Capacitor Sounds 3 - capacitances of 10 nF and smaller.

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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**

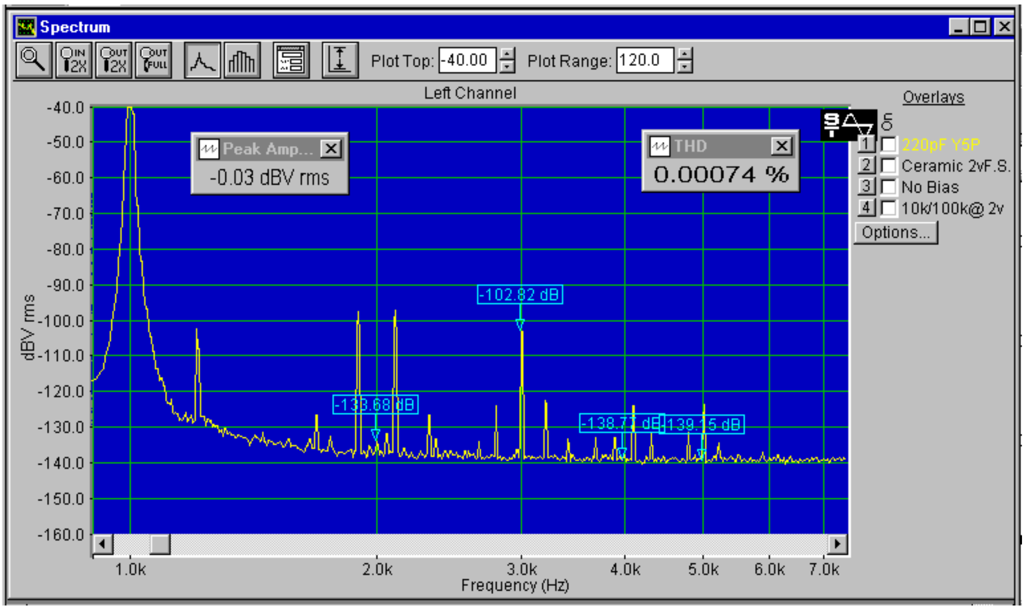

Fig 1) Y5P is a medium 'k' class 2 ceramic. Tested with two signals, 100 Hz and 1 kHz at 2 volts amplitude, with no bias network, the capacitor produces many new intermodulation distortion frequencies.

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**

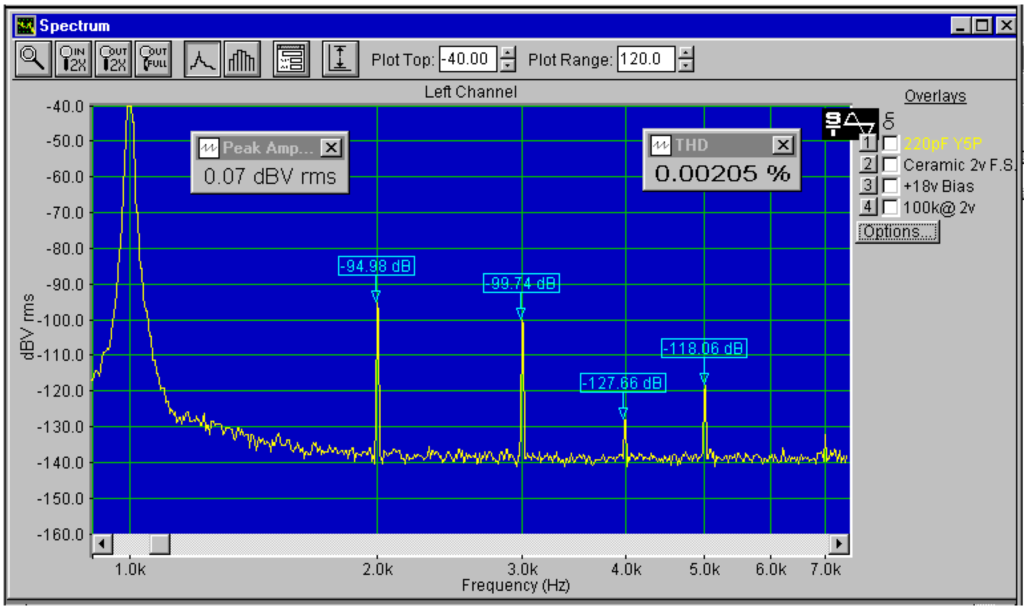

Fig 2) The figure 1 capacitor tested using 1 kHz only with 18 volt DC bias.

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**

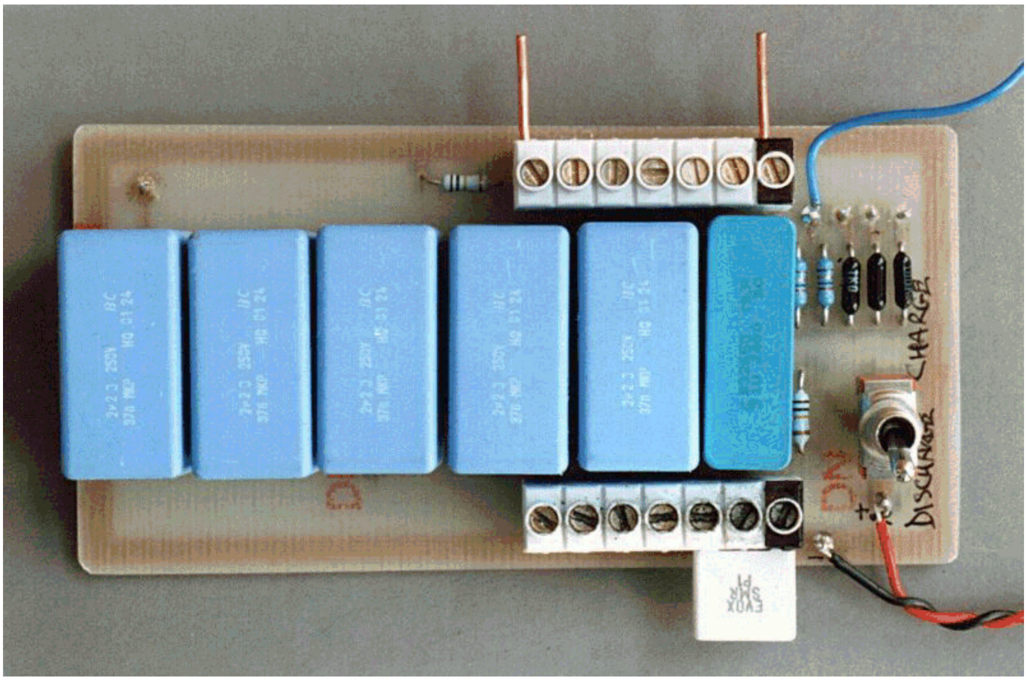

Fig 3) The new DC bias prototype assembly as used for all published tests.
A fly lead connected to the hot AOT resistor terminal, a duplicate set of source resistors and five 2.2 µF MKP blocking capacitors, couple the 1 kHz test signal to the test capacitor.
The test capacitor output is fed to the notch 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**

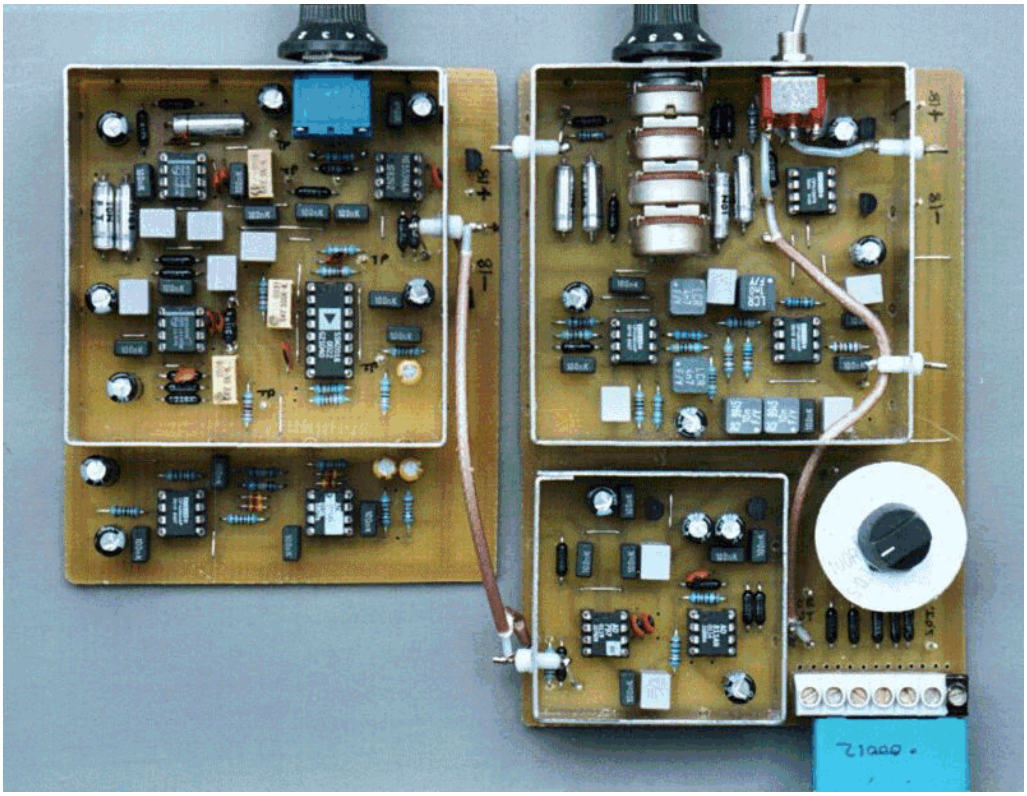

Fig 4) Low distortion test equipment measuring distortion of a capacitor with AC test signal, as described in my last two articles.

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**

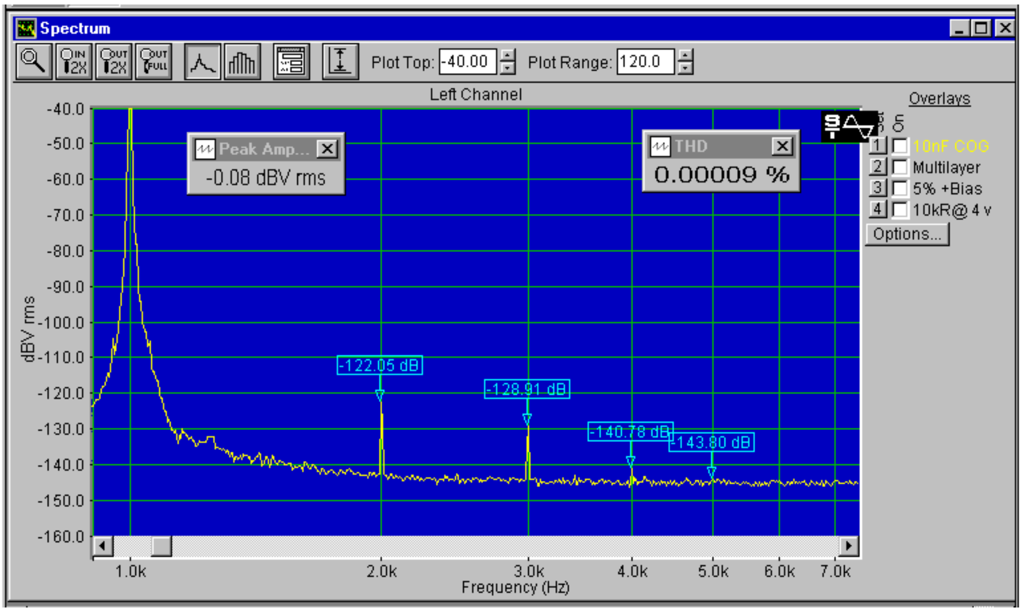

Fig 5) Distortion measurement of a 10 nF Class 1 COG ceramic using 100 Hz and 1 kHz signals at 4 volts and with 18 volt DC bias.

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.

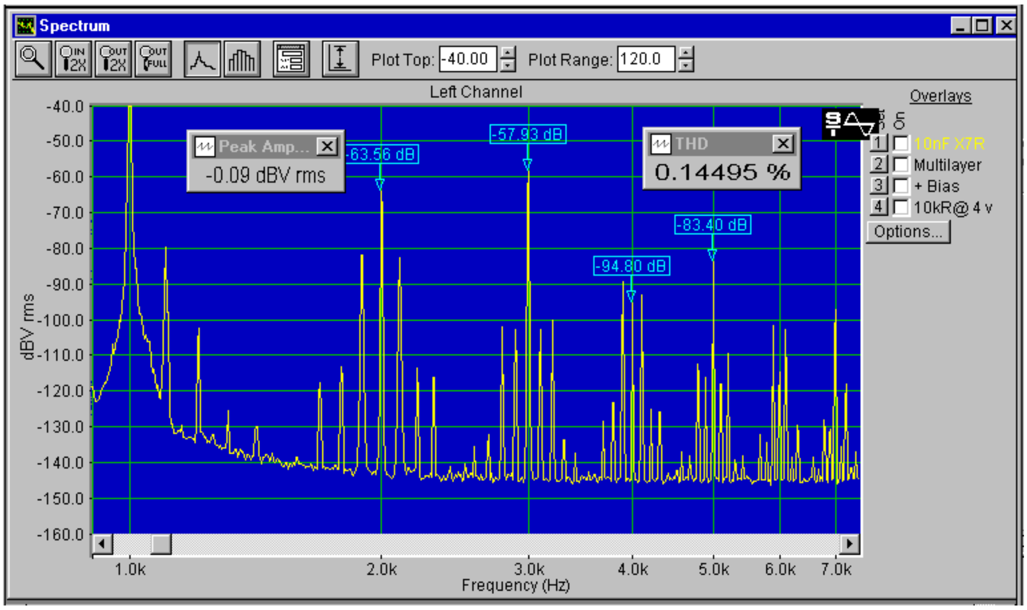

Fig 6) A Class 2 X7R ceramic 10 nF capacitor from the same European maker as figure 5 and tested exactly the same.

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.

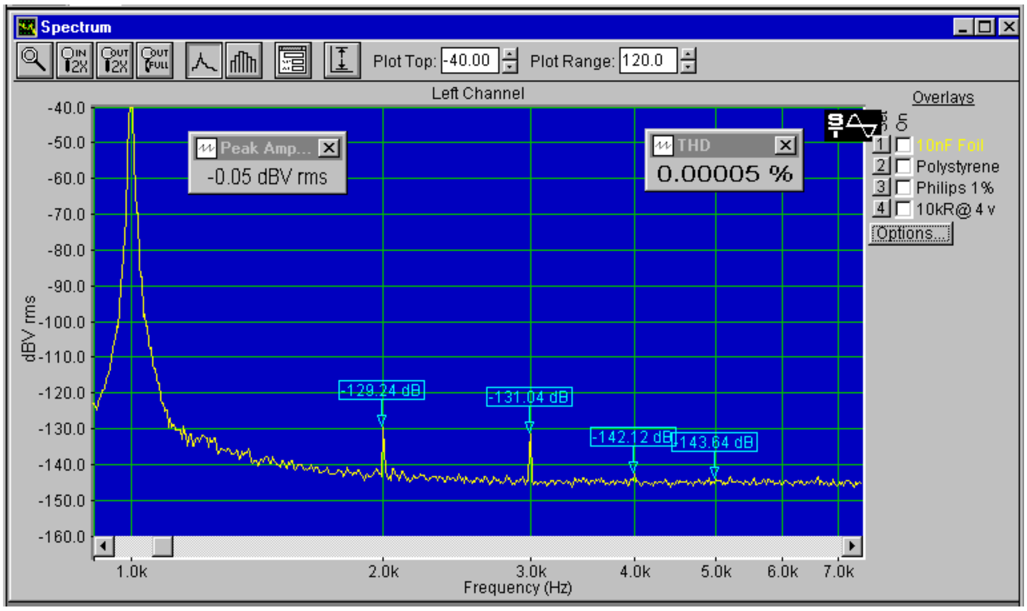

Fig 7) This now discontinued Philips extended foil/Polystyrene 1% axial lead capacitor, with 4 volt signals and 18 volt DC bias, shows negligible distortion.

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.**

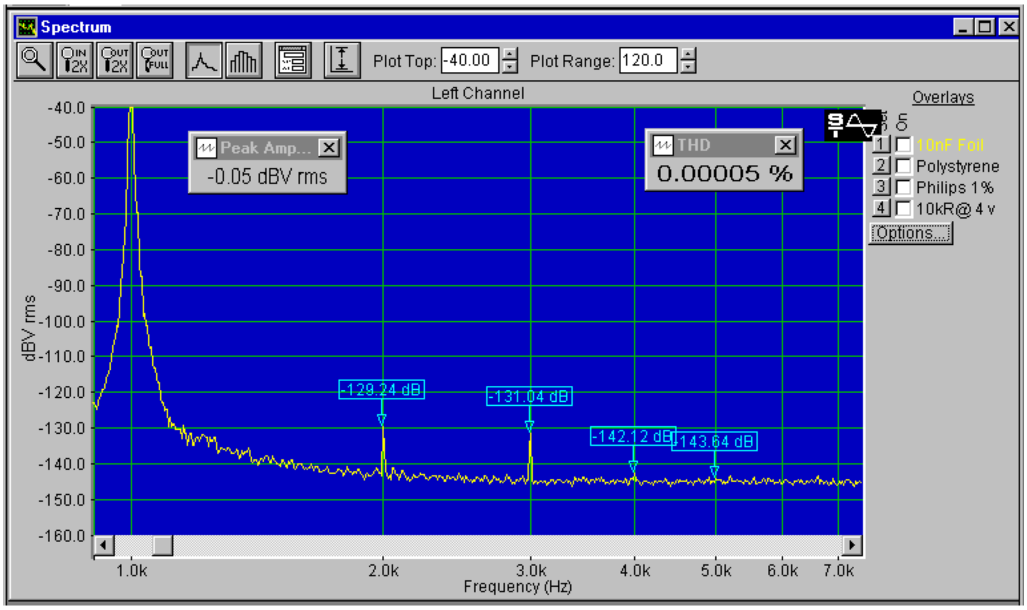

Fig 7) Repeated for reference.
This now discontinued Philips extended foil/Polystyrene 1% axial lead capacitor, with 4 volt signals and 18 volt DC bias, shows negligible distortion.

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.

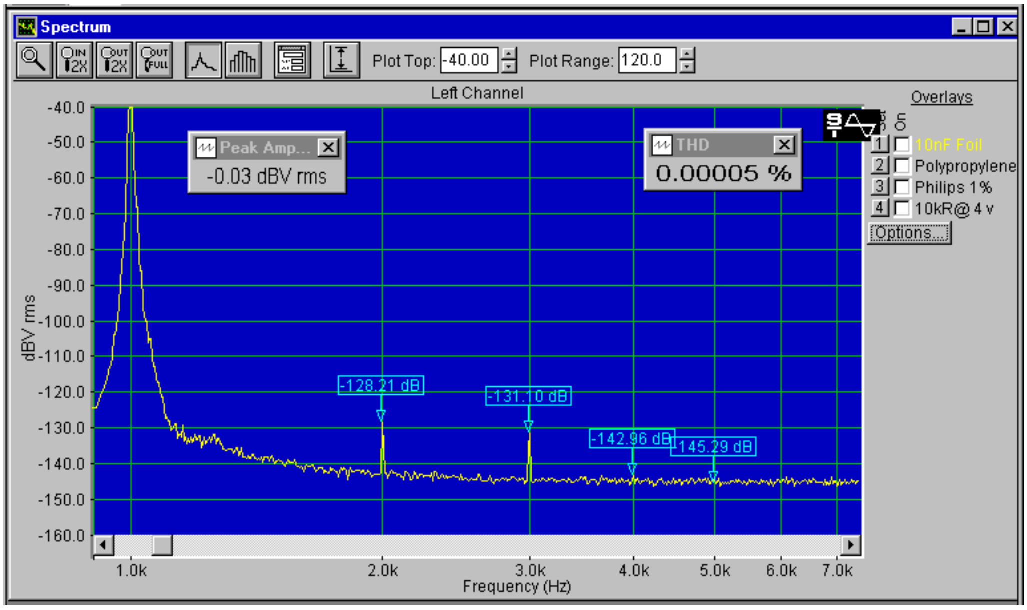

Fig 8) The makers replacement extended foil/Polypropylene shows the same 0.00005% distortion but second harmonic is 1 dB worse.

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 .

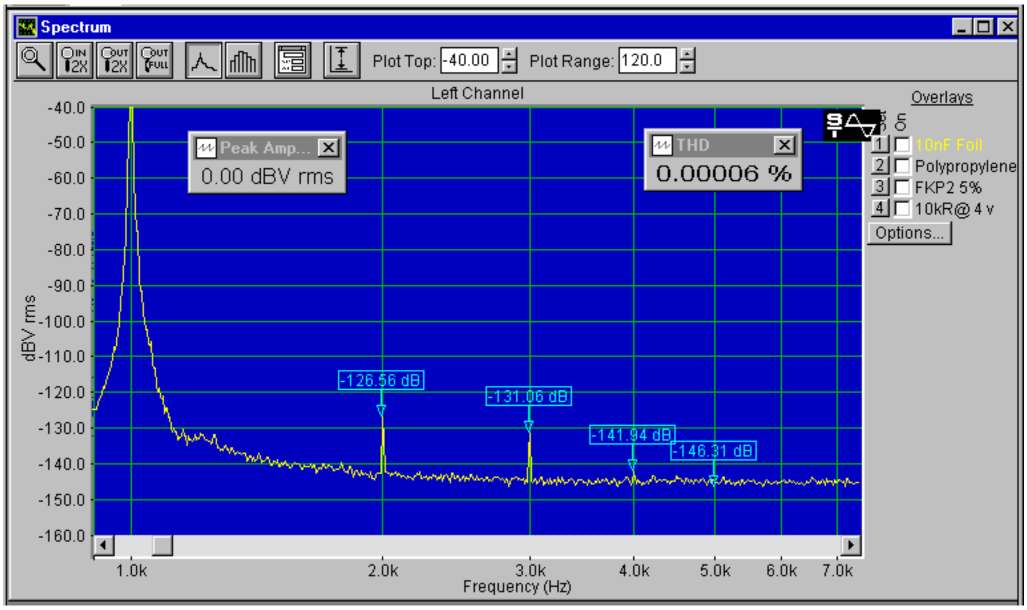

Fig 9) The tiny Wima FKP2 foil/Polypropylene capacitor shows similar performance except for 2 dB increased second harmonic.

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**

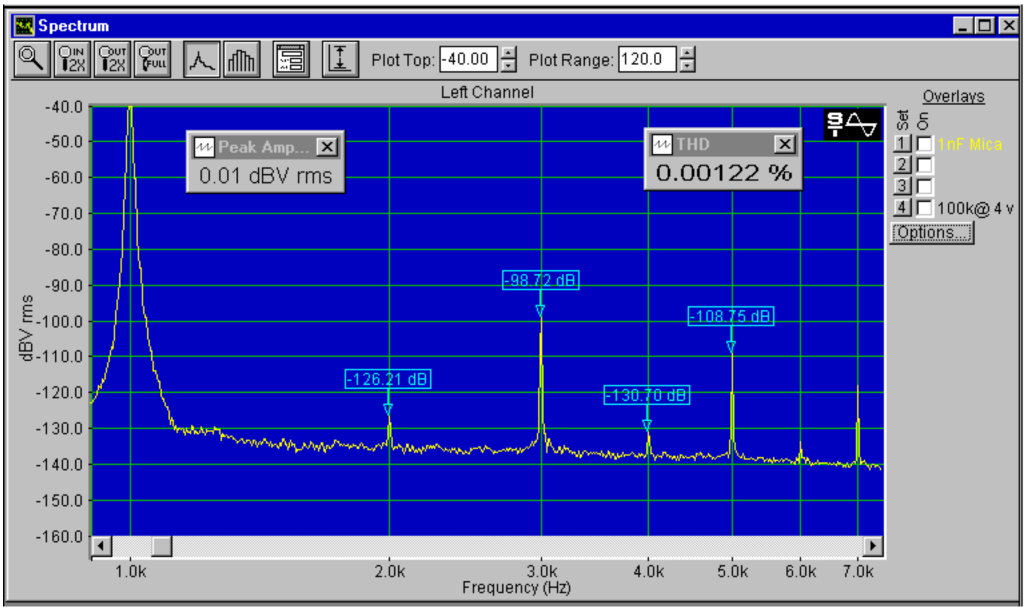

Fig 10) Despite cleaning and re-tinning its oxidised leadout wires, this 1 nF Mica capacitor, single frequency tested at 4 volts 1 kHz and no bias, clearly has an internal non-ohmic connection problem.

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**

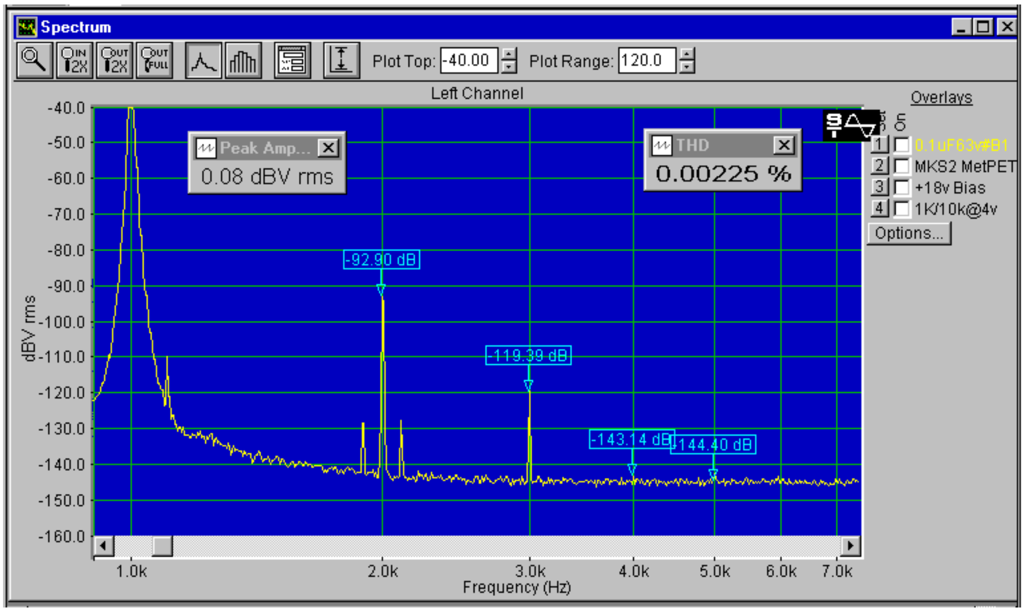

Fig 11) Tested with no bias, this 0.1 µF MKS2 metallised PET capacitor measured 0.00016% with clearly visible intermodulation products.

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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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**

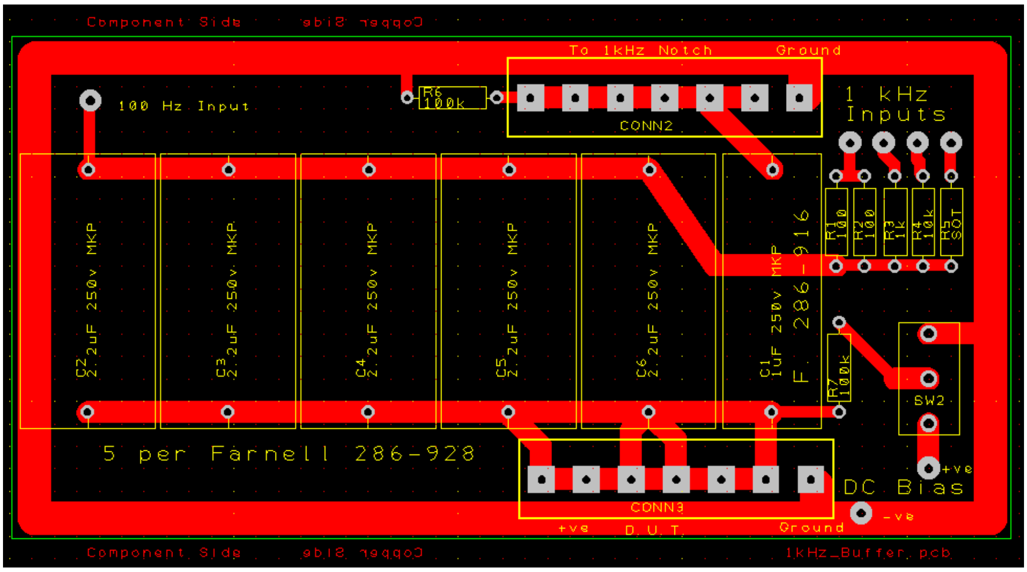

Fig 12) The 110 * 55 mm single sided PCB used to assemble Figure 3, the 1 kHz DC blocking buffer network.

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**

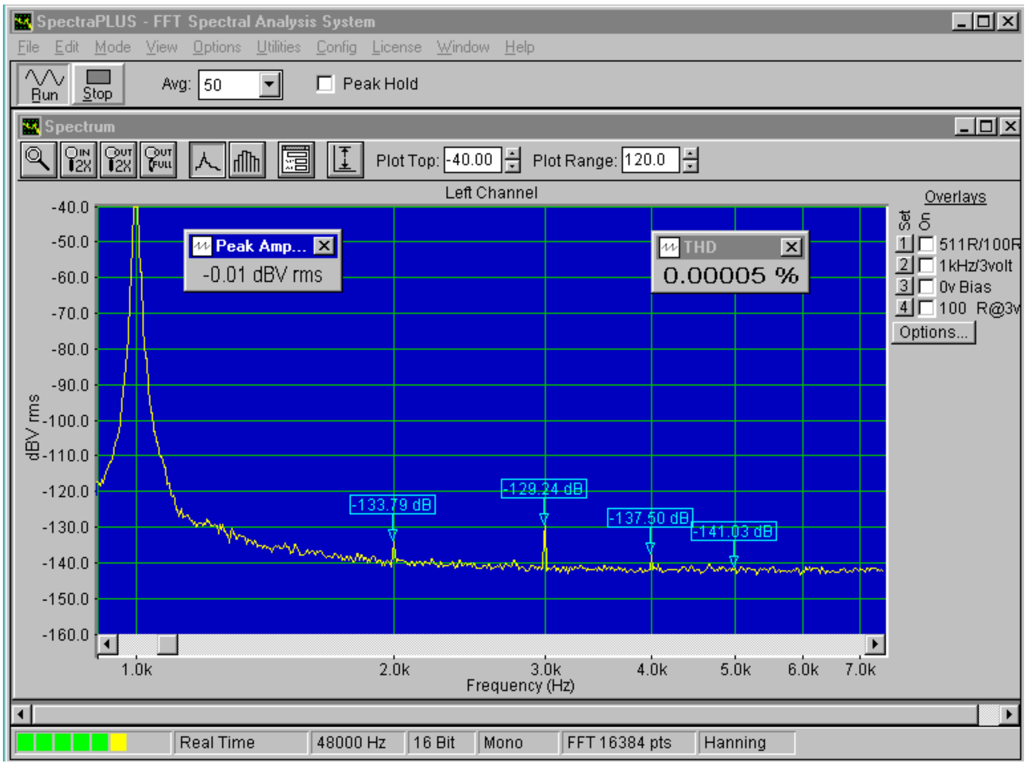

Fig 13) The Plus232 software shows a green then yellow signal strength meter, bottom left, changing dramatically to red at the soundcard overload level.

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		