Capacitor & Amplifier Distortions

Cyril Bateman uses his real-time distortion measuring system to investigate capacitor distortions in audio power amplifiers

Assembled using polar aluminium electrolytic capacitors for C1, 3, 9 and 11, my workhorse 100 watt Maplin Mosfet amplifier, tested at 1kHz and 25 watts into an 8Ω load, measured -81.5dB second harmonic, -91.4dB third harmonic, clearly meeting its claimed less than 0.01% distortion[1]. **Fig. 1.**

Replacing the four polar aluminium electrolytic capacitors in this schematic, with the same value and voltage rating bi-polar electrolytics and no other changes, amplifier distortion improved dramatically, becoming -92.1dB second and -94.3dB third harmonic, re-measured a few minutes later. This article is based on more than eighty distortion measurements, taken while investigating the possible reasons for these improvements.

In the past, many amplifier designers have stated that provided the capacitance value is chosen to ensure only a small AC signal voltage drop can appear across capacitors at the lowest frequencies, then capacitor distortion can be ignored.

My original *Capacitor Sounds* series[2] found measurable distortions occurring in un-biased polar aluminium electrolytic capacitors tested at 0.1 volt AC, my smallest practical test voltage. With signals this small, second harmonic of the lowest distortion 100μF 25 volt DC rated polar capacitor I tested, measured -99.5dB with 6 volt bias and -94.4dB with 12 volt bias. Using 0.2 volt AC and larger test voltages, second and third harmonic distortions in polar aluminium electrolytic capacitors increase dramatically, measured with and without DC bias voltage.

Tested using a 1 volt signal, this capacitor's third harmonic remained close to -100dB, with no bias its second harmonic was -93.2dB, increasing to -77.9dB at 6 volt bias and -72.9dB with 12 volt bias. Application of a very small, optimal bias, typically less than 3 volts DC, to selected capacitors may minimise the second harmonic, however for every electrolytic capacitor I tested, further increase of bias voltage resulted in increased second harmonic distortion.

Contrary to the popular belief that a polar aluminium electrolytic capacitor should be biased to 50% rated voltage for minimal distortion, my measurements show that second harmonic distortion can only be minimised by using very small or no DC bias. Any further increase in DC bias increases the second harmonic generated by the capacitor. Application of DC bias at 50% of the capacitor's rated voltage as shown in the figure, results in exceptionally large second harmonic distortions, even for this, the lowest distortion, the best polar capacitor, of those measured. **Fig. 2.**

At very low frequencies, as capacitor impedance increases, signal

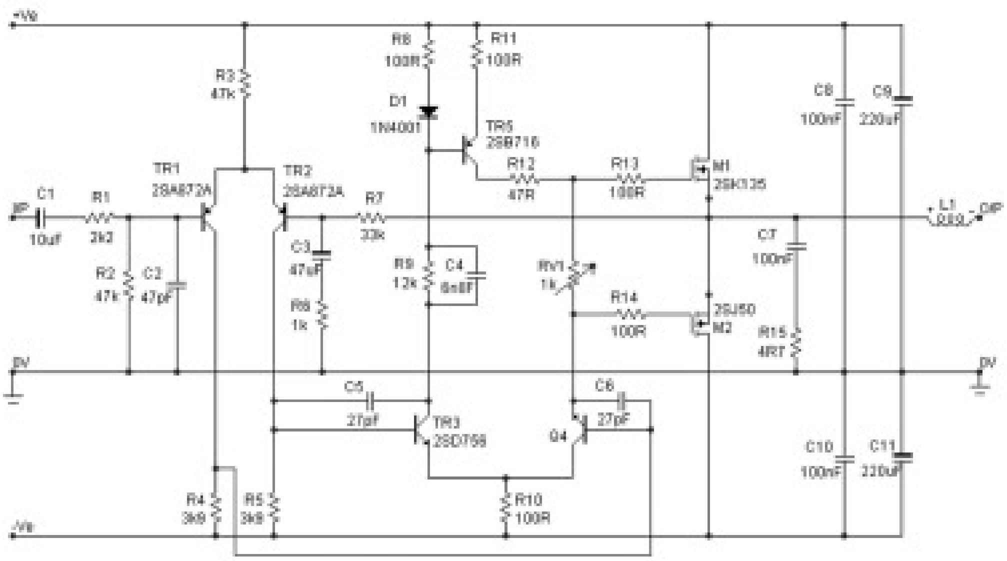


Fig. 1. Schematic circuit of my Maplin Mosfet 100W amplifier, redrawn for convenience using my Microcap MC6 circuit simulator.

voltages could occur in the circuit sufficient to generate measurably increased distortion. However at my 1kHz distortion measurement frequency, all four capacitors have low impedance, so are subject only to small AC signal voltage drops, apparently not sufficient to explain my measured reduction in distortion when replaced by the same value and voltage bi-polar types.

At a given test frequency, capacitor distortions do vary with capacitor AC signal levels and DC bias voltage, but for my Maplin amplifier comparison tests, nominal capacitance values were unchanged so both sets of polar and bi-polar capacitors experienced the same signal voltages. Why should simply changing these capacitors from polar to bi-polar types, provide such benefit?

Capacitor C3 conditions

I ran a few simulations to identify the capacitor most likely to influence this amplifier's distortion. As in many power amplifiers, a 47μF polar aluminium electrolytic capacitor, C3, is used in the feedback network, to roll off amplifier gain at low frequencies, minimising DC offset at its output. With 33kΩ for R7 and 1kΩ for R6, this capacitor is presented with a high impedance for charge and discharge currents. My original *Capacitor Sounds* measurements used lower impedances. Might this high impedance condition affect the capacitor's distortion contributions?

It seemed possible that distortions generated in the capacitor result from two mechanisms, a current dependant component in addition to the voltage component already identified. Throughout that series, I related distortions measured in capacitors to their signal and bias voltages, using test circuit source impedance some two thirds that of the capacitor's at 1kHz for values to 1μF, 100Hz for 1μF and larger values.

I expected to find some third harmonic current dependency from non-ohmic resistances in the capacitor internal connections. Second harmonic distortions in capacitors result from dielectric absorption effects, DC bias and test voltage level, so I wondered whether a change of measuring current with constant bias and test voltage, would reveal changes also in the second harmonic?

In my original *Capacitor Sounds* series I described test equipment designed and built to measure capacitor distortion at 100Hz and 1kHz. For another project last year I assembled a 5kHz test oscillator, buffer amplifier, notch filter/preamplifier, using 1kHz PCBs with smaller tuning and filter capacitors.

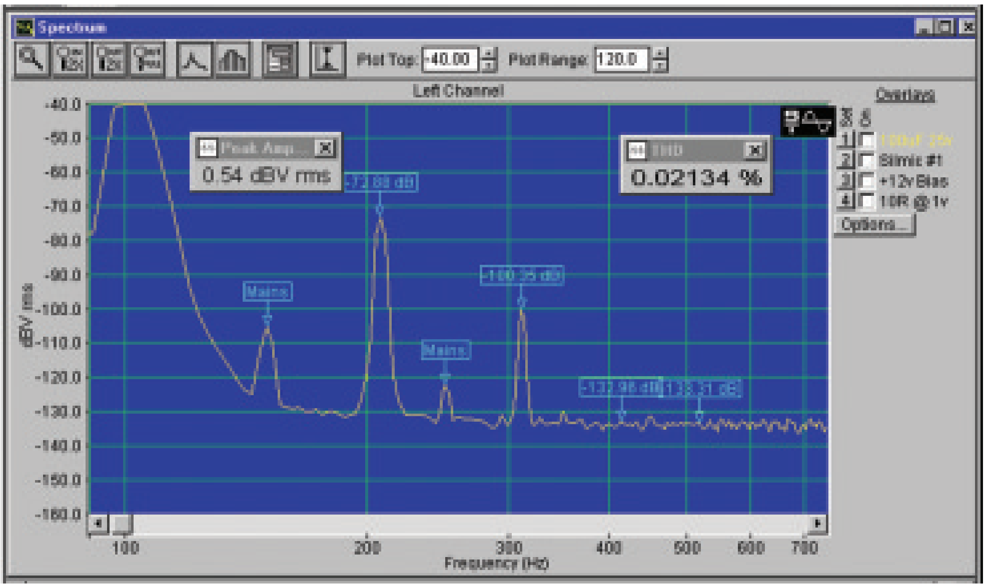


Fig. 2. Distortion results for a Silmic 100μF 25 volt rated polar aluminium electrolytic capacitor, with 12 volt DC bias and tested using 10Ω source impedance generating 1 volt across the capacitor. With no bias, second harmonic distortion for this capacitor was -93.2dB and -77.9dB with 6 volt bias.

Following a few tests, I found this equipment could develop an undistorted 0.5 volt 5kHz signal across my 1μF FKP reference capacitor using 100Ω source impedance. I could measure distortions produced by a 1μF polar aluminium electrolytic capacitor at three test frequencies, 100Hz, 1kHz and 5kHz, using 100Ω source impedance, increasing capacitor test current from 314μA at 100Hz to 15.7mA at 5kHz at constant test voltage. Perhaps that would clarify any capacitor current dependant component.

Using 100Ω source impedance and no bias, I adjusted test levels to develop a 0.5 volt AC voltage across the capacitor at each frequency. Second harmonic distortion increased by 8dB and third harmonic 4.3dB with this change of capacitor current. Clearly both second and third harmonic distortions do increase with capacitor current and AC voltage drop.

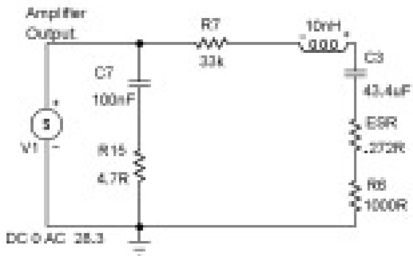


Fig. 3. To simplify my simulations, I extracted the C3 and C7 capacitor sub circuits from the Figure 1 schematic and used the amplifier output voltage as my calculation stimulus. Much simpler, quicker and less prone to simulation errors than when modelling the amplifier.

Second harmonic distortion increases rapidly with DC bias voltage.

Circuit conditions

A few simulation runs using measured capacitance and ESR values by frequency, would establish the voltage and current for capacitor C3, from 10Hz to 20kHz and beyond. Analogue behavioural modelling techniques could be used, but determining the capacitor model can be time consuming and many readers may not have a suitable simulator. Far simpler and quicker - make several frequency runs using measured values for a specific frequency in turn, noting the result for that frequency. This method is practical using the simplest simulator.

Table 1: With 0.5 volt AC test voltage, 100Ω source impedance and no bias, I found second and third harmonic distortion increasing with capacitor current. Clearly both second and third harmonic distortions do increase with capacitor current, voltage drop and second harmonic with DC bias.

Frequency	Impedance	Test Current	Second Harmonic	Third Harmonic	% T.H.D.
100Hz	100Ω	314μA	-107.8dB	-115.7dB	0.00047%
1kHz	100Ω	3.14mA	-102.4dB	-111.6dB	0.00083%
5kHz	100Ω	15.7mA	-99.8dB	-111.4dB	0.00117%

Table 2: Measured values of a 47µF 50 volt Panasonic 'S' bi-polar aluminium electrolytic capacitor as used for C3, with results from my eight simulation runs

Measured Values.				Simulation Results.	
Frequency	Capacitance	Actual ESR	Impedance.	Voltage drop	C3 Current
10Hz	49.08µF	25.74Ω	325.29Ω	270.82mV	832.0µA
20Hz	48.54µF	12.97Ω	164.52Ω	138.02mV	832.03µA
100Hz	45.41µF	1.862Ω	35.09Ω	29.28mV	832.31µA
300Hz	44.24µF	0.575Ω	12.01Ω	10.07mV	832.33µA
1kHz	43.40µF	0.272Ω	3.67Ω	3.05mV	832.35µA
3kHz	42.74µF	0.210Ω	1.26Ω	1.05mV	832.35µA
10kHz	41.71µF	0.191Ω	0.426Ω	0.35mV	832.35µA
30kHz	40.00µF	0.182Ω	0.225Ω	0.18mV	832.35µA

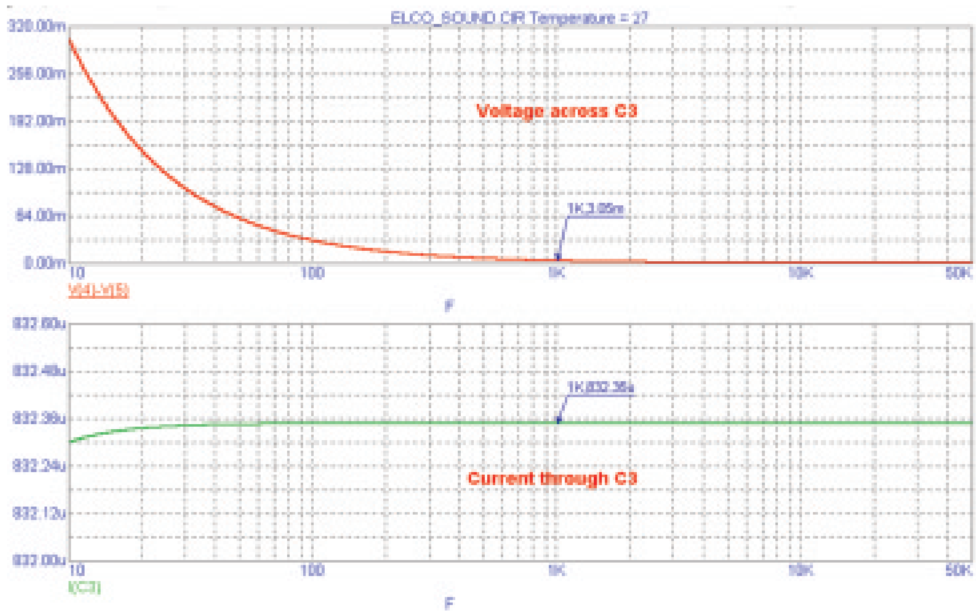
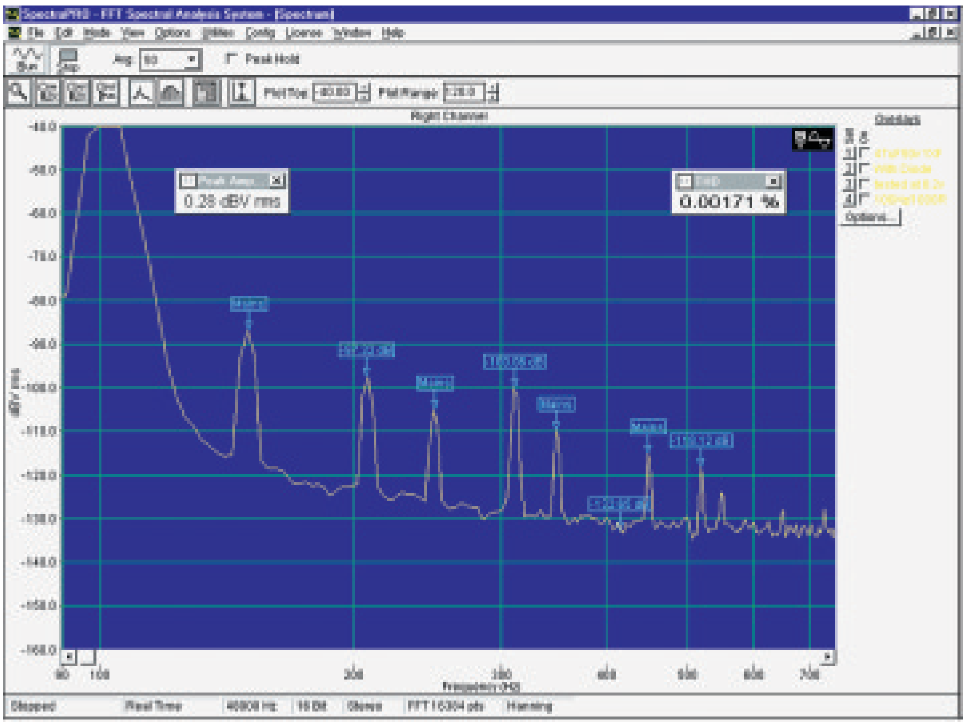


Fig. 4. One of eight simulations needed to accommodate C3 measured parameters by frequency, showing the 1kHz results. Voltage across C3 reduces with frequency but current through C3 remains almost constant regardless of frequency.



I extracted the feedback resistor network with this capacitor from the main circuit and used the amplifier's output voltage for 100 watt into 8Ω as the stimulus. I measured a radial lead, 47µF 50 volt Panasonic 'S' bi-polar electrolytic, the type used when exchanging the capacitors, for capacitance and ESR by frequency. Self resonance was 300kHz, so estimating 10nH for its self inductance, typical of many radial lead aluminium electrolytics in a 20 × 10mm case, completed the model. **Fig. 3.**

Using my Hewlett Packard reference test jig and Wayne Kerr B6425 precision digital LCR meter, I measured this capacitor from 10Hz to 30kHz, for capacitance value and ESR. These pairs of values were inserted into the model in turn for each of eight simulation runs, noting the voltage drop across the capacitor model, from the negative side of the 10nH to the junction of ESR and R6, also C3 through current.

For each run, similar voltage and current plots were observed with subtle changes at the frequency of interest, for the capacitor parameters used. Clearly capacitor signal voltage does reduce with increasing frequency but capacitor current remains almost constant, generating a near constant level of current dependant distortion. **Fig. 4**

Protection Diodes

Most published amplifiers using a polar aluminium electrolytic capacitor for this C3 position add a diode or pair of diodes in parallel, to

Fig. 5. A Rubycon YXF 47µF 25 volt rated polar aluminium electrolytic capacitor tested at 100Hz and 200mV with diodes. Without diodes, third harmonic was -122.67dB, a more than 20dB improvement. At this test voltage, low level AC mains harmonics cannot be eliminated, for clarity test frequency was 103.8 Hz and mains peaks labelled.

protect the capacitor should the amplifier ‘go DC’ with its output voltage ‘stuck’ to a supply rail. It has often been claimed such diodes do not distort at the capacitor’s signal voltage levels, but I wondered if that were correct. Using a pair of 1N4448 diodes and my 1μF FKP reference capacitor, I made measurements at 1kHz with 100Ω source impedance and test voltages of 75mV, 100mV, 150mV and 200mV, comparing distortion results with and without diodes.

Measured with diodes, third harmonic distortion was visible at -110dB for the 75mV test, increasing to -100dB for 100mV and -84.9dB tested at 200mV, when a fifth harmonic at -100dB was seen. These harmonics result from the diodes conducting slightly at these test voltages since without diodes, my FKP reference capacitor was distortion free.

I measured distortions at 100Hz, with and without diodes, for a variety of 47μF and 100μF polar aluminium electrolytic capacitors, rated at 25 volt and 50 volt, comparing these results with those for the same value bi-polar electrolytics. The results were overwhelmingly conclusive. At 200mV with diodes, third harmonic distortion increased by 20dB with polar and bi-polar capacitors. At 100mV I found smaller increases of third harmonic, depending on the level of distortion generated by the capacitor without diodes. Tested at 0.1 volt with diodes, this capacitor generated -96.8dB second and -108.2dB third harmonic distortion. **Fig. 5.**

I question whether these protection diodes are necessary for polar aluminium electrolytic capacitors in this circuit. They certainly are not needed using a bi-polar aluminium electrolytic capacitor of rated voltage similar to the amplifier’s power supply voltage. That capacitor will happily survive indefinitely, regardless of whether the amplifier has ‘gone DC’ or is working correctly. More important it will generate almost no measurable distortion. **Fig. 6.**

All polar aluminium electrolytic capacitors inherently include a reverse polarity diode[3] so should an amplifier ‘go DC’, reverse polarising the capacitor by more than 1 volt, capacitor reverse leakage current increases causing a voltage drop across R7. With ±50 volt power supplies and 10kΩ for R7, current cannot exceed 4.8mA. This reverse current may degrade the capacitor which should be replaced during repair, but is most unlikely to result in capacitor failure.

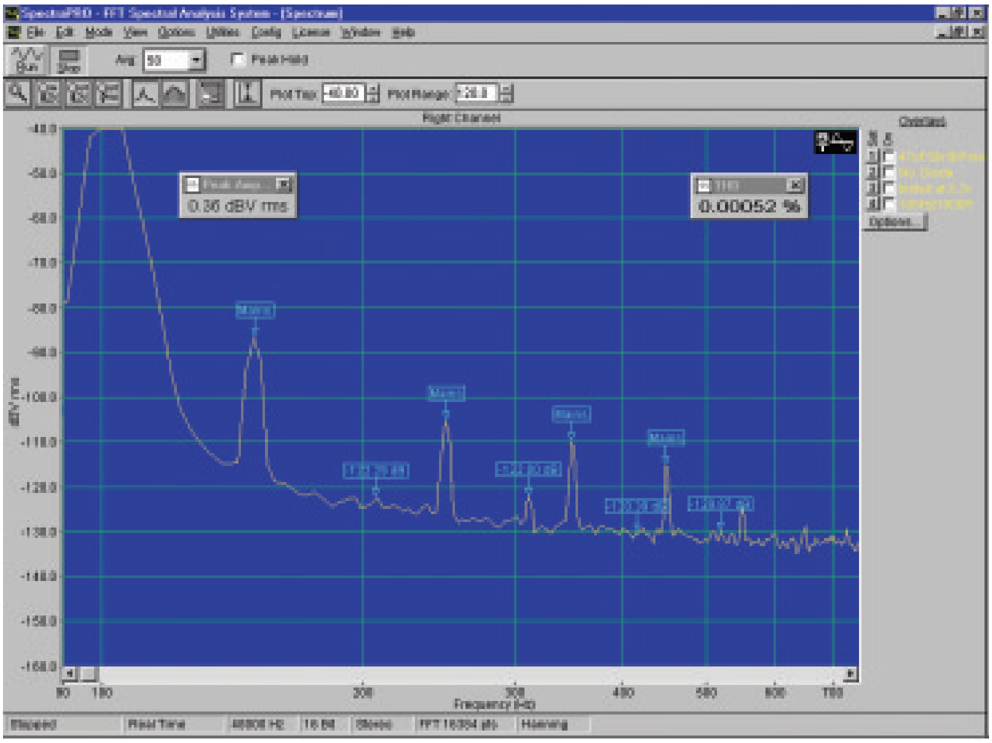


Fig . 6. Without diodes, but otherwise exactly as Figure 5, this Panasonic ‘S’ 47μF 50 volt bi-polar aluminium electrolytic capacitor shows the distortion reduction available by changing a polar capacitor for a bi-polar type. With diodes, third harmonic increased more than 20dB to -99.24dB, further proof of the diode effect.

Zobel circuit

Many designers have expressed concern to me about the output stage CR Zobel network, that the signal voltage across resistor R15 with this resistor’s voltage coefficient might generate audible distortion. With C7 and R15 already modelled, we can quickly explore this Zobel network.

With typical component values of 0.1μF and 4.7 to 10Ω, the 0.1μF capacitor sustains almost all the amplifier output voltage at least to 10kHz and is more highly stressed than the resistor. At higher frequencies, resistor voltage increases but capacitor voltage reduces little.

Technical support

Full details of the ‘Real Time’ hardware test method and my original *Capacitor Sounds* low distortion oscillator, buffer amplifier, notch filter/preamplifier and DC bias assemblies, complete with parts lists, assembly manuals and full size printed circuit board drawings, as .PDF files arranged for easy viewing of the figures, on screen or hardcopy, are provided in my CD.

This CD includes updated and much expanded re-writes with very many more figures, of my first series *Capacitor Sounds* articles, supported now by some ninety capacitor distortion measurement plots as well as articles from this new *Capacitor SoundsII* series.

Also included are PDF re-writes of my earlier *Understand Capacitors* series together with articles on how to diagnose failed printed board mounted capacitors and essential low cost capacitor measurement methods, more than twenty popular articles.

This CD costs £15 Sterling inclusive of post & packing.

I can also supply sets of three professionally manufactured printed circuit boards, FR4 with legend and solder resist also four gang potentiometers, as described in my original *Capacitor Sounds* articles.

One set of boards costs £27.50 but due to weight, post and packing is extra.
Four gang potentiometer if ordered together with PCBs costs £5.00.
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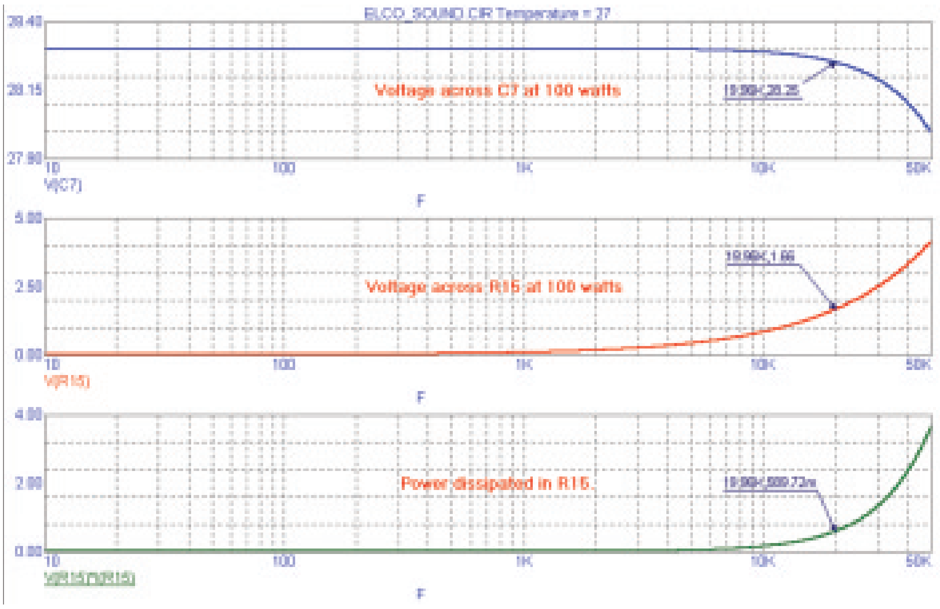


Fig.7. Using the Figure 3 simulation circuit to analyse for C7, we see the capacitor is highly stressed not resistor R15 and badly chosen C7 can generate large distortion. When an amplifier is used for high frequency sinewave tests with or without load, this capacitor frequently fails open, disabling the Zobel, the amplifier may oscillate. Yet R15 is frequently specified as 3 watt rating and C7 ignored.

With 100 watts output into 8Ω at 20kHz, the capacitor must still withstand more than 28 volts while the resistor is subject to less than 2 volts or 0.6 watts. At such voltage a metallised PET capacitor can generate significant distortion. **Fig 7.**

My test equipment cannot generate that voltage so I measured C7 distortions using an eight volt signal and 100Ω source impedance, equivalent to 8 watts power output, representative perhaps of normal listening. I measured a 0.1µF ‘stacked’ metallised PET capacitor, the unused spare for my ‘Self’ amplifier. At 8 watts output this capacitor generated -113.5dB third and -126.3dB fifth harmonic, distortions which would be reflected into the feedback network. **Fig. 8.**

Apart from this distortion, at 20kHz and 100 watts, this capacitor is subjected to more than twice the permitted sine wave rating for an Evox-Rifa MMK 0.1µF 63 volt metallised PET capacitor while almost any resistor easily manages the less than 2 volt and 0.6w R15 dissipates. To minimise distortion in normal use and survive no-load sine wave testing, the capacitor choice for this network is important. I prefer a foil and Polypropylene or Polyphenylene Sulphide capacitor.

Input capacitor C1

Many designs use an unbiased 10-22µF polar aluminium electrolytic capacitor, C1, to input the signal and block unwanted DC from entering the power amplifier, assuming that if sized to ensure minimal signal voltage across the capacitor at low frequency, low distortion is guaranteed. That may well be correct provided the capacitor is not subjected to DC bias. More than a few volts bias will result in second harmonic distortion which will be amplified.

I believe a polar aluminium electrolytic capacitor is false economy since quite small metallised PPS or PET capacitors are available. Polypropylene capacitors produce much lower distortion but are larger and expensive. An inexpensive bi-polar electrolytic is small and produces little distortion unless subject to significant DC bias voltage. For the best performance use a film capacitor.

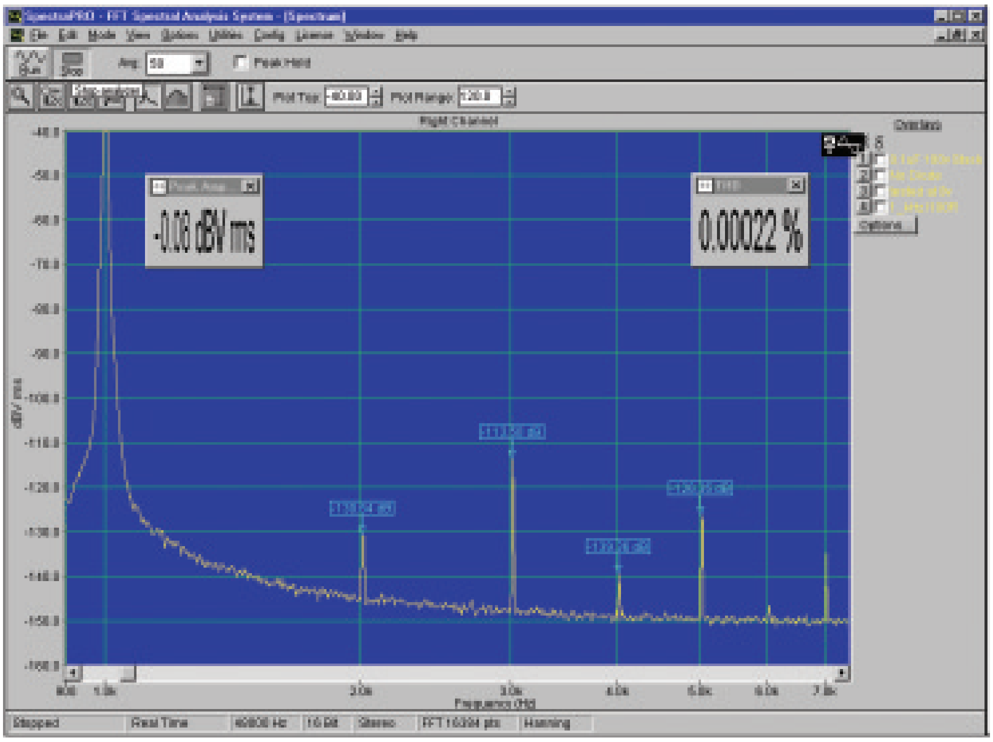
Class B bias stability networks

Many power amplifiers include another significant capacitor we should explore. Typically a 10-47µF is used to bypass the signal across the bias current stabilisation network. For values up to 22µF the lowest distortion most economic choice is a metallised PET style, closely followed by the ‘double bi-polar’ electrolytic capacitor[4]. For larger values, unless cost and size is no object, chose this electrolytic.

Many readers are familiar with the Douglas Self ‘Blameless 50 watt class B’ design, published in *Electronics World* February 1994. I have a pair, assembled on printed boards purchased from the magazine, which measured some 2.6 volts of DC bias voltage across their 47µF polar aluminium electrolytic capacitor C4, the bias current stabilisation network bypass capacitor.

Measurements of the AC voltage across C4, with the amplifier driven to 50 watts into 8Ω shows its AC voltage increasing significantly with frequency. At low frequencies, while the amplifier still has substantial open loop gain, this voltage remains small. As the amplifier open loop

Fig. 8. Actual measured distortion of the ‘stacked’ metallised PET capacitor in the Self Blameless 50 watt class B design, at 8 watts power in an 8Ω load. Distortion will increase rapidly with increasing power output.



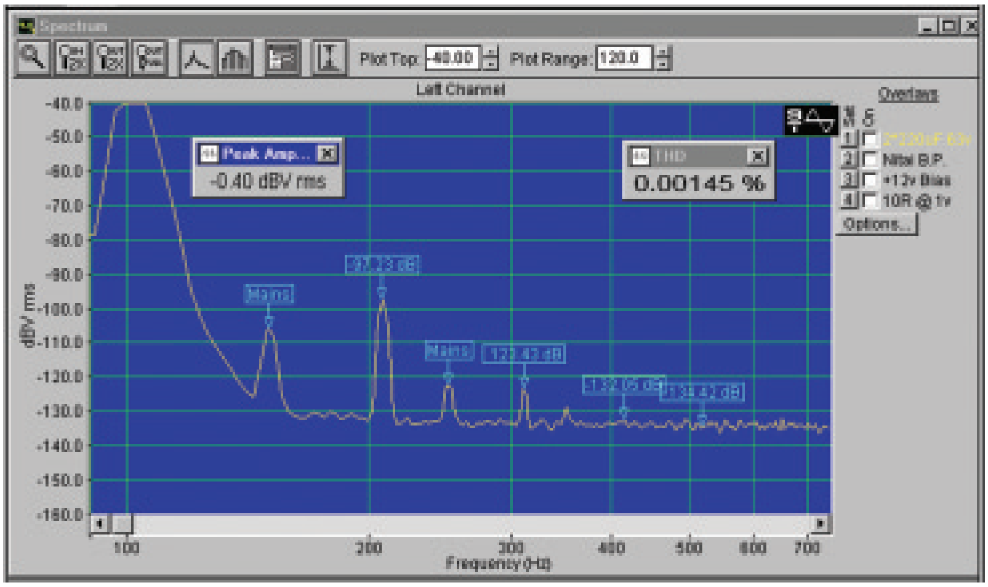


Fig. 9. Two 220µF 63 volt Nitai bi-polar capacitors in series made this 100µF "Double bi-polar" capacitor. Measured using a 1 volt AC and 12 volt DC bias as Figure 2, it generates almost twenty times less distortion. Second harmonic measured -101.75dB with 6 volt bias, -117dB unbiased.

gain reduces with increasing frequency, C4 is subjected to a significant signal voltage. At 10kHz I measured 1.15 volt AC using an AC coupled DVM to ignore the DC voltage. Any polar aluminium electrolytic capacitor subject to such AC voltage will generate very large second and third harmonic distortions.

The very best and quite expensive, specialist polar aluminium electrolytic capacitor of those I tested at 1 volt, generated some -93.2dB second and -100dB third harmonic with no bias. With 6 volt DC bias distortions increased dramatically, the second harmonic now -77.9dB. With 12 volt bias second harmonic increased tenfold to -72.9dB. Other polar aluminium electrolytics generated even more distortion when tested using a 1 volt signal.

The only cost effective, low distortion solution for this 1 volt signal level and DC bias voltage, is to use two double capacitance, 63 volt rated bi-polar aluminium electrolytic capacitors connected in series, the 'double bi-polar' configuration recommended in the last article of my first *Capacitor Sounds* series, *Electronics World* January 2003. Measured using 1 volt and no DC bias, this 'double bi-polar' capacitor combination measured -117dB second and -123dB third harmonic. With 6 volt bias, second harmonic became -102dB and -97.2dB biased to 12 volt DC as shown in this plot. An almost twenty times smaller distortion than measured using the best polar capacitor I tested, with or without bias. **Fig. 9**

Contrary to common belief, using an electrolytic well below its rated voltage does no harm, in fact it is beneficial, reducing leakage current, like choosing a more expensive, professionally rated, long life capacitor. Production electrolytic capacitors rated at 25-63 volt, provide better performance than lower and higher voltage types. In past years 'underunning' was frowned on because some badly designed electrolytes degraded the aluminium oxide dielectric. Subsequent application of rated voltage resulted in leakage current exceeding the maker's claim. Installed in circuit and underun for some time, a capacitor would not usually become subjected to rated voltage. Underunning never was a problem, rather a misunderstanding of capacitor and circuit behaviour.

Valve amplifiers

To date I have avoided discussing valve amplifiers because I do not possess one and so cannot make any confirming measurements. However, I believe the DC blocking AC signal coupling capacitor used between a valve anode and subsequent grid, subjected to large DC bias and AC signals, can create distortion.

I decided to measure a specialist metallised Polypropylene 1µF 630 volt MKP capacitor[5] and the 1µF paper capacitor reported in my August article, using a 6 volt test signal, the largest very low distortion signal I can generate across a 1µF capacitor using 100Ω source impedance, with DC bias from 0 to 100 volt, then compare the results.

The MKP capacitor performed as well as expected, second harmonic increasing from -132dB with no bias to -123dB with 100 volt DC bias, a superb result. In contrast the paper capacitor behaved rather less well, illustrating perhaps why second harmonic distortion often dominates a valve amplifier output.

With no DC bias, second harmonic of this paper capacitor measured -128.8dB but biased to 30 volts DC its -116.5dB second harmonic was worse than the MKP at 100 volts. Biased to 100 volts this paper capacitor performed badly, generating an enormous -108dB second harmonic. Third harmonic for both capacitors changed little with bias, staying close to -130dB. Second harmonic distortion for this and similar paper capacitors increases with DC bias or AC signal voltage. **Fig. 10.**

Power Rail Capacitors

The four polar electrolytic capacitors I exchanged for the bi-polar types included two 220µF power rail capacitors which are irretrievably linked with the power supply so cannot easily be evaluated in isolation. I plan to explore these as part of a future article.

In my next article, the last for this series, I measure distortions in low-level IC op-amp circuits and include a novel circuit technique that allows a modest op-amp to produce lower than usual distortion driving a low impedance load. In response to reader's requests, I also include a brief look at possible resistor and potentiometer distortions.

Conclusion

Having examined a variety of capacitor styles and their audio frequency distortions over the past two years, it is perhaps appropriate with the benefit of hindsight to summarise some findings.

For low level and pre-amplifier circuits but ignoring supply rail decoupling, most capacitors used will be small value and many will need

Table 3: AC and DC voltages measured on C4, with the amplifier set to generate 50 watts into 8R. This amplifier was assembled using printed circuit boards purchased from *Electronics World*.

Frequency	100Hz	1kHz	10kHz
DC bias volts	2.6v	2.6v	2.6v
AC signal voltage	0.095v	0.158v	1.15v

FFT Software

Throughout my *Capacitor Sounds* series except the first two articles, I used the SpectraPlus232 software for my distortion plots. This software is easy to set up and has served well. However some readers have asked whether lower cost software might be used, since a full set of options can become expensive.

I have now found two alternatives. Provided the reader can accept not having the on screen THD% display, all other facilities I used are provided by purchasing only the Spectra base module, almost halving the cost. The on screen THD% option can be purchased later.

My second alternative is 'WinAudioMLS Pro', I evaluated version 1.66, a new version having its microphone correction ability updated for use with my test equipment, or a conventional microphone. It can be obtained from the Dr. Jordan web site.

As standard this software provides a THD+N display and cursor controlled readout of harmonic levels. It accepts the microphone correction file, essential when using my notch filter/preamplifier assembly. In addition to all the features needed for my measurements it also provides an MLS measuring facility. This can be used to measure loudspeaker and room responses as well as the impedance and phase of low impedance components, especially those used in loudspeakers. All this for less cost than for the basic SpectraPlus232 module, makes this software well worth your evaluation.

This software also has a range of additional upgrade options, but I found the base WinAudioMLS Pro version with their THD% option, sufficient for my needs.

Contact
WinAudioMLS Pro
http://www.dr-jordan-design.de
SpectraPlus232
http://www.soundtechnology.com

1% tolerance. For values up to 47nF we have a choice of near perfect, very low distortion, extended foil and Polystyrene or extended foil and Polypropylene capacitors, available at 1% in both axial lead and 'tombstone' styles. COG ceramic capacitors at 5% tolerance, as low cost discs for small values and multi-layer capacitors to 100nF, are distributor items. Larger capacitance values and closer tolerances are manufactured. COG ceramic provides low distortion, unsurpassed capacitance stability with voltage, temperature, time and frequency, the almost perfect capacitor.

For values of 100nF and above, we could use multiples of the above types but foil and Polypropylene styles are available to 10µF, regardless of DC bias they assure very low distortion. Metallised PPS types produce little distortion unless subject to significant DC bias. Available to 10µF and 1% tolerance, PPS capacitors provide excellent temperature and long-term capacitance stability in smaller case sizes than Polypropylene types.

Power amplifiers needing larger value signal path capacitors, should use bi-polar aluminium electrolytic capacitors, avoiding the conventional polar aluminium electrolytic capacitor for audio signals. With signal voltages across a large capacitor of 0.5 or more volts, the 'double bi-polar' aluminium electrolytic capacitor, two double value conventional bi-polar aluminium electrolytic capacitors in series, is demonstrably the most economic low distortion choice. Many writers advocate using lesser value film capacitors, to bypass a polar aluminium electrolytic capacitor to reduce its distortion. My measurements show this has little effect, compared to using the bi-polar style, which produces much lower distortion at less cost.

Distributor stocks of bi-polar aluminium electrolytic capacitors rarely exceed some 470-1000µF at low voltage, this results from customer demand and not capacitor technology, manufacturers will respond to market demand as will distributor stockholdings.

More than 30 years ago I developed a range of bi-polar or *reversible* electrolytic capacitors up to 10,000µF at 63 volt and the Erie Company manufactured many thousands. The largest example which I still have today, a 2,000µF 100 volt in a 115 x 45mm case, was developed as the output coupling capacitor for a very high power audio amplifier. ■

References

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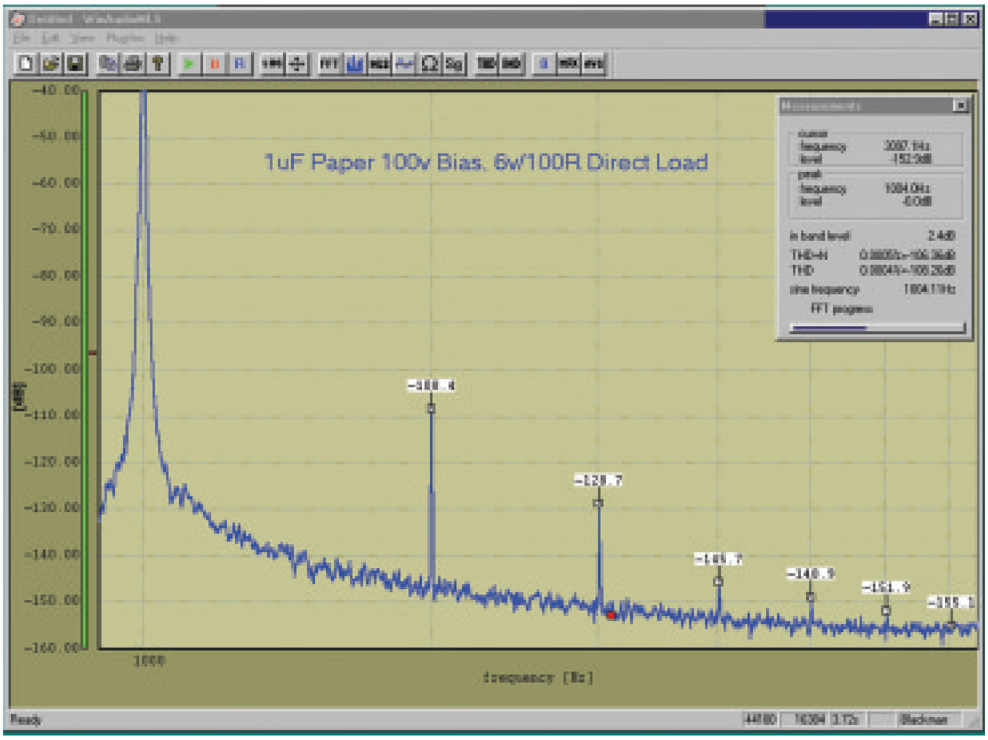

Fig. 10. A typical 1µF paper capacitor, with 6 volts AC at 1kHz and 100 volt DC bias, produced this excessively large second harmonic distortion. The 630 volt 1µF MKP Polypropylene capacitor was five times better with second harmonic -123dB, third -130dB, just 0.00008% distortion. This plot was measured using the Dr.Jordan software, the SpectraPlus232 gave almost identical results.