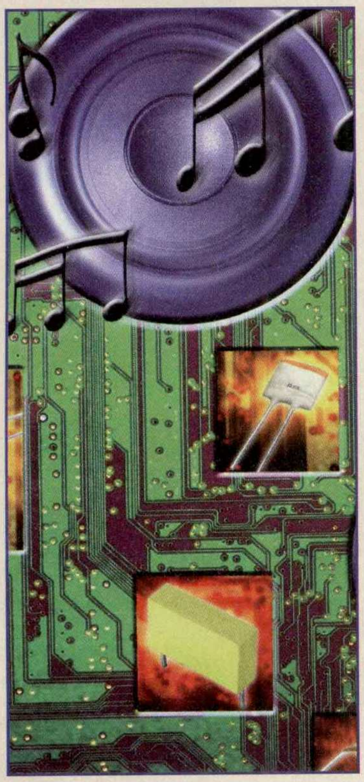
# Capacitor sound 3



## Capacitances of 10nF and smaller.

Readers of my recent articles have seen that many capacitors do introduce distortions onto a pure sine wave test signal.[1] In some instances this distortion results from the unfavourable loading the capacitor imposes onto its driver circuit and 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. **Fig. 1.** 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.(see box Soundcard FFT Software.)

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

### 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. Dielectric absorption does not appear to significantly affect tanδ measurements, so I reasoned it should not greatly affect a capacitor's sound. I certainly was not alone in this belief.

More than 2000 distortion measurements have been made, using test signals from 0.1 volt to 6 volts AC and DC bias from 0 volt to 30 volt . Using a variety of capacitors, purchased for these tests and observing the effect of changing one measurement stimulus at a time, I was able to analyse 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. I now realise dielectric absorption does influence measured distortions, even if the capacitor measures a low tanδ on a bridge. (See box Tanδ/ESR.)

As will be seen later in this series, when a capacitor is used with a significant DC bias, dielectric absorption 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 of a negative feedback loop.

### Repetition.

As a result, it became necessary to repeat most of my early single frequency tests, 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 an 18volt DC bias. Apart from Figure 1, the bias network was left in situ and switched to discharge for no bias measurements.

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

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

When tested with my near perfect 1μF KP test capacitor [2], this network introduced its own distortions. A new network was required. It was assembled using 11μF and 1μF MKP capacitors with a 100kΩ charge/discharge resistor. Another 100kΩ resistor to ground, protects the pre-amplifier input from charge/discharge transients, but restricts measurements to using 10kΩ and smaller sense resistors. **Fig. 3.**

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.[1] It is designed to mount in place of the test capacitor, shown in the figure. (see DC Bias Network, **Fig. 4**)

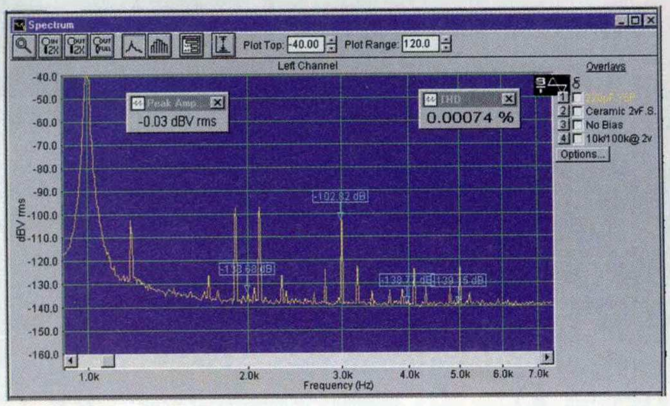



*Figure 1: Y5P is a medium 'k' class 2 ceramic. Tested with two signals, 100Hz and 1kHz at 2 volts amplitude, with no bias network, it produces many new intermodulation distortion frequencies.*

## 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 false capacitor myths have emerged.

I will try to relate some of these myths to 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 1kHz. Capacitance values of 100μF and smaller are measured at 1MHz. Capacitors larger than 1μF are usually measured at 100Hz.(see box Tanδ/ESR.) Each capacitor is 'voltage proof' tested to ensure reliable operation at rated voltage. Leakage current or insulation resistance will be measured at the specified time interval or less. To expedite this time consuming measurement, leakage currents/insulation resistance are 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 that routinely tests for harmonic distortion, at 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, dielectric absorption affects the second harmonic, so is transparent when measuring tanδ. **Fig. 2.**

## 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

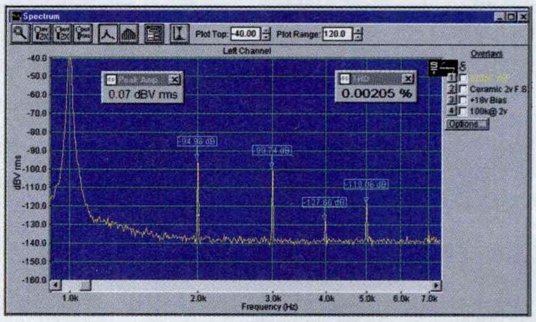



*Figure 2: The figure 1 capacitor tested using 1kHz only with 18 volt DC bias. Compared to its 0 volt bias test, second harmonic has increased 23dB, a 14 times distortion increase.*

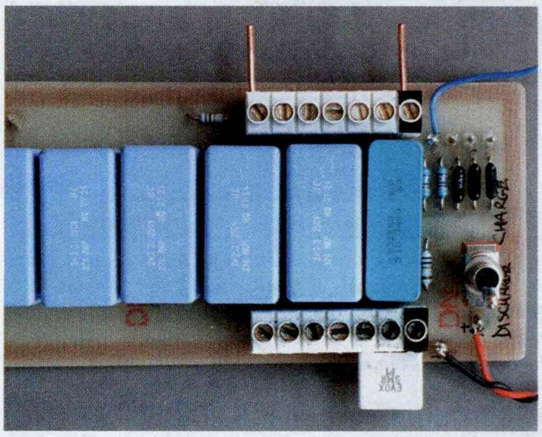


*Figure 3: A fly lead connected to the hot AOT resistor terminal, a duplicate set of source resistors and five 2.2μF MKP blocking capacitors, couple the 1kHz test signal. The test capacitor output is fed to the pre-amplifier via a 1μF capacitor. A current limited 100Hz test signal may be input to the top left terminal, DC bias to bottom right.*

## 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 Windows 98SE 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.Fig. 12

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 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 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 the internet and also on 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 the internet. One site that links to some of the better packages is www.pcavtech.com/links/index.htm.

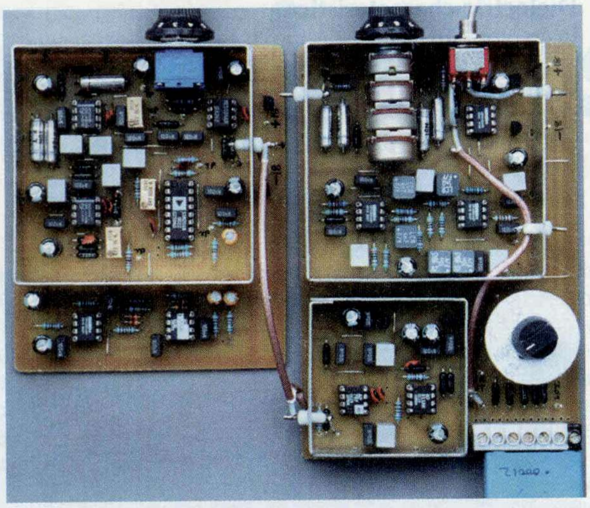


*Figure 4: Low distortion test equipment measuring distortion of a capacitor with AC test signal, as described in my last two articles. To measure capacitors with DC bias, the network of Figure 3 with test capacitor attached, replaces the test capacitor shown bottom right.*

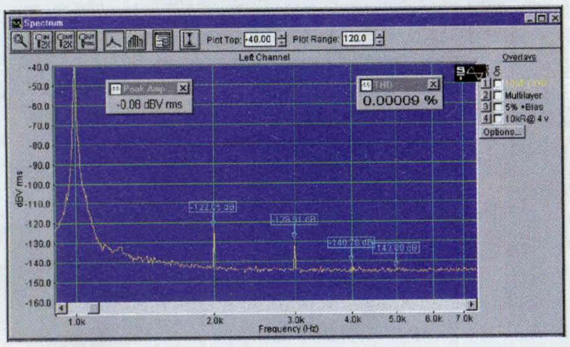



*Figure 5: Distortion measurement of a Class 1 ceramic using 100Hz and 1kHz signals at 4 volts and 18 volt DC bias. With no bias this tiny 10nF 50 volt C0G multilayer capacitor measured just 0.00006%. Second harmonic was -128.5dB, the other levels remained as shown.*

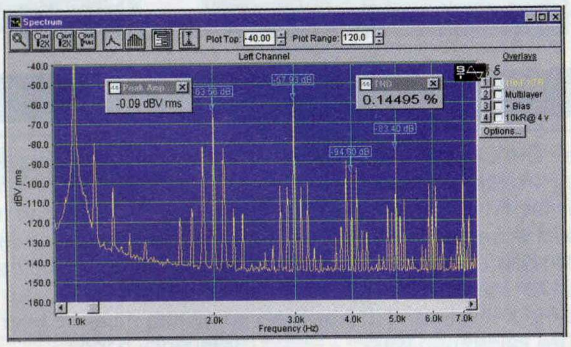



*Figure 6: A Class 2 X7R 10nF capacitor from the same maker as figure 5 and tested the same. This test dramatically shows the impact an increase in both tand and dielectric absorption have on capacitor distortions.*

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. This produces heat in the dielectric with power loss, called dielectric loss, together with second harmonic distortion.

Non-polar dielectrics exhibit very small dielectric loss. Polar dielectrics are lossier and take longer for the dielectric to return to its original uncharged state. Polar dielectrics produce easily measured 'dielectric absorption' effects, especially apparent in thin dielectrics

Dielectric absorption is 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.

## Ceramic capacitors.

'Ceramic' covers an extremely wide range of dielectrics, sub-divided as Class 1 (non-polar) or Class 2 (polar) according to the materials used to make up the ceramic. Class 1 ceramics do not use Barium Titanate and 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. **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 and yet as a small disc capacitor, it costs only pennies. Assembled as a multilayer, it can provide capacitances of 100nF and above, rated for 50 volts working, and can achieve higher working 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 almost no measurable 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. Class 2 ceramic is strongly polar and its capacitance varies with applied voltage and temperature. It exhibits an easily measured

## DC Bias Network

Two DC blocking capacitors are needed, one to couple the signal to the test capacitor and 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 2.2μF 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 1μF 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. Fig. 3.

All were mounted on a single sided PCB size 110 x 55 mm. For convenient interconnections, I mounted two lengths of the terminal strip, one on either side of the buffer. **Fig. 13** To avoid overloading the soundcard input, the 100Hz/1kHz connections to the bias network should be completed before connecting the pre-amp output to the sound card.

## Tanδ/ESR

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 6425 precision LCR meter, Tanδ of a most nearly perfect capacitor at 1kHz measured just 0.00005, a phase angle deviation less than 0.003°. These measurements were made on a Philips 10nF 1%, axial lead, extended foil and Polystyrene capacitor. Fig. 7

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

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

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

In which case,

$$\mathrm{Tan}\delta = \frac{\text{resistive vector}}{\text{reactive vector.}}$$

This resistive vector is called ESR.

$$\mathrm{ESR} = \frac{\mathrm{Tan}\delta}{\text{reactive vector.}}$$

Obviously ESR must 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 0.8Ω for 1kHz, 0.26Ω for 10kHz and 0.08Ω for 100kHz.

Self-inductance reduces the capacitor's measured reactance value. This means a capacitor's self inductance actually increases its measured capacitance value.

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

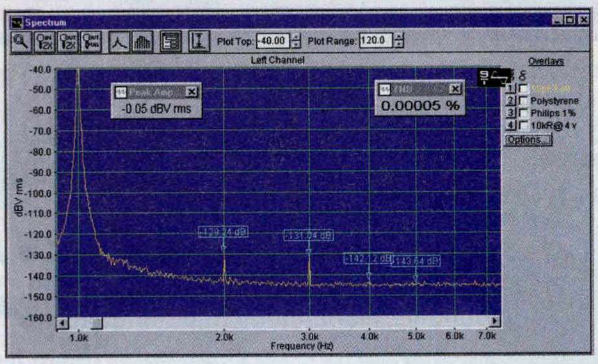



***Figure 7: This now discontinued Philips extended foil/Polystyrene 1% axial lead capacitor, with 4 volt signals and 18 volt DC bias, shows negligible distortion. With test signals increased to 6 volt and DC bias to 30 volt second harmonic increased less than 4dB and distortion to 0.00007%. There was no visible intermodulation.***

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 produce extremely large measured distortions. **Fig. 6.**

### Film capacitors.

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

Perhaps the best 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. **Fig. 7.**

For years it was wound with solderable soft metal electrodes, producing vast quantities of 1% tolerance, high quality capacitors, with values up to several μF.

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

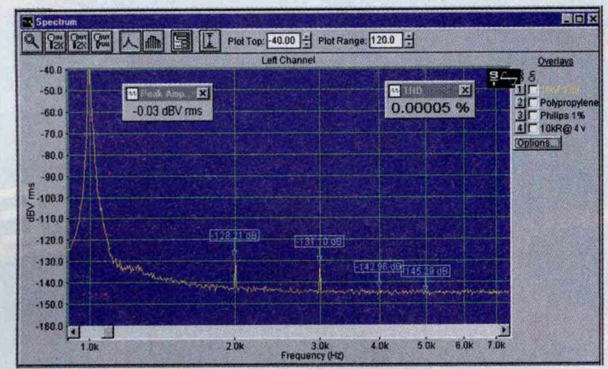



***Figure 8: The makers replacement extended foil/Polypropylene shows the same 0.00005% distortion but second harmonic is 1dB worse. With test signals increased to 6 volts and DC bias to 30 volts second harmonic increased just over 5dB, distortion to 0.00008%. Again, no visible intermodulation.***

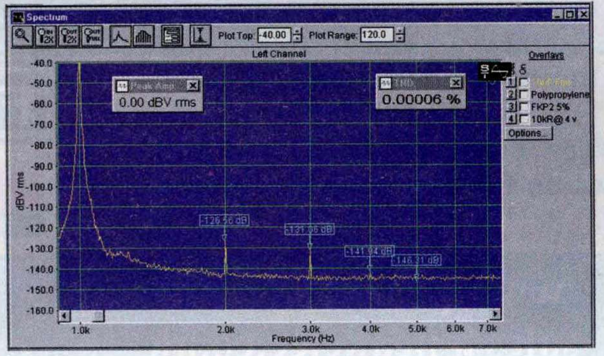



***Figure 9: The small Wima FKP2 foil/Polypropylene capacitor shows similar performance except for 2dB increased second harmonic. Distortion just 0.00008% with 6 volts stimulus and 30 volts DC bias.***

## Table 1

Correction Table for 1 volt at 1kHz distortion measurements.

| Frequency (Hz) | Value (dB) | Frequency (Hz) | Value dB | Frequency (Hz) | 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 | | |

AC currents, than metallised film types.

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 a large capacitance in a small package. Conversely, foil and film capacitors cannot self-heal, so they must be made using film of sufficient thickness to withstand the required voltage without self-healing and being wound with metal foil electrodes.

PET has very high tensile and voltage strengths and is easily metallised. Film thinner than one 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 tand are strongly temperature and frequency dependant and 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 one micron thick. A foil and film PET capacitor might be made using five micron thick film. With five 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 a low tand of 0.03%. It has less tensile strength and is 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 105ºC, 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, 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.[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.

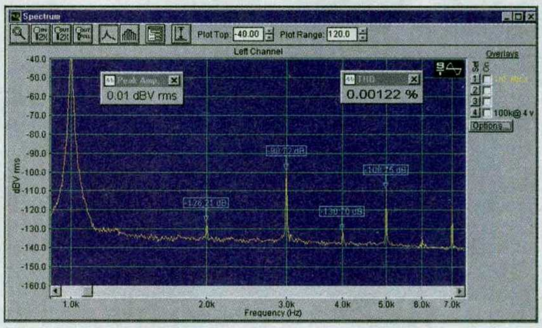



***Figure 10: Despite cleaning and re-tinning its oxidised lead out wires, this 1nF Mica capacitor, tested using 1kHz only at 4 volts and no bias, clearly has an internal non-ohmic connection problem.***

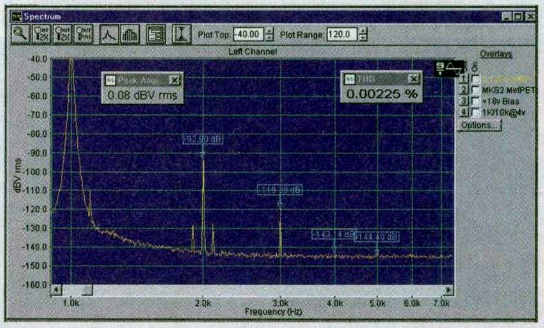



***Figure 11: Tested with no bias, this 0.1mF MKS2 metallised PET capacitor measured 0.00016% with clearly visible intermodulation products. With 18 volts DC bias, the second harmonic increased dramatically, from -119.0dB to -92.9dB and harmonic distortion to 0.00225%.***

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 +20dB 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. **Fig. 7.**

Unfortunately, few manufacturers still make PS capacitors and 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 also 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 lead wire. These capacitors have almost no self-inductance, apart from the 7nH per cm of the lead wires used to connect them into circuit.

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

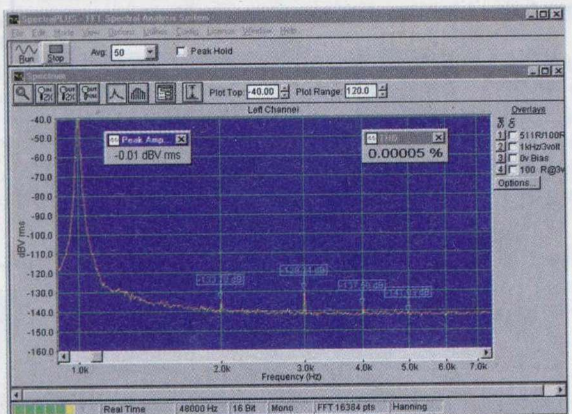



***Figure 12: The Plus232 software shows a green then yellow signal strength meter, bottom left, changing dramatically to red at the soundcard overload level. My 'standard' measurement settings can be seen. Loaded with a 511Ω resistor, all harmonics are well below 0.5 ppm distortion.***

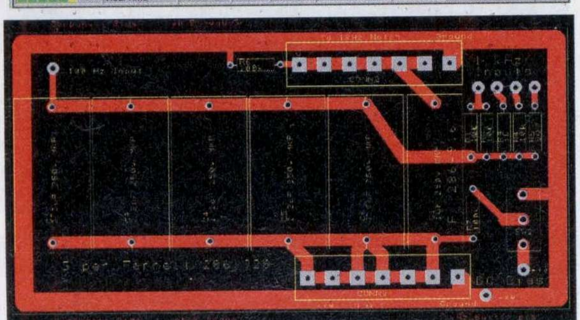


***Figure 13: The 110 x 55 mm single sided PCB used to assemble Figure 3, the 1kHz DC blocking buffer network.***

## 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 10nF. **Fig. 7, Fig. 8.**

For low distortion capacitors up to 10nF, my personal choices would be C0G ceramic, perhaps also including discs up to N750, extended foil/PS or extended foil/PP, with the lead out wires soldered to the electrodes. **Fig. 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 1nF, purchased specially for these measurements, distorted badly. One sample was even unstable, showing significant and variable third harmonic. **Fig. 10.**

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 10nF 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 2dB worse than for the PP capacitor. Unfortunately, this FKS2 style is not available in bigger 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. **Fig. 11.**

For capacitances up to 10nF, low distortion, low cost capacitors are easily available, so I would avoid using metallised PET capacitors. For capacitance values above 10nF, the near perfect C0G, foil/PS and foil/PP types are not easily available. Our best options for capacitance values from 10nF to 1μF will form the subject of my next article.

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

## Technical Support

Interested readers are free to build a system for personal use or educational use in schools and colleges. Commercial users or replicators should first contact the author.
A professionally produced set of three printed circuit boards is available for the 1kHz low distortion signal generator, the 1kHz low output impedance buffer amplifier/notch filter/pre-amplifier and the 1kHz DC bias buffer network. This set of three boards provides a complete 'with DC bias, single frequency, distortion test system'.
Supplied with component parts lists and assembly/usage notes, these single sided FR4 boards have solder resist and component legends. The set of three boards costs £32.50.

Post/packing to UK address £2.50.
Post/packing to EU address £3.50, rest of world £5.00.

Please send Postal Orders or Cheques, for pounds sterling only, to C.Bateman. 'Nimrod' New Road. ACLE. Norfolk NR13 3BD.

### References.

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