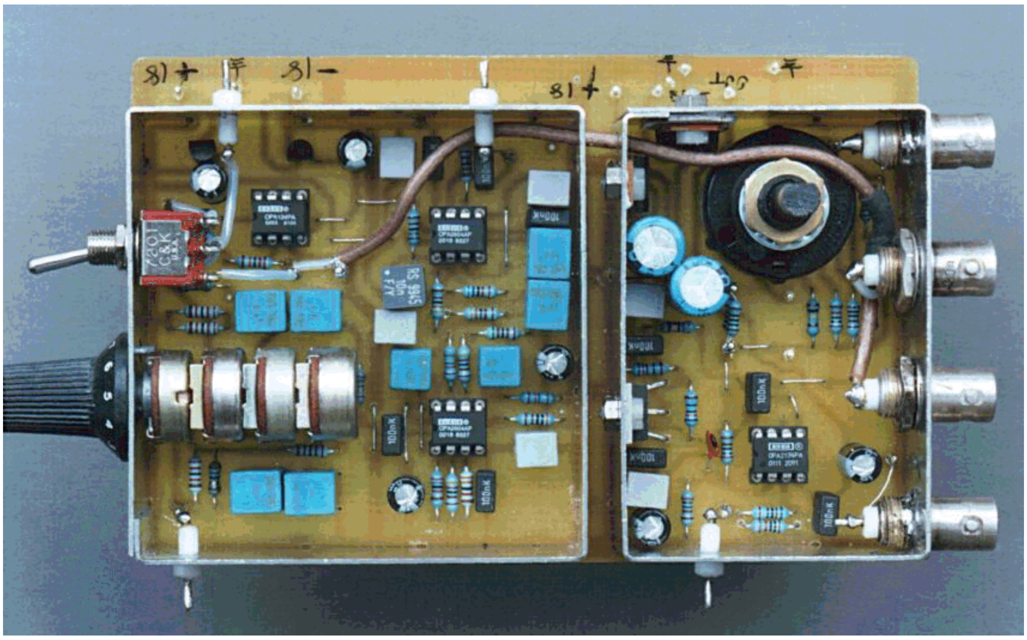

Fig. 2) The higher power 100 Hz test system. Four BNC connectors, are arranged to accept Hewlett Packard test jig fixtures.

The DC bias network inserts between this buffer amplifier and the test jig fixture.

Alternately instead of the Hewlett Packard test jigs, this buffer amplifier can be used with four BNC test leads fitted with ‘crock’ clips.

Box **100 Hz test equipment.**
The oscillator and notch filter printed boards can be used at other frequencies by scaling the values of a few capacitors. **Ref. 2**

Oscillator board.
For 100 Hz use 100 nF 1% metallised Polypropylene for C1, C2, and C3. Bypass R16 by a wire link. To differentiate between test capacitor and mains frequency harmonics, replace R23, R24 and R25 with wire links.

Notch filter/pre-amplifier board.
For 100 Hz use 100 nF 1% metallised Polypropylene for C41, C42, C43, C44, C47 and C48. Use 47 nF 1% metallised Polypropylene for C45 and C46. Use 10 nF 1% metallised Polypropylene for C49.

Output Buffer.
At 100 Hz, 10 µF capacitors can be tested to 5 volts, using the AD811 output buffer amplifier described. **Ref. 3** Adding a 10 Ohm current limiting resistor allows 100 µF to be tested to 0.5 volts.

To fully test 100 µF capacitors, a higher power buffer amplifier is needed. It should develop at least 5 volts signal across a 100 µF capacitor via a 10 Ohm current limiting resistor. I designed a buffer amplifier and printed circuit board, able to drive up to 7 volt or 400 mA, with extremely low distortion. An Elantec EL2099CT output amplifier is used with an input buffer. This can be an OP295, OPA2134 or an NE 5532A, by connecting one link.. I used an OPA2134 in my prototype.   **see Fig. 1**

Larger decoupling capacitors are used with 1.5 Amp stabilisers. A Perancea 75 by 50 mm PCB case serves as heat sink for the EL2099CT and the stabilisers. Apart from these changes, the buffer amplifier schematic circuit and the current limiting resistors/switch follow the approach previously used for my 1 kHz AD811 output buffer.

When testing 100 µF, a four wire test method should be used. Four BNC connectors, two to output the test current and two to measure the capacitor distortions, are spaced at 22 mm centres to fit Hewlett Packard capacitor test jigs alternately four discrete BNC cables and crock clips can be used.

To measure capacitors larger than 10 µF with DC bias voltage, a DC blocking buffer circuit as already described but made with larger capacitors is essential.

Two 50 µF 450 volt metallised Polypropylene motor run capacitors, replaced the 11 µF current carrying capacitors of my 1 kHz design. Three 3.3 µF MKP capacitors provide 10 µF for the voltage measuring circuit. These components were mounted in a die-cast box and hardwired.

Four BNC connectors, were mounted on opposite sides of this box, to mate with my 100 Hz output buffer amplifier and the Hewlett Packard capacitor test jigs.   see **Fig. 2**

A selectable DC bias voltage was provided, by mounting 20 AA cells and a range switch, in a second die cast box. This was used with both DC blocking buffer designs.

Tantalum bead capacitors.
Some audio power amplifier designs have used small Tantalum bead capacitors, with apparent success. Initial measurements of a number of Tantalum capacitors revealed large distortions. Measured at 0.3 volts with and without DC bias, my Tantalum capacitor stocks produced at least ten times more distortion than found with low cost polar Aluminium electrolytics. I decided to exclude Tantalum bead capacitors from further tests. see **Fig.3**

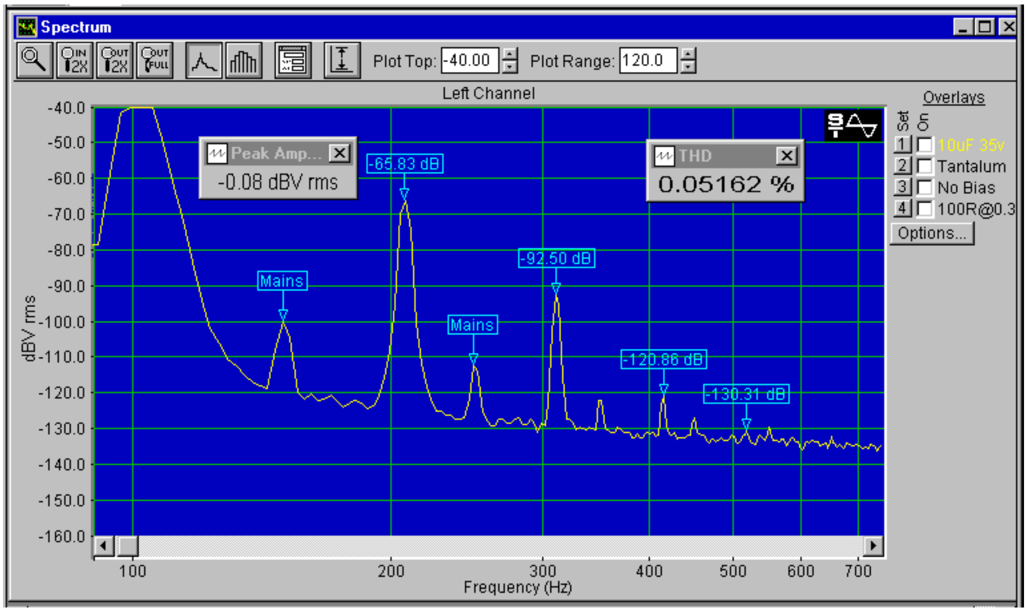

Fig. 3) Distortion of this Tantalum bead capacitor, is ten times worse than found with similar value and voltage aluminium electrolytic capacitors.

Distortion does reduce slightly with application of DC bias.

Aluminium Electrolytic capacitor myths.
As with other capacitor types, much has previously been written about the sound distortions electrolytics produce. As a result, many false myths, specific to electrolytics have emerged. Most were discussed in my last article, the remainder in this.

a) High ESR Electrolytics degrade sound quality, low ESR is always best.
b) Electrolytics are highly inductive at audio frequencies.
c) Polar electrolytics should be biased to half rated voltage to reduce distortion.
d) Electrolytic capacitor distortion is mostly third harmonic.

A working knowledge of aluminium electrolytic capacitor construction combined with careful measurements, leads to somewhat different conclusions.

Is a low ESR/tanδ capacitor always better ?
Capacitor makers test every production capacitor for four key parameters. Capacitance, tanδ, insulation resistance and voltage withstand. The need to test for capacitance, insulation resistance and voltage withstand is obvious, but why test tanδ ?

The most nearly perfect capacitor needs conducting electrodes, which inevitably have some resistance. This appears in series with the capacitive reactance to degrade the theoretical -90° of phase difference to a smaller negative angle. As a result the complementary angle called δ (delta) increases. Every practical capacitor also incurs losses in its insulators and dielectric system. These further degrade this phase difference, increasing the angle δ.

The ratio of these resistive losses to the capacitors reactance or tanδ is the simplest way to monitor capacitor quality. As losses increase so does this ratio and the tangent of the angle δ, usually called tanδ. Consequently a large tanδ implies large resistive losses. These losses do not exist as discrete resistors so are described as 'equivalent series resistance' conveniently abbreviated to ESR. Tanδ and ESR are not finite values but do vary widely with change of measurement frequency.

The most nearly perfect capacitor would exhibit near zero ESR. Low ESR is essential for use in switched mode power supplies, but does a low ESR electrolytic ensure low audio distortion ?

Of the 100 µF capacitors I tested, the 10 volt Oscon measured the lowest 100 kHz ESR of all, 0.012 Ω and 100 Hz tanδ of 0.035. It would be unreasonable to compare a 10 volt capacitor with higher voltage types so I also measured 10 volt Rubycon YXF and Elna RSH types. The YXF ESR measured 0.550 Ω, tanδ 0.091. The RSH ESR was 0.505 Ω and tanδ 0.104.

Tested at 0.5 volt with and without 6 volts DC bias, the Rubycon YXF produced the least distortion, 0.0351% with DC bias and 0.00331% unbiased. The Oscon distorted worst of the three, measuring 0.05321% with DC bias and 0.02499% unbiased.

Clearly low tanδ at 100 Hz and low ESR at 100 kHz does not ensure low audio distortion.

Are Electrolytics Inductive at audio frequencies?
Radial lead electrolytics are assembled with their connecting tabs attached towards the centre of their anode and cathode foils. Wound together this produces a near non-inductive winding. As explained in my last article, the main contribution to the capacitor's self inductance then comes from the connecting leadwires and tabs, and not the wound element. **Ref. 4**

This 'inductive at audio frequencies' myth is easily proved to be false. The largest capacitor I measured for distortion, the Nitai 220 µF 63 volt Bi-polar, has a case size 25×16 mm. Apart from in the power supply, this is the largest value commonly used in an audio system. I mounted one on a test jig, its self resonant frequency was 250 kHz, well above audible frequencies. **Ref. 5**

At all audio frequencies this capacitor must present a capacitive reactance. Self inductance of a lesser value or smaller case size radial lead capacitor being even less, self resonance of smaller capacitors will occur at higher frequencies. They cannot become inductive at audio frequencies.

Exceptionally large value capacitors, as often used in power supplies, may appear as either inductive or capacitive depending on their capacitance value, case size and their connecting leadwires/tracks. Inductance of the leadwires/circuit tracks used to connect the capacitor, usually well exceed that of the capacitor's own self inductance. Due to its internal series resistance or ESR the capacitor's phase angle will be much smaller than -90° and the capacitor will appear to the circuit as a series combination of a resistor with a capacitor or as a DC blocking inductance in series with a resistor.

Using a Wayne Kerr B6425 precision LCR meter fitted with my Hewlett Packard capacitor test jigs, I measured a few capacitors removed from one of my old bench amplifiers at 10 kHz, as representative of capacitors which may be used in amplifier power supplies, to illustrate the point:-

Elna 4,700 µF 63 volt Cerafine size 82 mm by 35 mm dia, phase angle +7.5°, ESR 11.05 mΩ Impedance 18.3 mΩ
Marcon 4,700 µF 63 volt size 30 mm by 40 mm dia, phase angle -6.5°, ESR 16.65 mΩ Impedance 16.69 mΩ
Marcon 10,000 µF 63 volt size 42 mm by 65 mm dia, phase angle -14.5°, ESR 9.68 mΩ Impedance 10.0 mΩ

At 20 kHz both Marcon types remained as a capacitive reactance having a negative phase angle. At 100 kHz the Elna measured as an 83 nH inductor, the 4700 µF Marcon as a 26 nH inductor while the 10,000 µF Marcon measured as a 256 µF capacitor.

This last value shows why it is not possible to estimate capacitor self inductance from published impedance/frequency curves. As frequency increases, the capacitance of all aluminium electrolytic capacitors reduces, some more quickly than others. As the capacitive reactance reduces with frequency, the capacitors ESR becomes almost a constant value. Phase angles become small and the impedance curve becomes 'flat bottomed'. see **Fig. 4**

Any calculation of resonant frequency based on using the correct self inductance value together with this capacitors nominal 10,000 µF value, obviously produces a very false result.

Measured using the Wayne Kerr B6425 with Hewlett Packard test jigs as above, this Philips 1000 µF capacitor exhibited a -6° phase angle and 820 µF capacitance at 30 kHz. At this frequency ESR measured 61.5 mΩ, impedance was 61.6 mΩ.

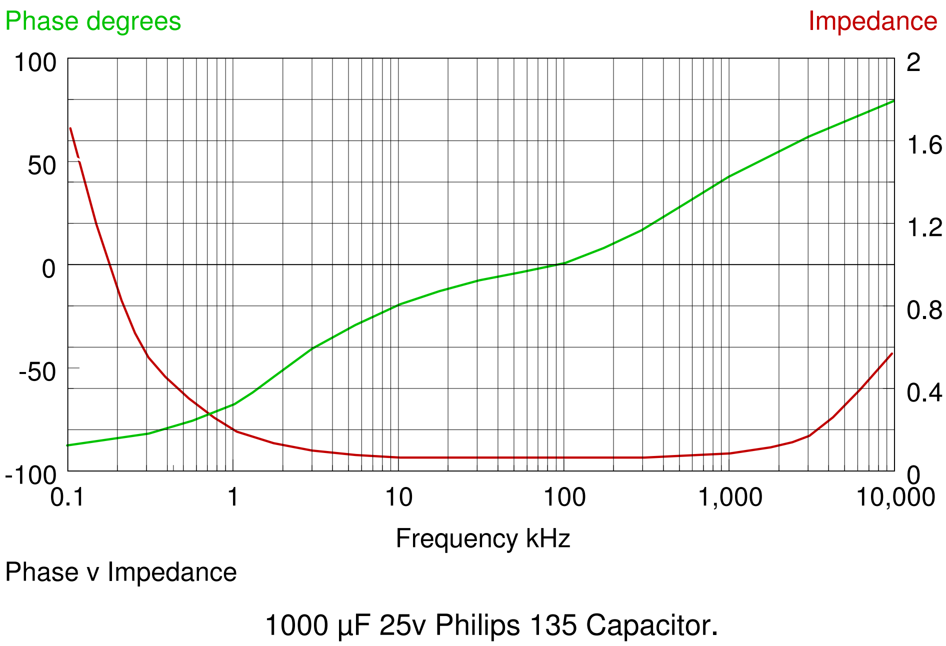

Fig. 4) This 1000 µF 25 volt capacitor has been measured using two quite different methods.

The Wayne Kerr bridge up to 300 kHz, its maximum frequency.

This graph was plotted up to 10 MHz from results using my 'High-frequency impedance meter' with jigs and methods as in EW January 2001.

As can be seen both methods gave almost identical results.

Polar electrolytics.
In my last article we saw that every polar aluminium electrolytic capacitor comprises two polar capacitors in series, back to back. **Ref. 1** Wound with an anode and cathode foil, each foil with the electrolyte, comprises one capacitor. The cathode foil provides a larger capacitance, lower working voltage, than the anode foil.

With no bias voltage, the capacitor produced predominantly second harmonic distortion. In some instances, application of a very small optimum DC bias did minimise this second harmonic. Increased bias however resulted in increased second harmonic distortion.

For the 100 µF 25 volt capacitors tested for this article, optimum bias varied by capacitor, from 1.1 to 4.2 volts. Optimum bias voltage varies with capacitor rated voltage, capacitance value and even from capacitor to capacitor within a small batch. However the important point is that with all the polar aluminium electrolytic capacitors I tested, (several hundred in all) this optimum low distortion bias with no exceptions, was a small voltage. Not the half rated voltage as commonly suggested.

Bi-polar electrolytics.
A Bi-polar electrolytic is made in exactly the same way as a polar capacitor, with one important difference. In place of the unformed 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 voltage. To make the desired value, two anode foils of double 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 deduced an equivalent circuit for a polar aluminium electrolytic capacitor. see **Fig.5**

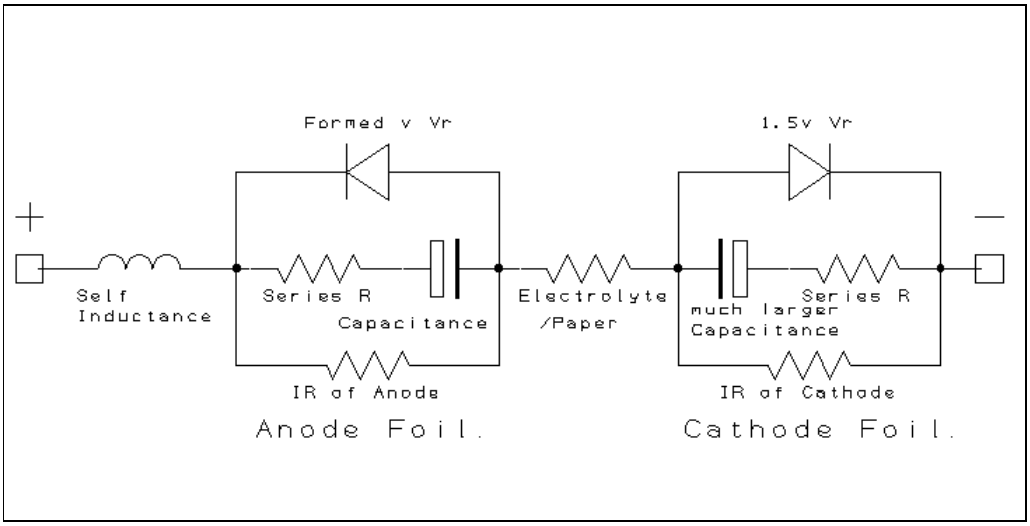

Fig 5) Simplified equivalent schematic shows how a polar electrolytic capacitor behaves with AC signals, with and without DC bias.

Dielectric Oxide. Aluminium oxide has a 'k' of eight, similar to that of COG ceramics or some impregnated paper capacitors. **Ref. 6** It is higher than PET, which at 3.3, has the highest 'k' of commonly used film dielectrics. It is a low value compared to the 'k' of some thousands, found in 'high k' BX, X7R and Z5U ceramics.

More significant is dielectric thickness. Aluminium electrolytic dielectric is much thinner than used in other capacitors and the dielectric oxide film has a small but easily measured voltage coefficient of capacitance, typically +0.1% with +18v DC bias, but this is overshadowed many times by its much larger dielectric absorption. An electrolytic capacitor is exceptionally sensitive to dielectric absorption effects and the applied AC and DC voltages.

Voltage effects.
When our 1 µF 63 volt polar electrolytic was tested using two 0.7 volt frequencies, its third harmonic was -110 dB or 0.0003%. It created visible intermodulation distortion. We also noted small capacitors rated at 40 to 63 volt exhibit near optimum quality. **Ref. 1**

Many 100 µF capacitors will be made with lower voltage, thinner dielectric oxide, anode foil. This capacitance requires lengthy anode and cathode foils, housed in a larger diameter can. To generate the test voltage across the capacitor, increased current must pass through the tab connections into the winding, amplifying the affects of any non-linear resistance. It seems probable that similar harmonic and intermodulation levels will be found but at smaller test voltages.

To allow direct comparison between the low cost 1 µF 63 volt polar capacitor and the physically larger Elna Silmic 100 µF 25 volt, I show its distortions measured at 1 volt. This capacitor provided the best 1 volt, no bias, results of the 100 µF polar types tested for this article.   see **Fig. 6**

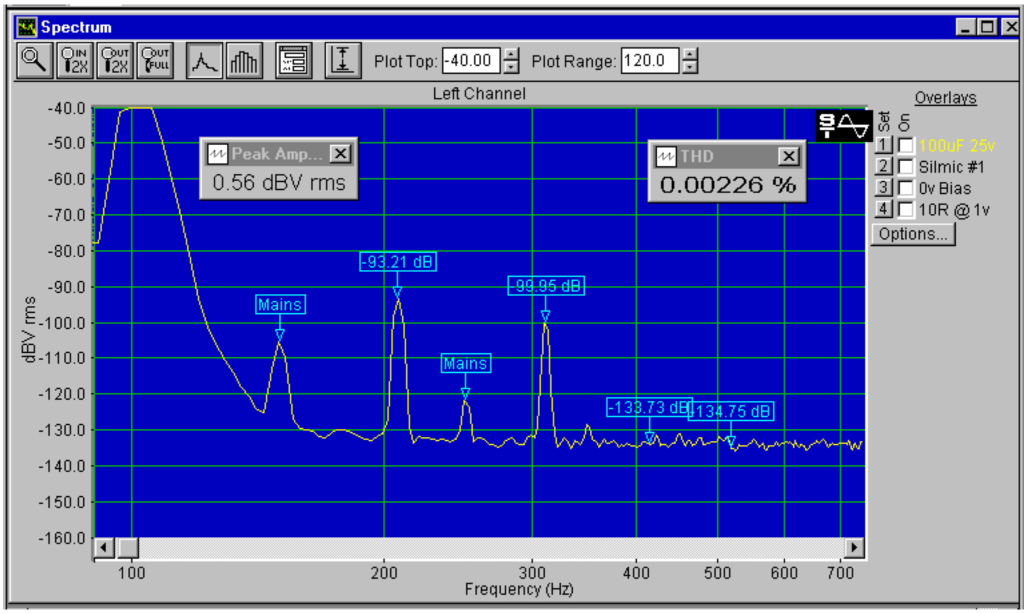

Fig 6) The lowest distorting 100 µF 25 volt polar capacitor of those tested, at 1 volt. It should be compared with Figure 6 (Fig 7 as published in EW) of my last article.

Both capacitors produced similar second harmonics. Third harmonic of the 100 µF has increased by 4.5 dB indicative of increasing non-linearity with increasing capacitance values.

Lower voltage measurements.

Accurate 100 Hz distortion measurements using test signals smaller than 1 volt become quite difficult, for two main reasons.

Supply mains harmonics intrude everywhere and are difficult to reduce using a computer based system.
The smaller test signal reduces the dynamic range of our measurement, dramatically inflating indicated distortion.

For example, using a 0.1 volt test signal, my noise floor is around -112 dB, hence a perfect capacitor producing no distortion at all will still register some 0.0005%. However if we compare the measured harmonic levels of our electrolytic with those found for the identical measurement using a metallised film capacitor. We will see any increase in distortion caused by the electrolytic capacitor.

To distinguish between harmonics from the mains and the test capacitor, my test frequency was displaced a few Hz away from 100 Hz. The Spectra software then ignores mains harmonics when calculating distortions. To assist visual identification, I used ‘Mains’ markers to identify mains harmonics and amplitude markers to indicate the first four harmonics from the test capacitor.

At 100 µF, a metallised Polypropylene capacitor is both large and costly. I used an assembly of 10 µF Evox Rifa MMK metallised PET capacitors. This works well for small test voltages as a low distortion ‘reference’ capacitor.   see **Fig. 7**

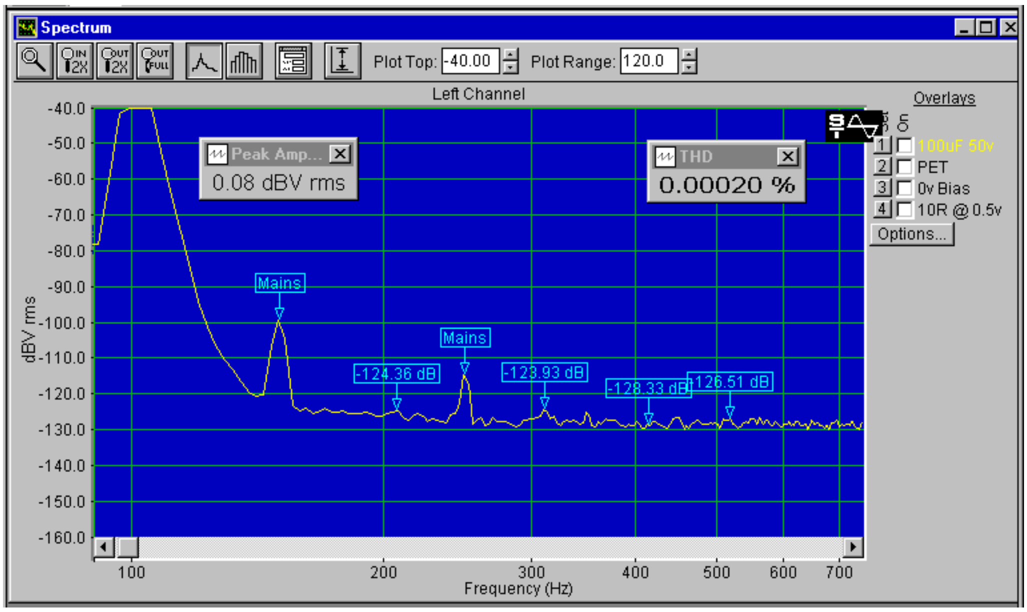

Fig. 7) Distortion plot of an assembly of ten Evox Rifa 10 µF 63 volt MMK metallised PET capacitors, tested at 0.5 volt.

This 100 µF assembly was then used as the distortion reference for each 100 Hz low voltage distortion test.

N.B. Labels ‘Mains’ indicate 150 and 250 Hz harmonics of the 50 Hz AC supply mains.

Electrolytic distortion.
Despite some marketing claims, capacitors are not categorised for distortion so a distorting capacitor would not be considered defective by its maker. It is the responsibility of the equipment designer to select the correct capacitor for each circuit.

During this investigation I measured many other polar electrolytic capacitors, rated from 10 to 100 volt and with capacitance ranging from 1 to 220 µF, produced by several different, major manufacturers.

To illustrate this article, I decided to measure three quite different 100 µF 25 volt polar electrolytic capacitors and my metallised PET assembly. The low cost Rubycon YXF, typical of a modern miniature low ESR capacitor, the much larger and more expensive Elna Silmic and the considerably more expensive Black Gate FK, physically larger than the Elna Silmic.

The Black Gate FK is a 21×10 mm semi Bi-polar, built using a low voltage anode as its cathode foil. The Silmic is 17×10 mm and uses a special separator paper incorporating silk extracts. Both were purchased from Audiocom UK.

The Rubycon YXF is a 12×6.5 mm conventional, miniature, low ESR low cost capacitor purchased from Farnell.

Tests were performed using 0.1 volt AC to 0.5 volt AC in 0.1 volt steps, each using DC bias voltages of 0 volt, 6 volt, 12 volt and 18 volt, a total of 65 separate distortion measurements.

100 µF 25 volt tests.
With the 0.1 volt test signal, measurement noise floor was reduced to -112 dB. With no bias, distortions for the PET reference capacitor and the Black Gate FK were lost in this noise. Second harmonic for the Silmic measured -106.1 dB and the YXF measured -102.8 dB.

With 6 volt DC bias, second harmonic for the Black Gate FK measured -99 dB, the Silmic measured -99.5 dB and the YXF measured -93.5 dB.

With 12 volt DC bias, second harmonic for the Black Gate FK increased to -95.9 dB, the Silmic was -94.4 dB and the YXF measured -91.8 dB.

With 18 volt DC bias, second harmonic for all three electrolytic capacitors increased again to -93.6 for the Black Gate, -91.3 for the Silmic and -90.0 for the YXF. Distortions now measured some three times greater than the PET assembly. see **Fig.8**

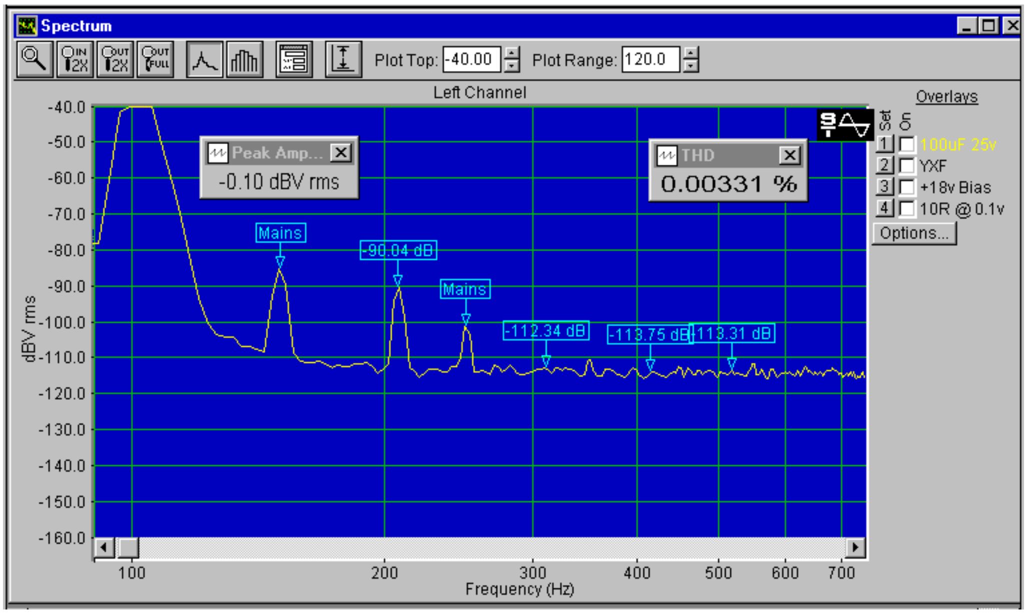

Fig. 8) Distortion of a low cost, very small Rubycon YXF capacitor, tested at 0.1 volt with 18 volt DC bias, was less than 50% worse than the two larger, more expensive capacitors.

0.2 Volt Tests.
Using a 0.2 volt test signal, the measurement noise floor improved to -118 dB. With and without bias, all electrolytic distortions increased more than the change of test signal. With no bias the Silmic performed best of the three polar electrolytics, outperforming the Black Gate FK by almost 6 dB. **Fig. 9 B, C**

With 18 volts DC bias, dielectric absorption effects increased the second harmonic of the Silmic by 21.7 dB and it's distortion to 0.0054%. The Black Gate was less affected and its distortion increased to 0.0037%. The YXF distorted rather more, at 0.0063%.

Third harmonic distortions were visible above the noise floor, but not sufficient to produce measurable intermodulation distortion.

0.2 volt tests with 0 volt DC bias:-

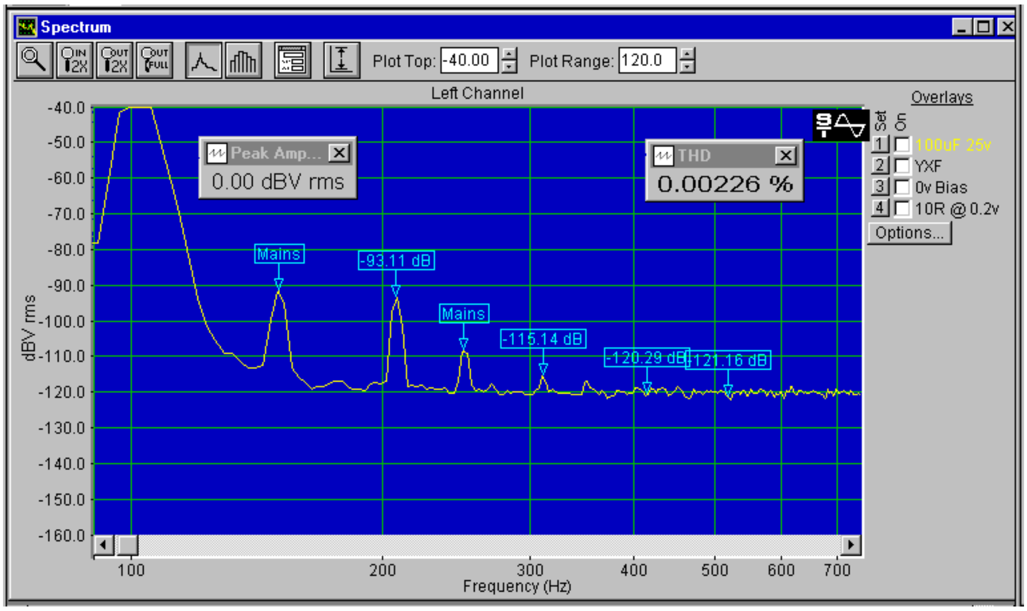

Fig 9A) With second harmonic at -93.11 dB, third at -115.14 dB, this very low cost, miniature electrolytic produces near 3 times more distortion than the more expensive specialist capacitors.

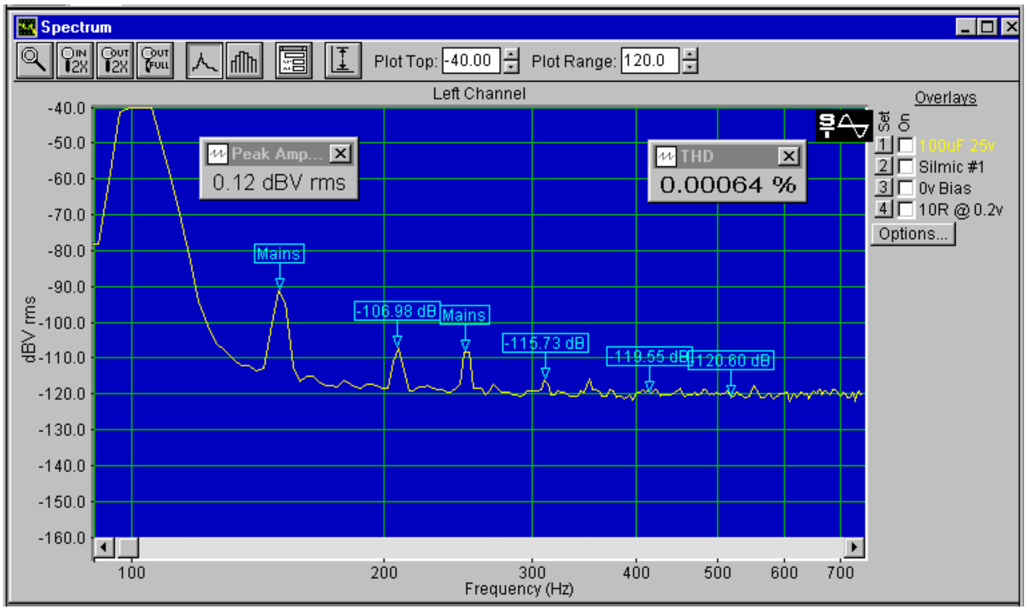

Fig 9B) This specialist audio capacitor ‘Silmic’ from Elna provides the best no bias distortion of the three types tested at 0.2 volts.

However it produces much larger distortions than measured for the reference capacitor.

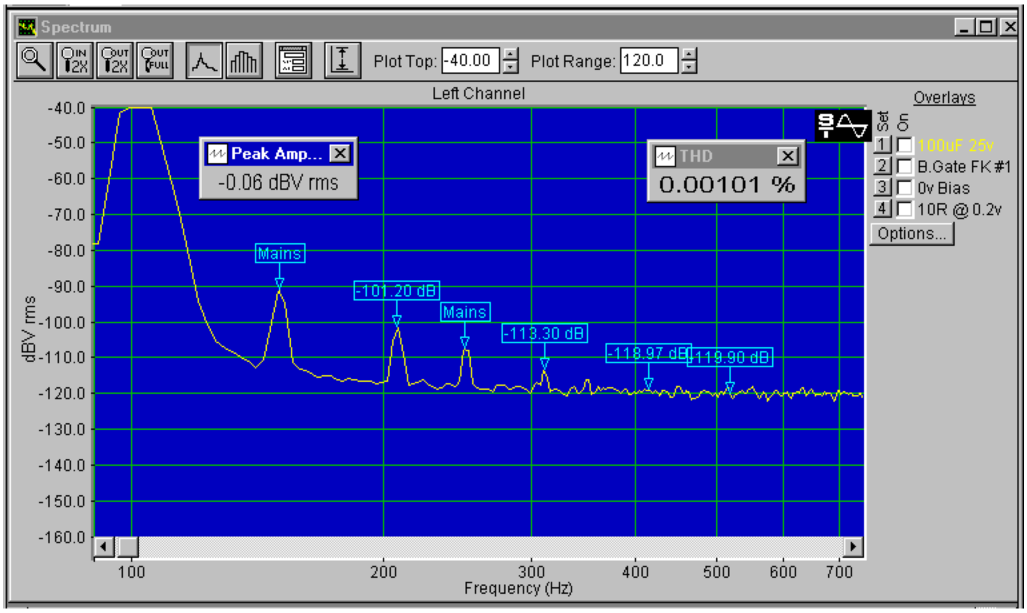

Fig 9C) This specialist audio capacitor the Black gate-FK, produces almost 6 dB more second harmonic than the Silmic when tested at 2 volts with no DC bias.

Tested using 6 volts DC bias, the Silmic and Black Gate capacitors produced almost identical second harmonic distortions at -93.6 and 93.8 dB respectively. Measured distortion for both was 0.0021%. The YXF second harmonic was at -90.52 dB.

0.2 volt tests with 18 volt DC bias:-

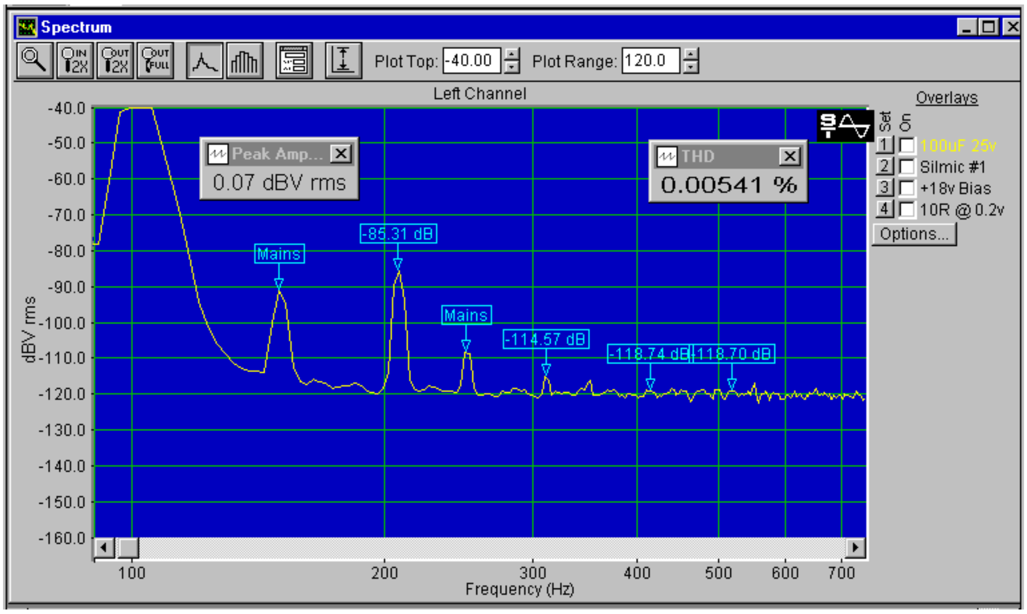

Fig 9D) Measured with 18 volt DC bias, second harmonic for the Silmic increased by almost 22 dB to -85.3 dB, third remained at -114.6 dB. Distortion is now 0.00541%.

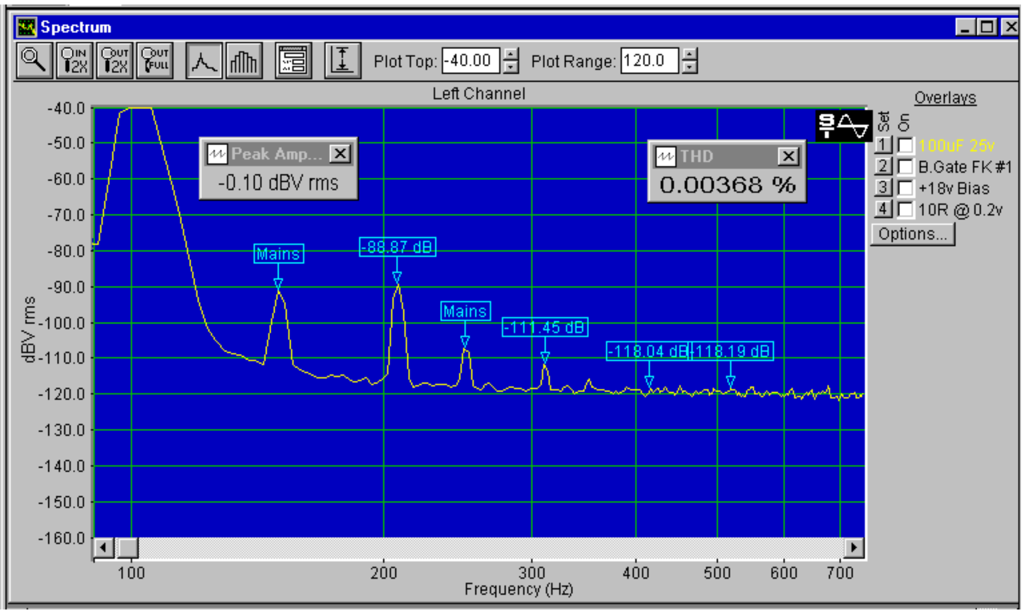

Fig 9E) Measured with 18 volt DC bias, second harmonic for the Black Gate-FK increased rather less, by some 12 dB to give -88.8 dB, third remained at -111.5 dB. Distortion is now 0.00368%.

With 18 volts bias this BlacK Gate FK has now become the better capacitor.

However the reference capacitor harmonics remain lost in the noise floor.

0.3 Volt Tests.

With a 0.3 volt test signal, measurement noise floor improved to -123 dB but the PET reference capacitor harmonics remain buried in noise. Second and third harmonics of the polar capacitors are now clearly visible, their distortions having increased much faster than the test signal level.

With a 0.3 volt test signal and no bias, the Silmic, at 0.00098%, produced the least distortion of the three electrolytics. It's second harmonic measured -100.6 dB, Black Gate -98.5 dB and YXF -89.1 dB. This is the best electrolytic of those I tested with no bias, however it still produced more than three times the distortion of the PET assembly. **Fig.7**

With 6 volt DC bias, the Silmic and Black Gate, with second harmonics around -90 dB, produced similar 0.003% distortion. The YXF second harmonic was -87.3 dB for 0.0043% distortion.

With 18 volt DC bias the Black Gate develops fifteen times more distortion than the PET assembly but now distorts less than the other two electrolytics. Its second harmonic at -84.1 dB was some 3 dB better than the Silmic and 4 dB better than the low cost YXF type. Distortions now measured 0.00637%, 0.00840% and 0.00951% respectively. **Fig. 10 I**

Third harmonics for all three electrolytics have reached the level for measurable intermodulation, which was confirmed by more tests, using 18 Hz as the second frequency.

0.3 volt tests with 0 volt DC bias:-

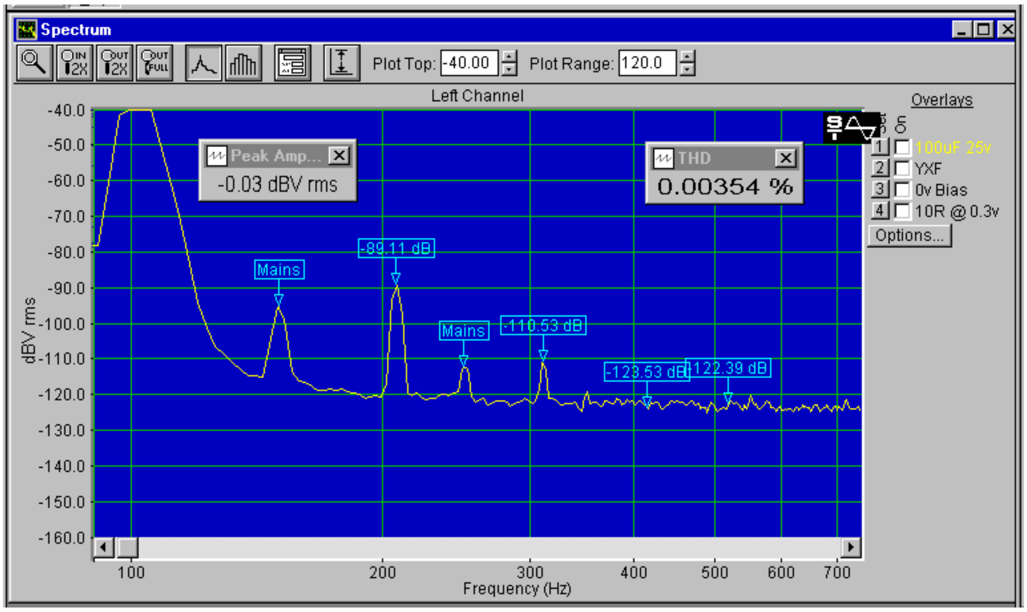

Fig 10A) Measured at 0.3 volts but no DC bias, second harmonic for the YXF at -89.1 dB was some 10 dB larger than for the two specialist capacitors.
Distortion has increased to 0.00354%.

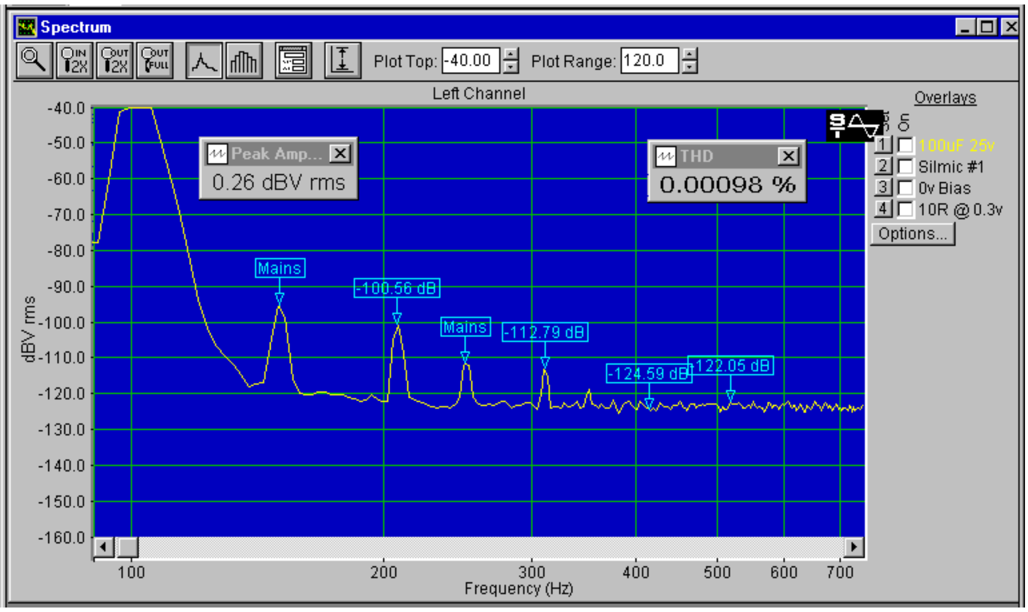

Fig 10B) Measured at 0.3 volts but no DC bias, second harmonic for the Silmic at -89.1 dB was again the best polar capacitor of the three I measured.
Distortion has increased to 0.00098%.

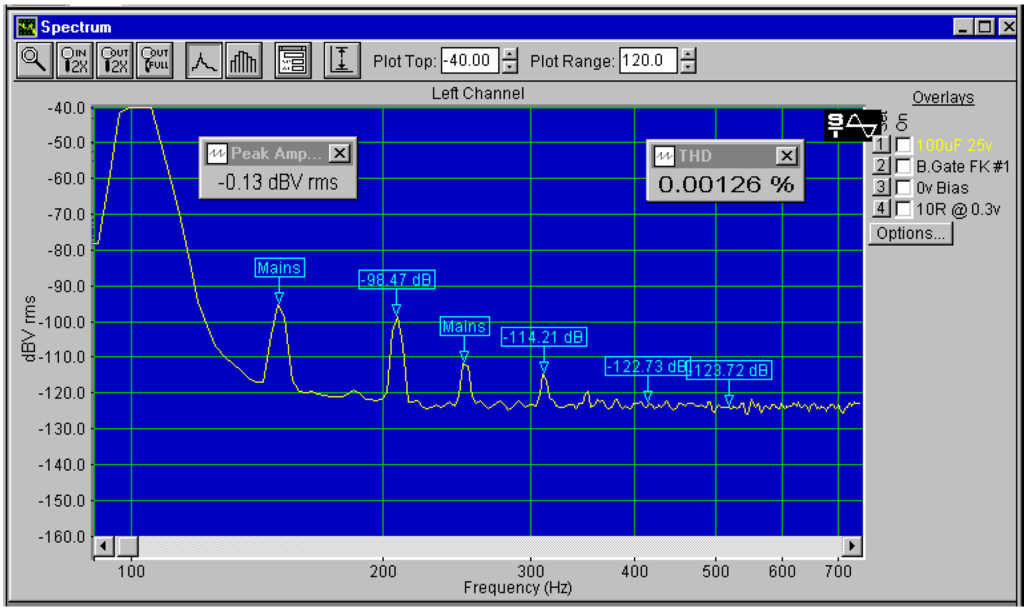

Fig 10C) Measured at 0.3 volts but no DC bias, second harmonic for the Black Gate-FK was some 2 dB worse at -89.1 dB than measured for the Silmic.
Distortion now measures 0.00126%.

0.3 volt tests with 6 volt DC bias:-

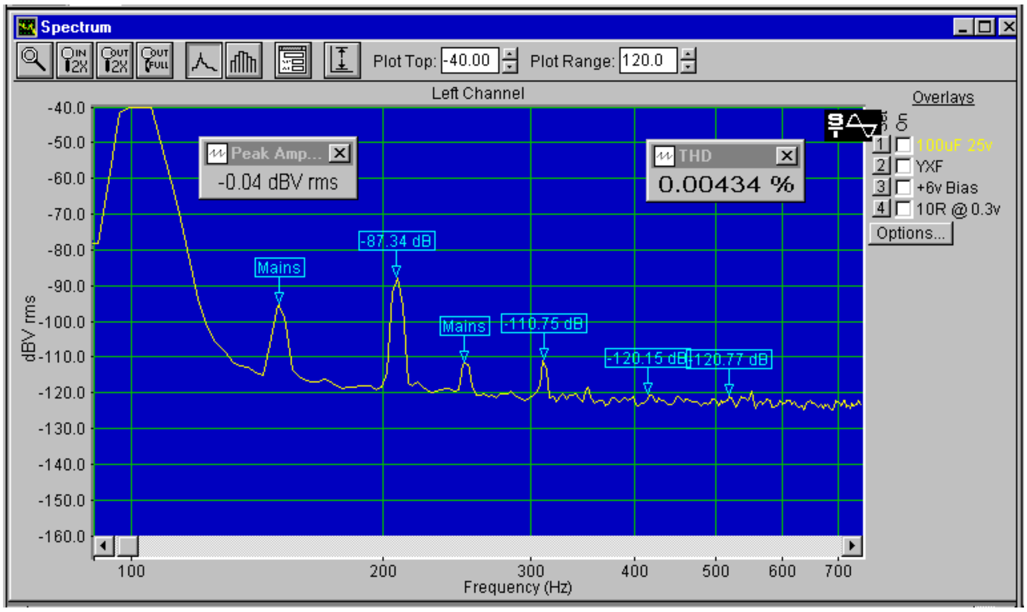

Fig 10D) Measured at 0.3 volts with 6 volt DC bias, second harmonic for the YXF increased by 2 dB to -87.3 dB, third remained at -110.7 dB. Distortion is now 0.00434%.

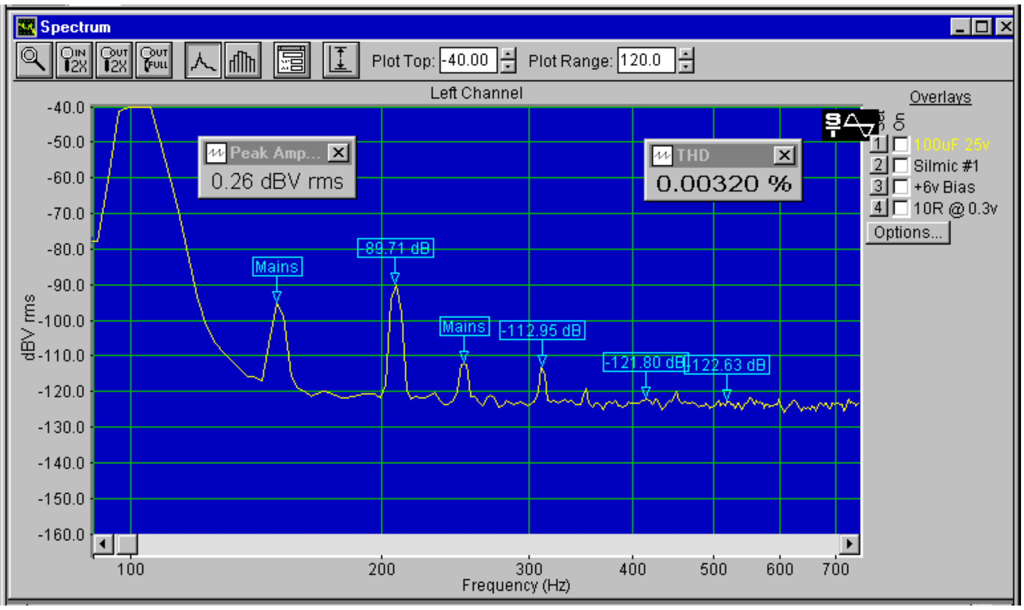

Fig 10E) Measured at 0.3 volts with 6 volt DC bias, second harmonic for the Silmic increased by near 11 dB to -89.71 dB, third was at -112.95 dB. Distortion is now 0.00320%.

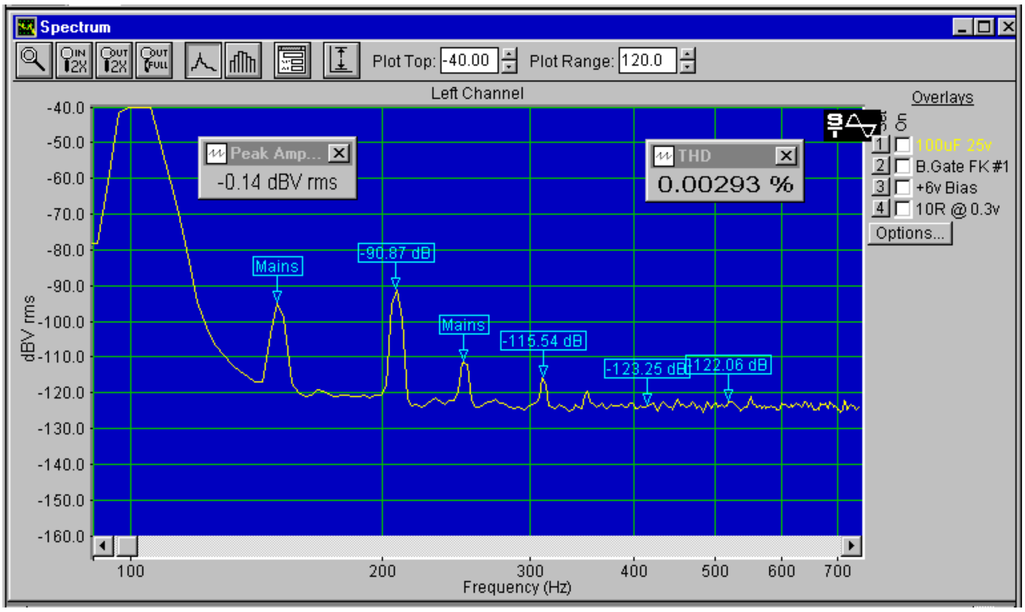

Fig 10F) Measured at 0.3 volts with 6 volt DC bias, second harmonic for the Black Gate-FK increased by near 8 dB to -90.9 dB, third remained at -115.5 dB. Distortion is now best of this three at 0.00293%.

Once more applying just 6 volts DC bias has narrowed the distortion gap between the inexpensive YXF and the expensive Black Gate-FK style.

0.3 volt tests with 18 volt DC bias:-

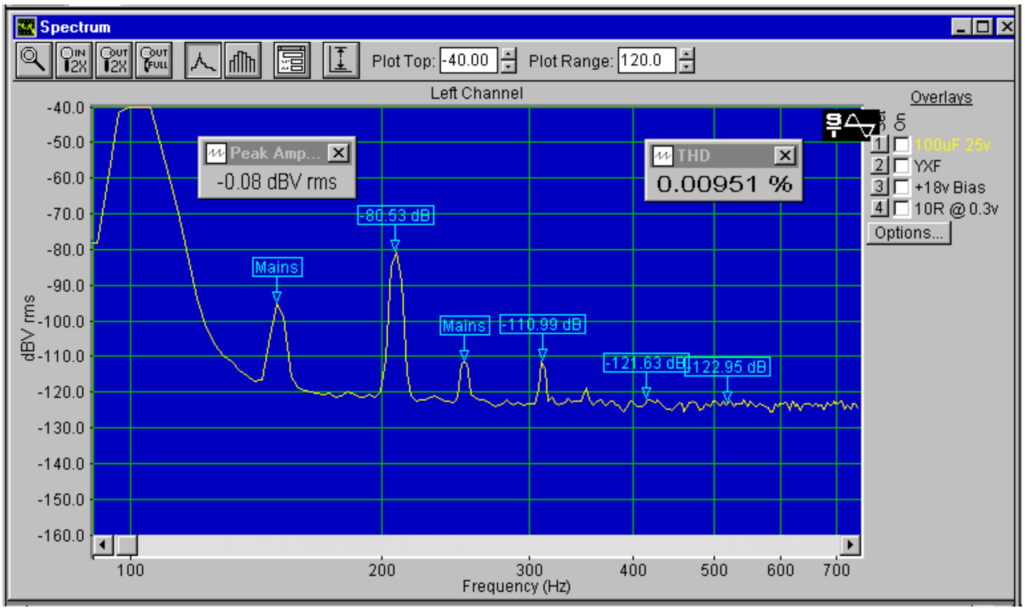

Fig 10G) Measured at 0.3 volts with 18 volt DC bias, second harmonic for the YXF increased by nearly 9 dB to -80.5 dB, third remained unchanged at -110.9 dB.
Distortion has increased significantly and is now 0.00951%.

I consider this distortion is far too high for use in the signal path of an audio system.

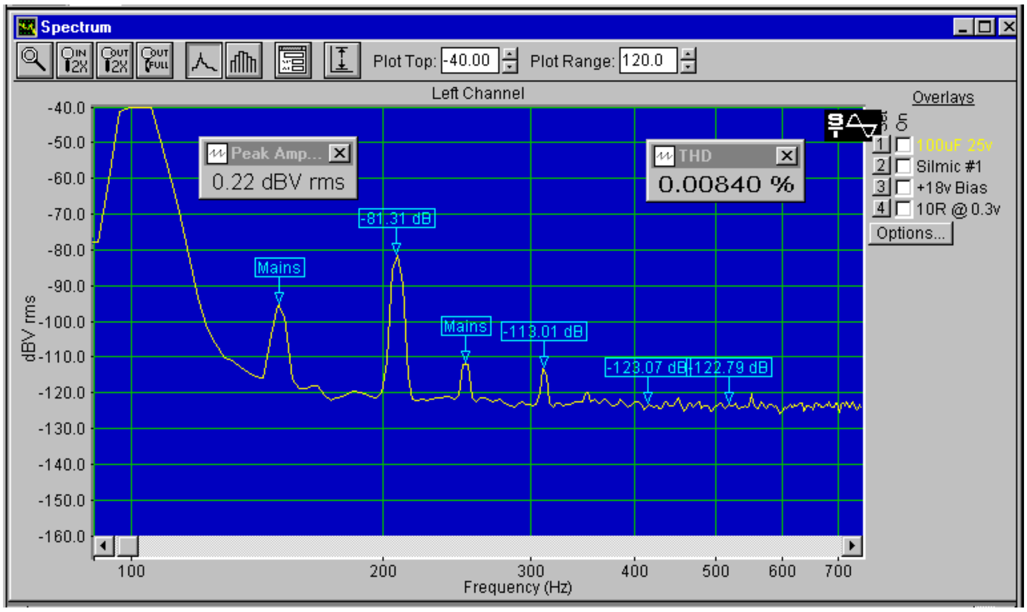

Fig 10H) Measured at 0.3 volts with 18 volt DC bias, second harmonic for the Silmic increased by some 19 dB to -81.3 dB, third continues at -113 dB.
Distortion is now 0.00840%.

I consider this distortion is also far too high for use in an audio system.

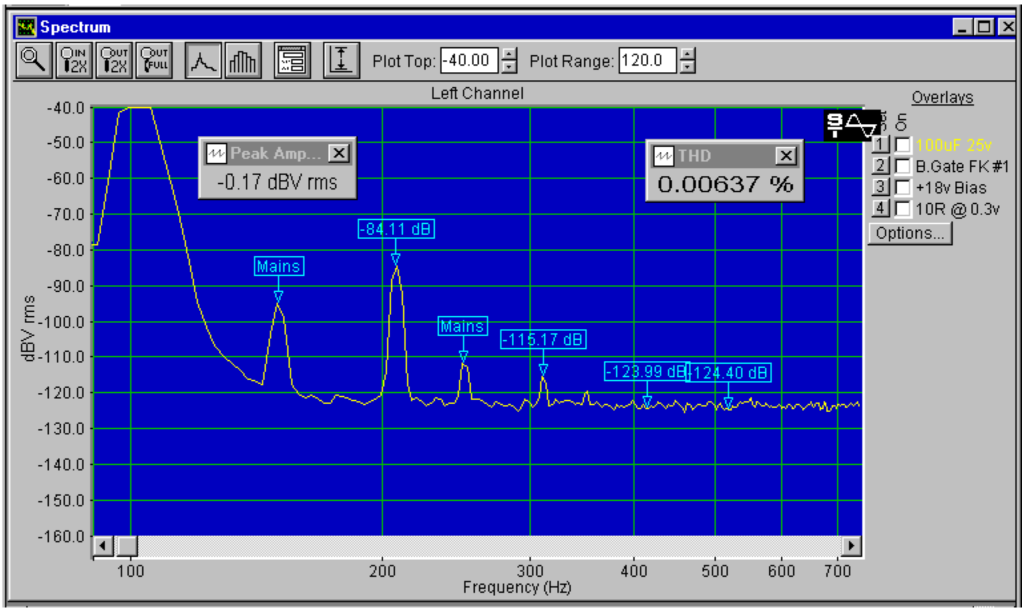

Fig 10I) Measured at 0.3 volts with 18 volt DC bias, second harmonic for the Black Gate-FK increased by some 14 dB to -84.1 dB, third remained at -115.2 dB.
Distortion is again best of the three at 0.00637%.

I consider this distortion is far too high for use in an audio system.

Increasing DC bias to 18 volts has had a disastrous effect on distortion for all three types.

All three electrolytics produced significant distortions in these 0.3 volt tests. Almost five times larger with no bias, at least fifteen times larger with bias, than my PET assembly. I consider distortions from these 100 µF polar capacitors tested at 0.3 volts, far exceed the sensible limit for use in the signal path of high quality audio.

Using a Film Shunt.
Some writers advocate using a low distortion film capacitor in parallel with an electrolytic, to reduce distortion. Does it work ? To find out I made a few measurements on these capacitors using a 1 volt test signal, unbiased then with 18 volt DC bias. As shunt I used my low distortion 1 µF MKP also a 10 µF bank of three 3.3 µF low distortion metallised PPS capacitors.

With 1 µF shunt, second and third harmonics of the Silmic reduced by just 1 dB. Using the 10 µF, both harmonics reduced by a further 1 dB. This small reduction is not worth the additional PCB space and extra cost, because even with a 10 µF shunt, distortions far exceed those of my metallised PET assembly.

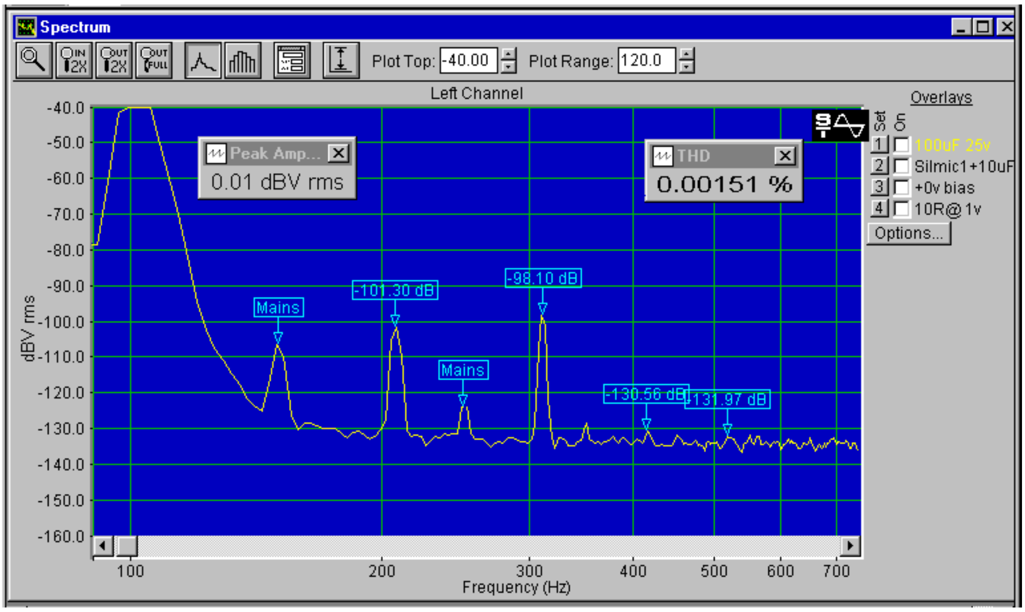

Fig 11A) Re-measured at 1 volt without DC bias but using the 10 µF film capacitor as shunt, we find second harmonic has reduced by only 1.5 dB Distortion was 0.00184% is now 0.00151%.

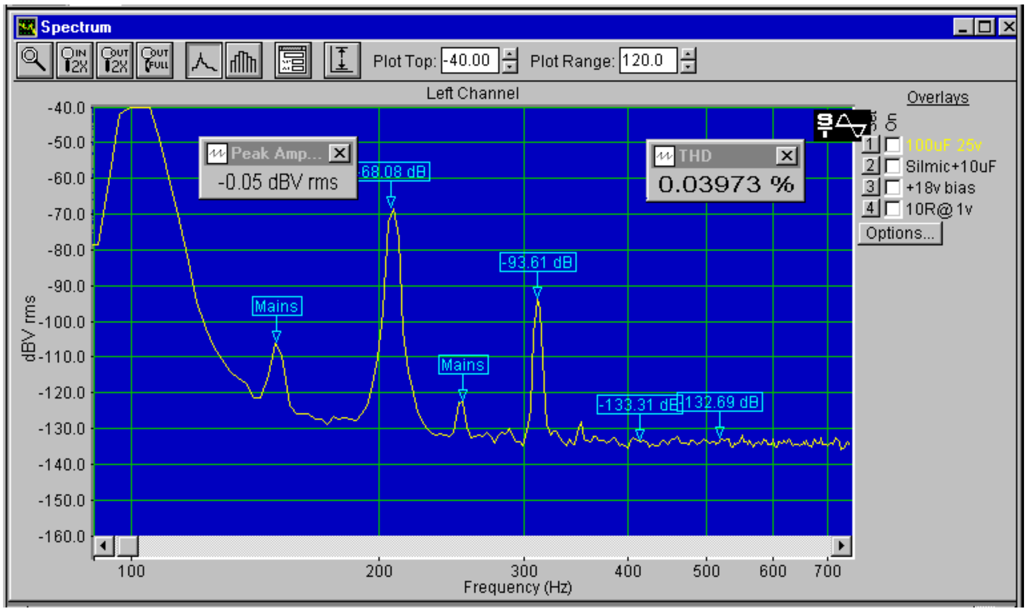

Fig 11B) Measured at 1 volt with 18 volts DC bias and using the 10 µF film capacitor as shunt, we find second harmonic increased to -68 dB. Distortion is 0.03973% .

I consider these distortions are far too high for use in the signal path of an audio system.

Perhaps a higher voltage capacitor would measure better, or would its much larger area anode and cathode foils simply make matters worse ?

100 µF 50 volt tests.
Examination of my earlier distortion plots suggested the only suitable 100 µF electrolytic types I had which might measure lower distortion were the 22×12.5 mm 50 volt Silmic and the 26×12.5 mm 50 volt Panasonic S Bi-polar, Farnell 218-698.

With 0.3 volt test signal and no bias, the 50 volt Silmic distorted more than the 25 volt version. Because of its much longer and wider foils, second harmonic increased 2 dB, third increased 7 dB and distortion measured 0.00134%. see **Fig.12A**

Due to the thicker dielectric used for the 50 volt capacitor, with 18 volt DC bias, second harmonic increased less, now almost 6 dB smaller than the 25 volt version. Distortion at 0.00460% was just over half that of the 25 volt version.

Comparison tests, 100 µF 25 volt and 50 volt rated 'Silmic' capacitors.

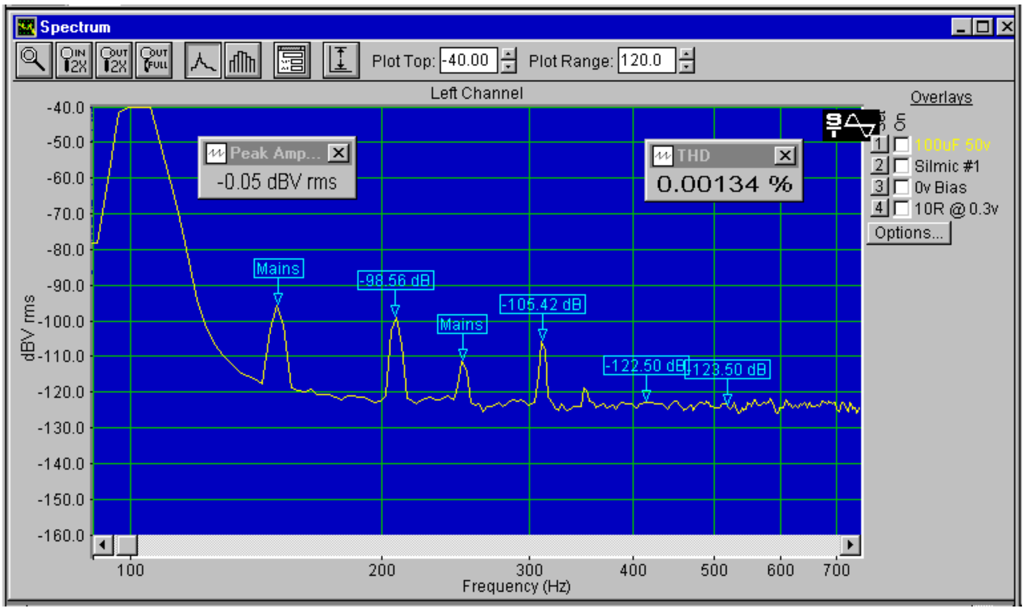

Fig 12A) Measured with no DC bias at 0.3 volt, we find second harmonic has increased by 2 dB and third harmonic by 7 dB when compared with the 25 volt capacitor. Distortion has increased to 0.00134% for 50 volt capacitor, from 0.00098% for the 25 volt version.

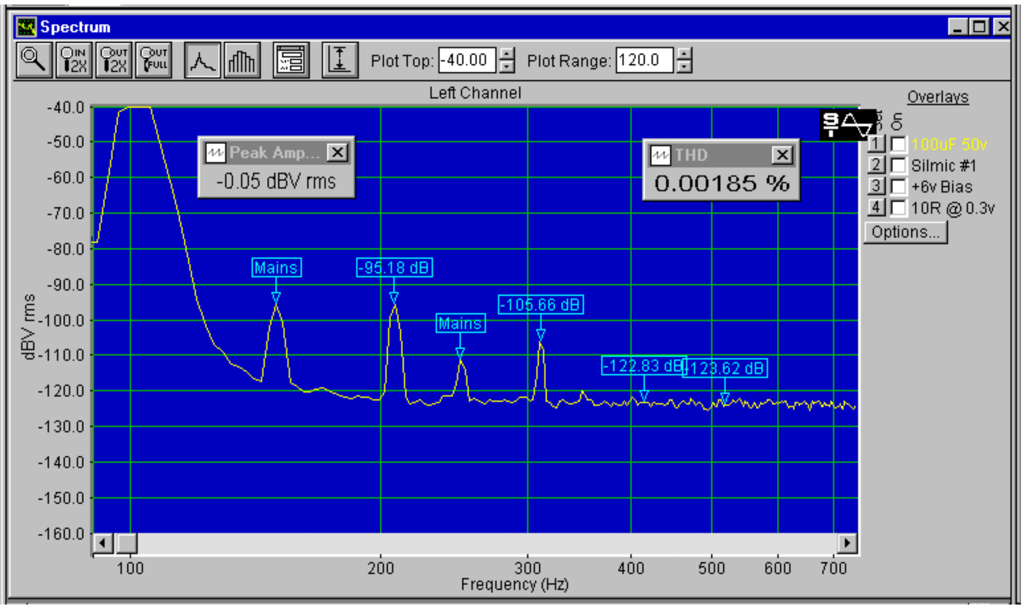

Fig 12B) Measured with 6 volt bias at 0.3 volt, we find second harmonic has increased by another 3.5 dB but third harmonic at -105.6 dB has not changed. Distortion now 0.00185%.

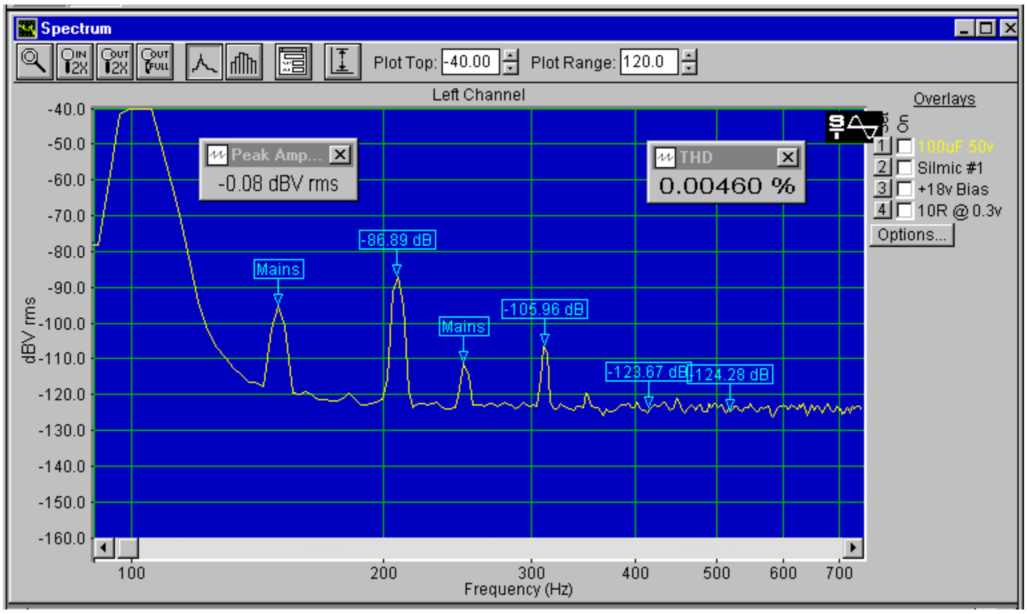

Fig 12C) Measured with 18 volt bias at 0.3 volt, we find second harmonic has increased by almost 12 dB, third harmonic at -105.9 dB unchanged. Distortion now 0.00460%.

Comparison tests, 100 µF 'Silmic' polar and 50 volt rated Panasonic Bi-polar capacitors.

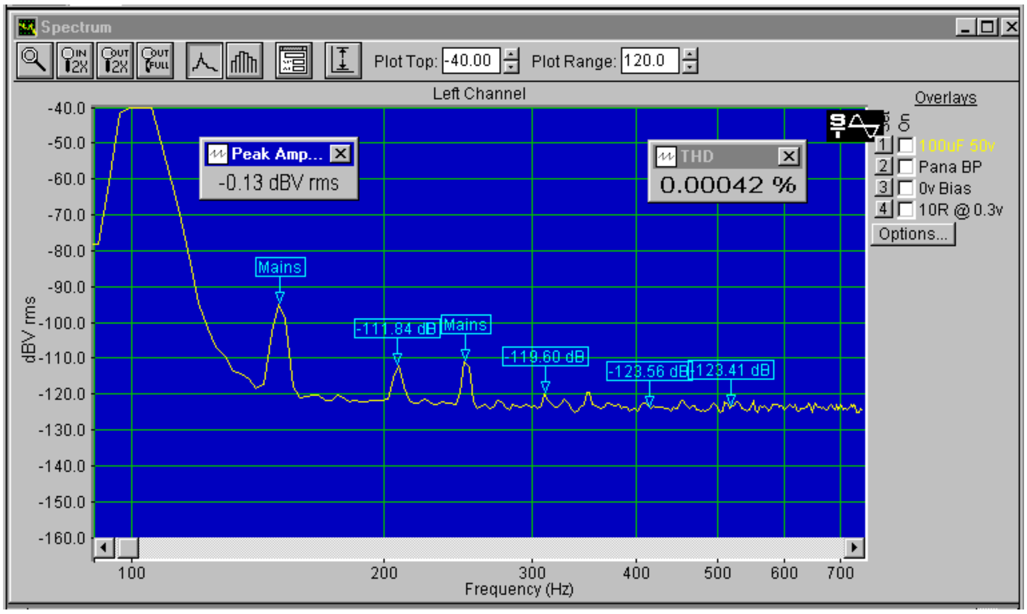

Fig 12D) Measured with no DC bias at 0.3 volt, we find second harmonic for this Panasonic Bi-polar reduced by nearly 12 dB. Third harmonic is now near the measurement noise floor at -119.6 dB.

Distortion is the lowest seen so far for an electrolytic and less than half that of the 25 volt Silmic.

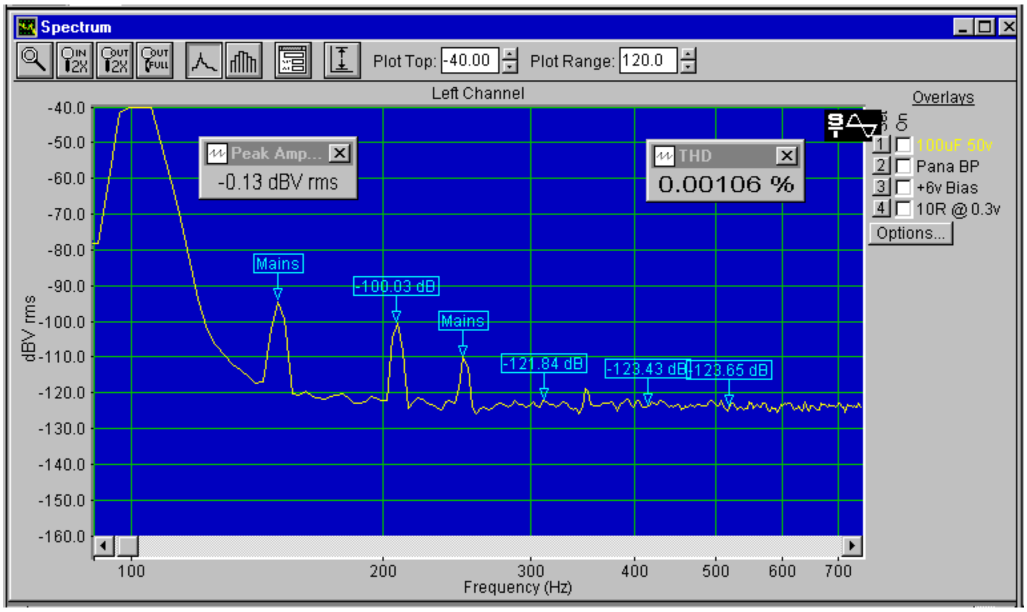

Fig 12E) Measured with 6 volt DC bias and 0.3 volt, we find second harmonic almost identical to that measured on the Silmic with no bias, 10 dB smaller than for the 25 volt Silmic with 6 volt bias.
Third harmonic remains near the measurement noise floor.

Distortion is now 0.00106%.

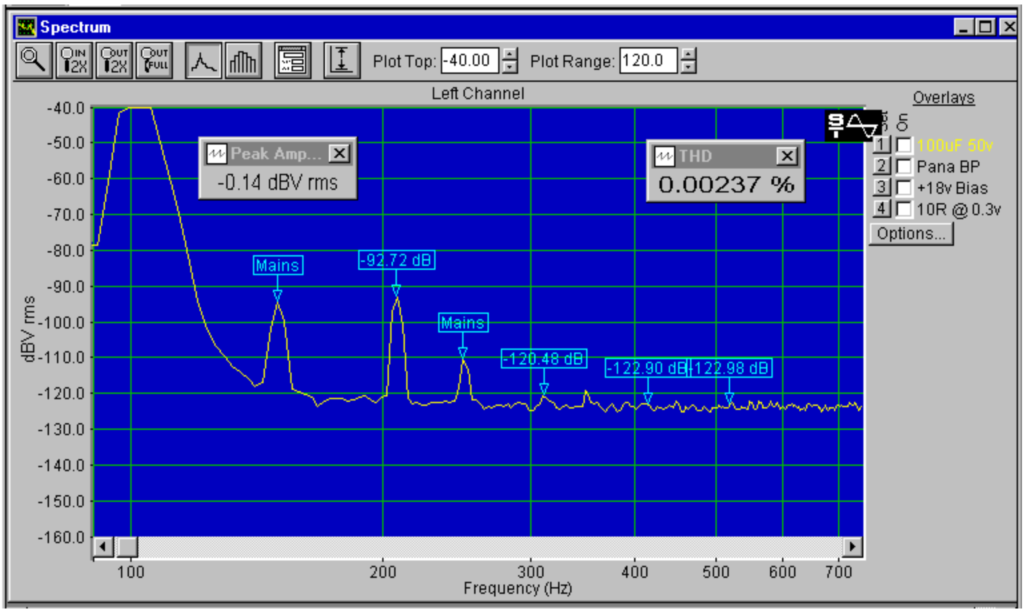

Fig 12F) Measured with 18 volt DC bias at 0.3 volt, while distortion has increased it is less than half that measured on the best polar capacitor tested.
Third harmonic remains near the measurement noise floor at -119.6 dB.

Distortion is now the lowest seen so far for an electrolytic with 18 volt bias, half that of the best polar type measured with 18 volt DC bias.

Bi-polar.
The Panasonic S Bi-polar capacitor at 0.3 volt with no bias, produced less than half the distortion of the 25 volt Silmic. Second harmonic measured -111.8 dB, third -119.6 dB and distortion 0.00042%.

With 18 volt DC bias, second harmonic increased to -92.7 dB and distortion to 0.00237%, half the distortion of the 50 volt Silmic.

The Panasonic S Bi-polar produced the lowest distortion of all single 100 µF electrolytic capacitors of those I tested, using a 0.3 volt signal and DC bias from 0 volt to 18 volts. see **Fig.12 D/F**

In my last article we saw how using two polar capacitors in series could reduce distortion. Let us now explore using two Bi-polar capacitors in series.

Two better than one?
I already had some 220 µF 63 volt Nitai Bi-polar electrolytics, Farnell 317-4906. Two connected together in series would approximate 100 µF.

Measured at 0.3 volts with no bias, second harmonic level reduced 6 dB compared to the Panasonic S Bi-polar. With second and third harmonics buried in the noise floor, distortion at 0.00033% measured the same as the PET assembly.

With 18 volt DC bias, second harmonic measured -105.3 dB and distortion 0.00063%. A near four fold improvement compared to the Panasonic S Bi-polar, more than seven times better than the best polar capacitor tested.

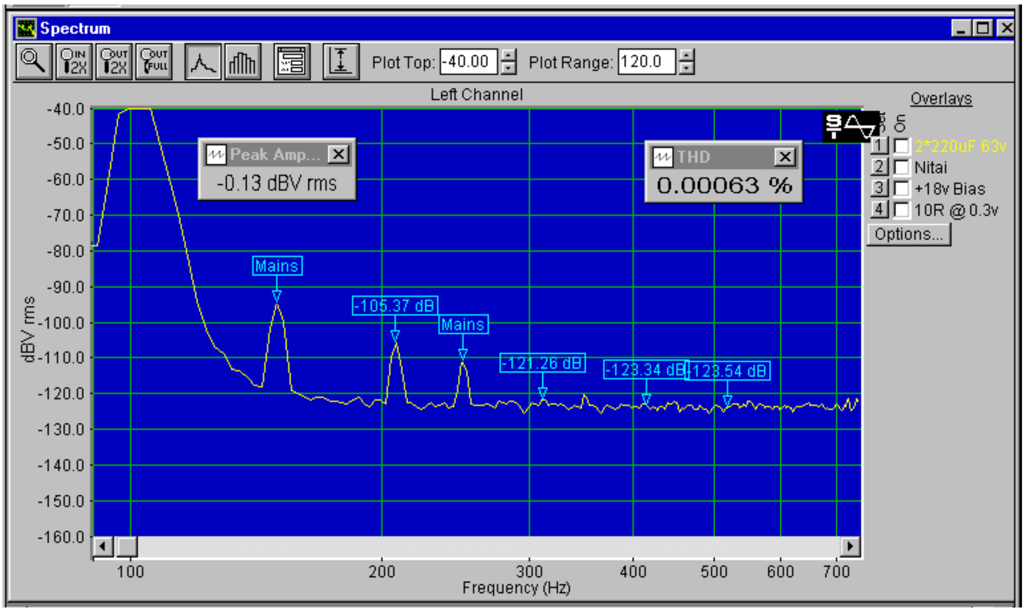

Fig 13) Series pair of 220 µF 63 volt Nitai Bi-polar electrolytics, measured with 18 volt DC bias at 0.3 volt, second harmonic distortion has reduced dramatically. It is now seven times smaller than measured on the best polar capacitor tested.

Third harmonic remains on the measurement noise floor.

To better compare harmonics I examined performances using a 0.5 volt signal. With no bias, those for my PET assembly can just be seen emerging from noise. Second harmonic -124.3 dB, third -123.9 dB and distortion 0.00020%. see **Fig 7**

The double 220 µF 63 volt Bi-polar second harmonic -117.7 dB, third -124.1 dB, and distortion 0.00023%, measured practically the same distortion as the PET assembly. see **Fig.14A**

With 18 volt DC bias, second harmonic of the double Bi-polar increased to -100.7 dB and distortion to 0.00093%, slightly more than double the distortion measured on the PET assembly with this bias. see **Fig.14C**

This is an excellent performance from a pair of inexpensive electrolytic capacitors, but how does this series pair of Bi-polar capacitors stack up for size and cost ? Can this Bi-polar series pair still produce low distortion tested with a 1 volt signal ?

At 1 volt with no bias, noise floor improved to -132 dB. Distortion of the PET assembly measured 0.00011%, a single Panasonic S Bi-polar 0.00054% and the Silmic 25v with 10 µF shunt 0.00151%.

The 220 µF 63 volt Nitai series pair measured 0.00016%, practically equalling that measured on the PET assembly, and ten times less distortion than the Silmic 25 volt polar capacitor.

With 18 volt DC bias, the 220 µF 63 volt Nitai series pair distortion measured 0.00217%.

Double Bi-polar series connected pair of 220 µF 63 volt Nitai capacitors tested at 0.5 volts.

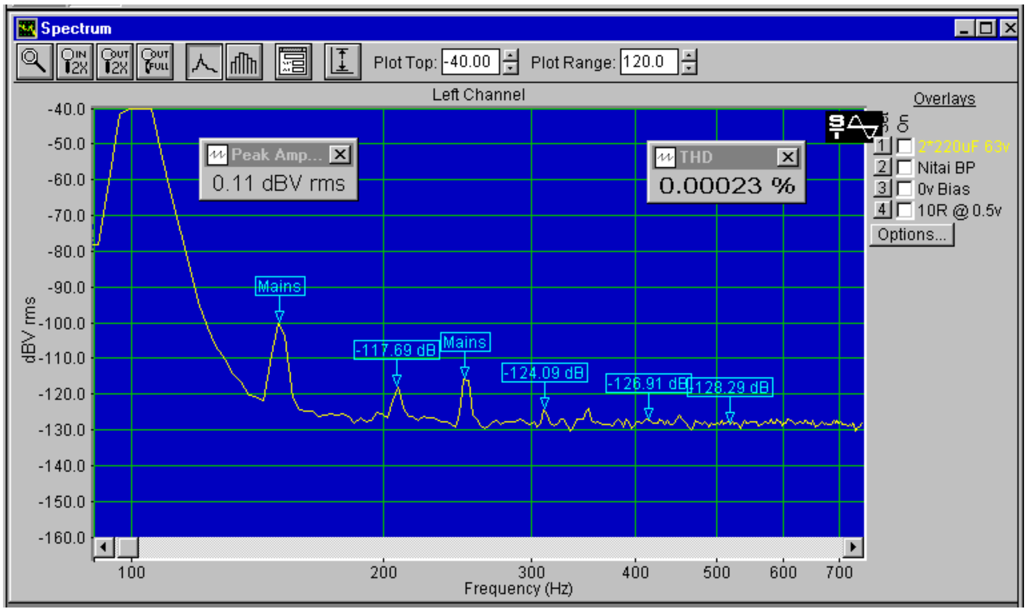

Fig 14A) Series pair of 220 µF 63 volt Nitai Bipolar electrolytics, measured with no DC bias at 0.5 volt. Second harmonic distortion now -117.7 dB, third harmonic remains near the measurement noise floor.

Distortion measures 0.00023%, practically the same distortion as measured using my PET assembly.

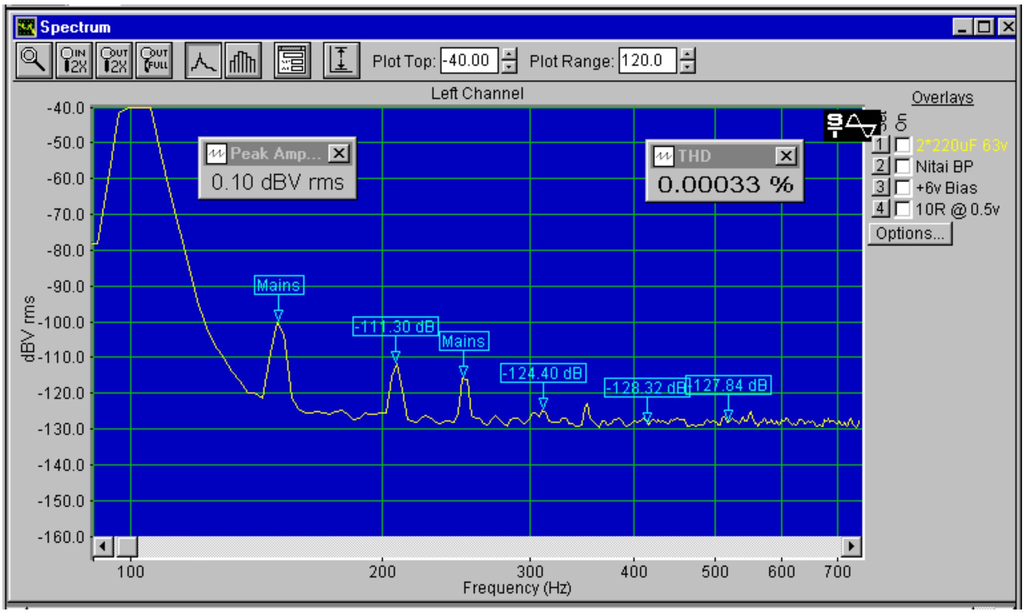

Fig 14B) Measured at 0.5 volt with 6 volt DC bias. Second harmonic distortion now -111.3 dB, third harmonic remains near the measurement noise floor.

Distortion now measures 0.00033%.

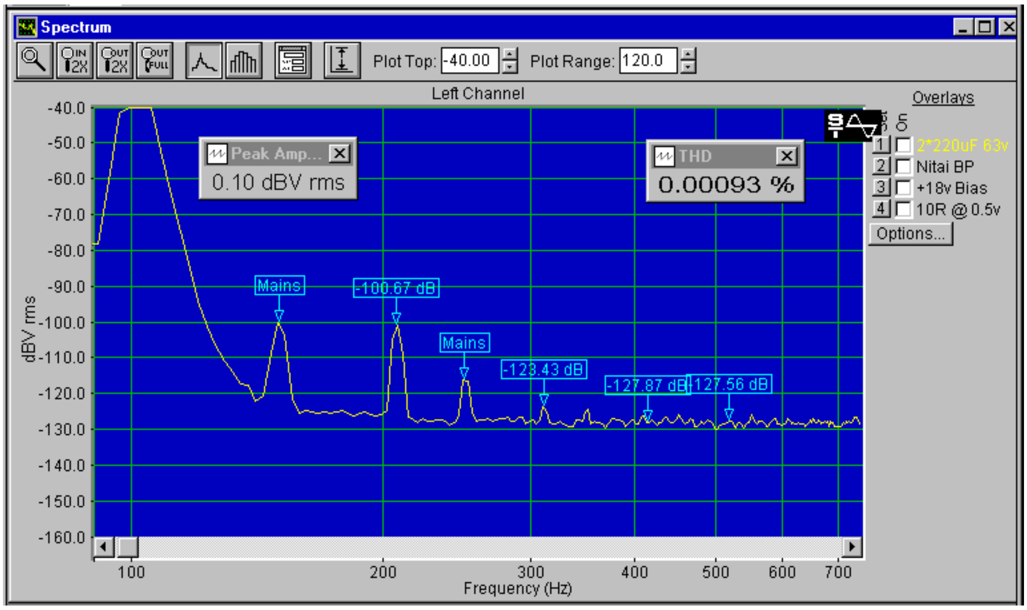

Fig 14C) Measured at 0.5 volt with 18 volt DC bias. Second harmonic increased to -100.7 dB. Third harmonic remains near the measurement noise floor.

Distortion is 0.00093%, little more than double that measured for my PET assembly.

At this voltage the Silmic measured 0.01312% the Black Gate-FK was 0.01041%.

Double Bi-polar v alternatives.
The series pair requires less PCB area, is lower cost and dramatically outperforms a polar capacitor with film shunt.

At 1 volt with no bias, noise floor improved to -132 dB. Distortion of the PET assembly measured 0.00011%, a single Panasonic S Bi-polar 0.00054% and the Silmic 25volt with 10 µF shunt 0.00151%.

The 220 µF 63 volt Nitai series pair measured 0.00016%, practically equalling that measured on the PET assembly, ten times less distortion than the Silmic 25 volt capacitor.

With 18 volt DC bias, the 220 µF 63 volt Nitai series pair distortion measured 0.00217%. Slightly more than six times that of the PET assembly but nearly seven times less distortion than using the 50 volt Silmic polar capacitor.

This series pair of 220 µF 63 volt Nitai Bi-polar capacitors costs one eighth and takes just one fifth the PCB area of my PET assembly.

To explore other double Bi-polar options, I purchased 35 volt and 16 volt 220 µF Nitai Bi-polar capacitors for tests.

Smaller Doubled Bi-polar.
With no bias and tested at 0.5 volt, distortion for all three voltage Bi-polar doubles, measured almost the same as the PET assembly, but 18 volt DC bias revealed large differences. The 16 volt series pair measured 0.00693%, the 35 volt series pair 0.00230% and the 63 volt series pair 0.00093%.

For the lowest possible distortion when DC blocking/signal coupling, I suggest the 16 volt pair is only used with negligible DC bias, the 35 volt pair be used to say 6 volt bias and the 63 volt pair to say 12 - 15 volts bias. With such small DC voltages, no voltage sharing resistors are needed.

Used in a ‘Long Tailed Pair’ amplifier feedback network to ensure unity gain at DC, the 63 volt series pair could be used with supply rails up to 63 volts, without voltage sharing resistors. For higher voltages use a series pair of 100 volt Bi-polar.

This 63 volt series pair can also benefit local supply rail decoupling, but for this use, voltage sharing resistors, passing a few mA from the supply to the capacitors central connection and ground, must be used.

Conclusions.
Having measured a considerable number of aluminium electrolytics using test voltages from 0.1 volt to 3 volt, with and without bias, a single Bi-polar type produced lower distortion than larger, more expensive, specialist polar capacitors..

Much better results were obtained by connecting two double capacitance value Bi-polar electrolytics in series. Using 1 volt or smaller test voltages and no bias, distortions for a double Bi-polar and the metallised PET assembly were similar.

With increasing bias or with increasing test voltage, the metallised PET assembly produced less distortion than any electrolytic I tested.

Distortion with voltage.
We have seen how the test voltage used influences various capacitors. With sufficient test signal, most film and all electrolytic capacitors will distort. It is prudent in any audio design to minimise the level of AC signals which are developed across any capacitor.

At low frequencies this becomes difficult and may force a trade off between capacitor size and distortion. Equally important is the level of DC bias voltage the capacitor must sustain. If more than a few volts, then for low distortion a low dielectric absorption material is essential.

Because distortion results from non-linearities inside the capacitor, inevitably it increases disproportionately both with capacitance value and applied voltage.

The change in amplitude of second harmonic, when tested at a constant signal with and without DC bias, clearly results from the DC bias voltage used, dielectric absorption and dielectric thickness.

Regardless of capacitance value, to minimise second and third harmonic distortions with increased AC and DC voltages, such as found in valve amplifiers, then a foil and Polystyrene, foil and Polypropylene or double metallised foil, two-series, MKP Polypropylene capacitor, should be used.

100 μF choice.
Provided the AC voltage developed across the capacitor at the lowest audio frequencies is 1 volt or less and no significant DC bias is used, a double Bi-polar series pair provides an economic solution.

When higher AC signal voltages, especially combined with significant DC bias, must be applied, the metallised PET combination produces less distortion. It costs eight times more and takes five times more PCB area than the double Bi-polar.

For the least practical distortion, an assembly of metallised Polyphenylene Sulphide capacitors might be feasible. It needs double the board area and is five times more expensive than the PET assembly.

For small AC signals with modest DC bias and for supply rail decoupling, I choose the double Bi-polar 63 volt solution.

10 μF choice.
We have three possibilities. A double Bi-polar using two 22 μF 50/63 volt Bi-polar electrolytics, a 10 μF metallised PET or an assembly of three 3.3 μF PPS capacitors.

The lowest cost solution for use with signal voltages less than 1 volt and no significant bias, is a double Bi-polar series pair.

A 10 μF MMK metallised PET takes the same PCB area and distorts less with DC bias.

The PPS capacitor assembly ensures lower distortion, especially when used with increased AC signals or DC bias voltage. However it occupies more board area and is expensive.

An assembly of Polypropylene capacitors, as used in the DC bias network, would provide the lowest possible distortion but requires a five times larger board area and is most expensive.

For small AC signals and modest DC bias, I choose the 10 μF MMK metallised PET capacitor.

END

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