Capacitor SoundsII - Real Time Hardware Method.

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Analysing Sound.
Many modern equipments now include an audio spectrum analyser comprising vertical chains of LED's which illuminate to indicate the level of the various frequencies being monitored. Frequently these analysers sample at third octave intervals, so use a third octave bandwidth filter and rectifier for each LED column, to provide a low cost, real time spectral analysis.

A number of readers asked whether my existing 1 ppm low distortion test oscillator/buffer amplifier and twin 'T' notch filter/preamplifier could be used together with a similar display arrangement. Replacing the computer soundcard/FFT software approach used for my Capacitor Sounds series, to provide a self contained, free standing portable test station. I felt such arrangement would also benefit my test workshop, enabling quicker and easier distortion measurements, both of capacitors and amplifier systems. **REF.1**

Measuring Distortion.
To reliably measure distortions produced by the better quality capacitors requires a measurement system producing less than 1 ppm distortion, together with a noise floor better than -120dB below a 1 volt test signal. Such equipment, although optimised for measurements of capacitor distortions, is ideally suited to measuring and identifying pre-amplifier and power amplifier distortion components.

Equipment Design.
This article describes the design and construction of a 'Real Time' hardware method able to measure second and third harmonic distortions from -60dB to -120dB below the test signal. Monitoring the rectified outputs from the second and third harmonic bandpass filters, shows that with some capacitors, distortion levels do change with time as well as with test voltage.

Comparison of measurement results using this prototype with those from the computer/soundcard software method have shown excellent correlation measuring good, low distortion capacitors. Comparing poorer capacitors especially when using DC bias, has since highlighted capacitor distortion anomalies while the capacitor charges or discharges, which were masked using the soundcard/software methods. As will be seen in later articles, investigations into these anomalies revealed significant additional insights into how dielectric absorption really does affect capacitor sound distortion. **Figs. 1 & 2**

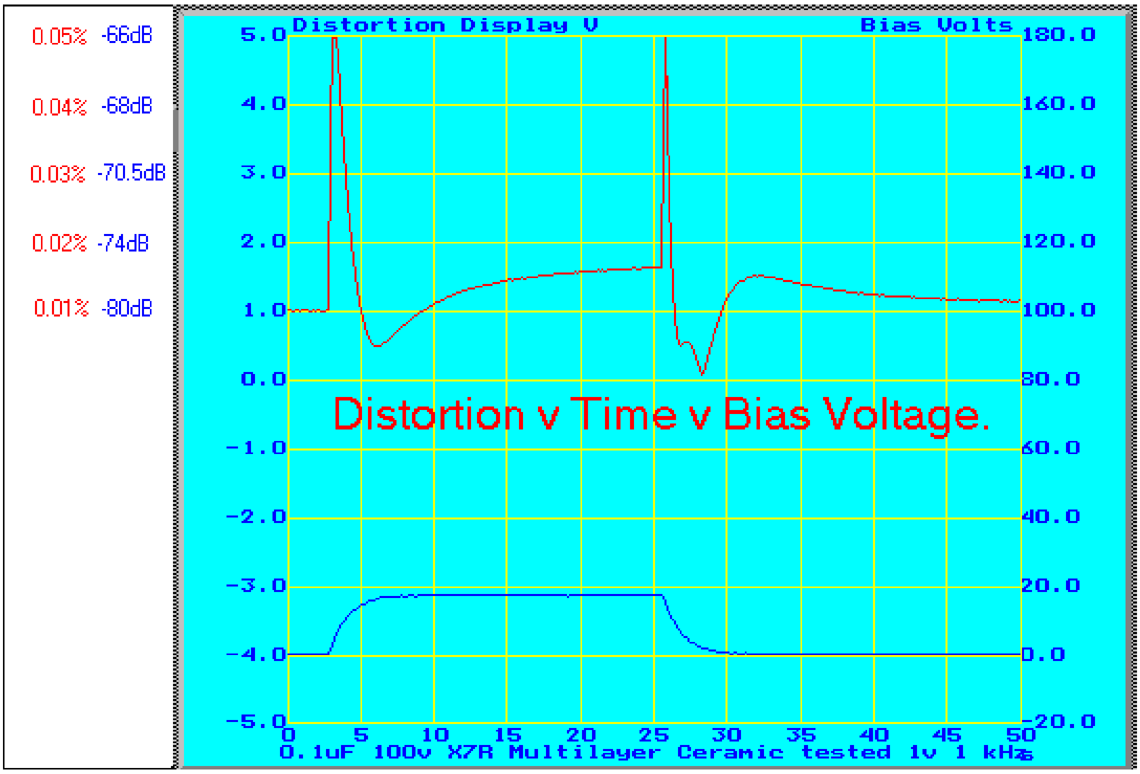

Figure 1) The top plot, left scale, of a 0.1µF X7R multilayer ceramic, shows second harmonic distortion both increasing and reducing prior to a prolonged settling period, in a capacitor having 1.76% dielectric absorption. This anomalous behaviour was hidden using the soundcard / software method. Bottom trace, right scale, shows DC bias voltage as measured across the capacitor.

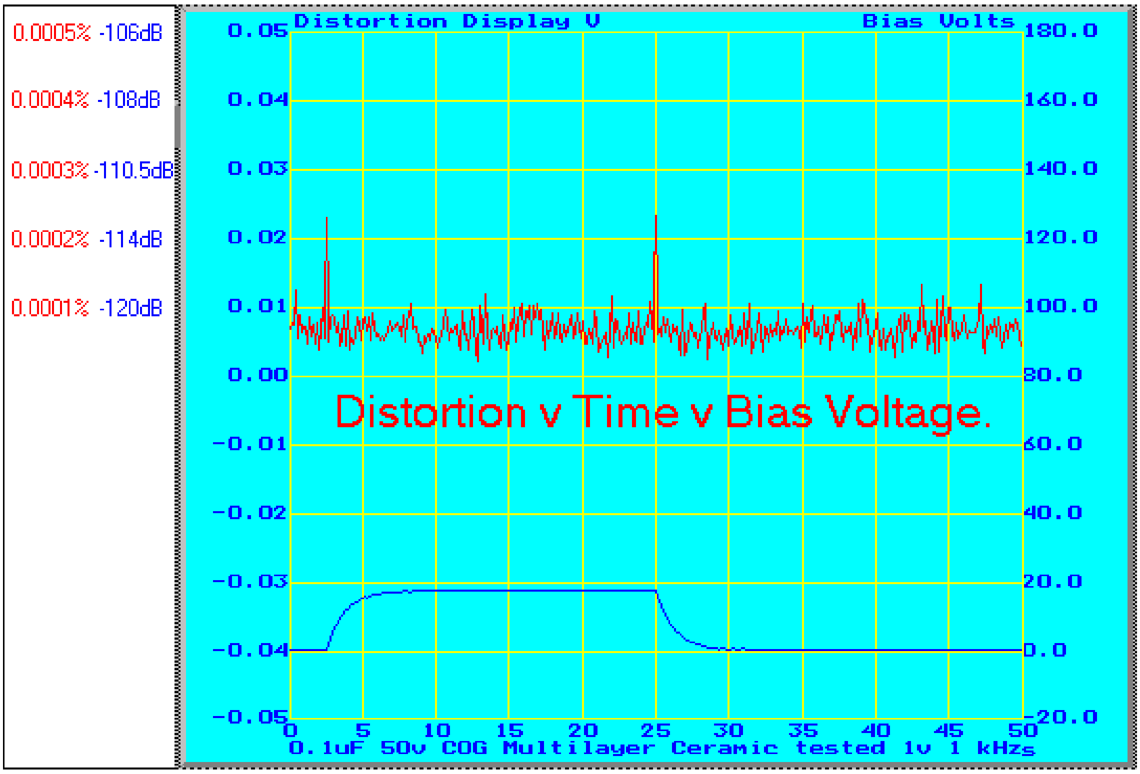

Figure 2) This distortion plot of a 0.1µF COG multilayer ceramic, scaled 100 times more sensitive than Figure 1, was made a few seconds later.

This 'normal' behaviour shows a near ideal capacitor having little dielectric absorption (0.06%). Two brief switching transients can be seen, caused when operating the bias charge discharge switch.

Distortion displays.
Two alternative display methods have been provided, a string of LED's showing 3dB level changes for the second and third harmonics over a -60dB to -120dB range together with two DMM displays which indicate 0.1dB level changes over the same range. The LED display reacts almost instantaneously to any change in distortion levels, significantly much quicker than the DMM displays which take some 1 or 2 seconds to settle. The soundcard/software method takes even longer to complete the averages needed to reduce noise. Both the LED and the DMM display methods can be used, as in my prototype, or to save cost, select the display method of your choice and omit the unwanted components.

Fig. 3

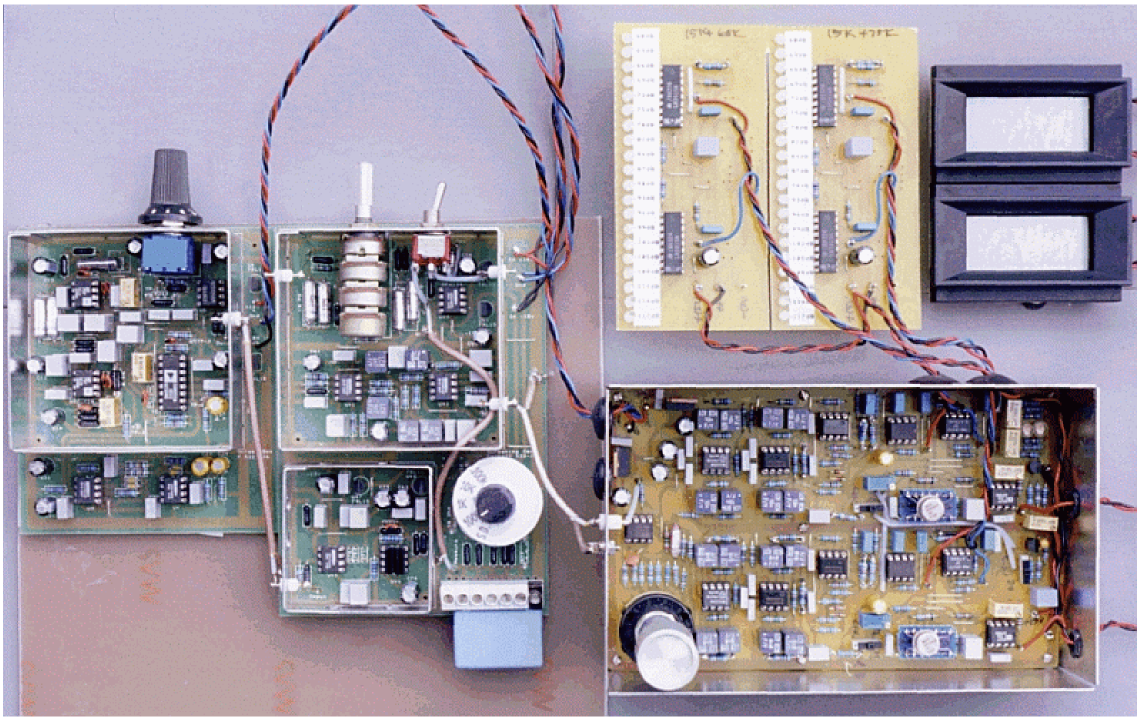

Figure 3) The full measurement set-up less screening lids, as used for Figures 1 & 2, shows this new real time hardware connected to my notch filter / preamp described in the capacitor sounds series.

The DC bias network simply fits in place of the calibration capacitor in the Figure.

The Design task.
Following a few simulations it became clear that third octave bandpass filters would not suffice and much better, narrower bandwidth, very deep sideband rejection, filters would be needed. Unlike the simple audio 'real time' analysers, we need the capability to measure very small second harmonic distortions in the presence of a much larger test fundamental. To provide similar performance to the soundcard method we should be able to measure to at least -120dB below a 1 volt test signal.

The twin T notch in my notch filter/preamp attenuates the test fundamental by some 65-70dB **REF.2**. This reduced fundamental together with harmonic components is then amplified by 40dB and bandwidth limited in the preamplifier. Our task then is to accurately measure distortion components having an amplitude of 100µV in the presence of a much larger 50 millivolt fundamental one octave away. We must use low noise, low distortion, bandpass filters having a relatively high 'Q' and sufficient gain to amplify distortion components to a measurable level. Requirements more easily met when using continuous time MFB style, RC active filters. **REF.3** Naturally it is essential the capacitors used in these filters are easily available in 1% tolerances and are low distortion types.

These requirements are most easily assured by choosing low cost extended foil and Polystyrene or extended foil and Polypropylene capacitors in the vertical mounting 'Tombstone' case, together with 1% metal film resistors.

The largest amplitude harmonic components which could be measured without overloading the soundcard software approach of my last series, were around -60dB, the smallest some -120dB below the test fundamental so I targeted to provide a similar 60dB dynamic range.

I decided to raise these -60dB distortion signals to some 6 volt RMS, the -120dB distortion harmonics would then be just 6 millivolts. From experience gained designing my RF millivoltmeter I knew these two extremes would be measurable with good accuracy and without range switching, provided the rectifier stage used well matched Schottky diodes and ±15 volt supplies. At these low frequencies this should be well within the capability of the inexpensive NE5532, TLE2072 or similar IC's, without sacrificing too much accuracy at the lowest harmonic distortion voltages. **REF.4**

Using an AD536 true RMS IC would allow this 60dB dynamic range to be displayed using a 200 millivolt DMM or a testmeter for a display having 0.1dB resolution. An alternative, much faster settling and less costly display using two of the National LM3915 log display LED drivers in series would also just suffice, driving a string of 20 LED's each LED then indicating a 3dB change in distortion.

Fig. 4

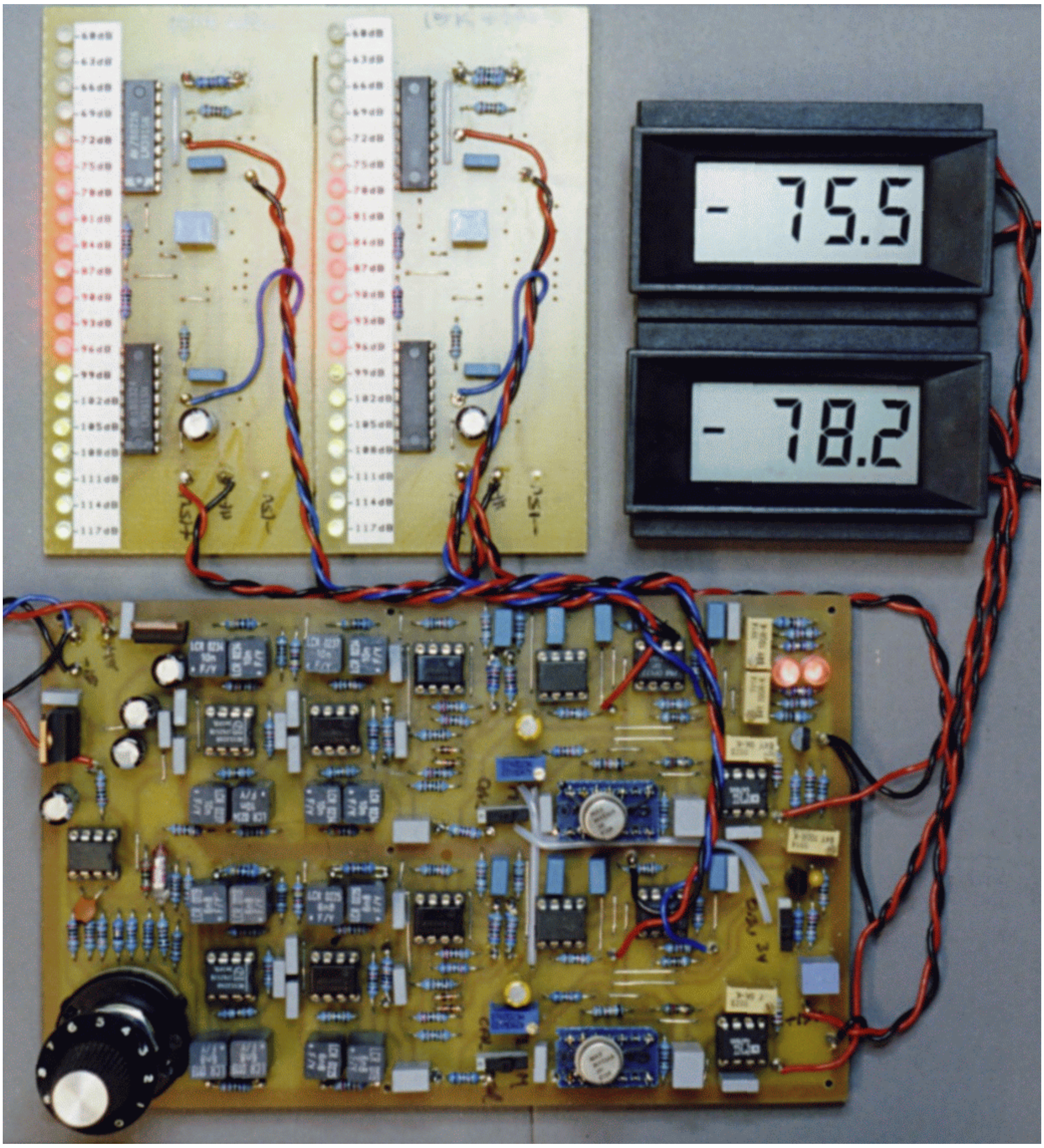

Figure 4) The real time hardware on initial tests, shows good agreement between the two LED tree displays and the two DMM displays.

The LED's respond instantly at each 3dB step in distortion, the DMM displays take time to settle but provide improved resolution.

Only the LED's reveal the anomalous responses of Figure 1.

Harmonic Bandpass Filters.
Following a number of simulations using Microcap6, I designed a multistage 2 kHz bandpass filter based on 10 nF 1% extended foil/Polystyrene capacitors, able to suppress both the 1 kHz fundamental and the 3 kHz harmonic by considerably more than 60dB, while providing some 35dB of gain at 2 kHz. This filter is low noise and has a reasonably flat topped response able to accommodate a few Hz variation in the 1 kHz fundamental test frequency, without needing variable frequency filtering.

Replacing the 10 nF capacitors with similar style 6n8F values, allowed an almost identical series of gains and 'Q's' to be used for the third harmonic 3 kHz filter, assuring matching performance for both harmonic distortion frequencies.

These bandpass filters were breadboarded. Careful testing confirmed the design was easily able to provide more than the needed rejection of the much larger fundamental test signal as well as rejecting the adjacent harmonic distortion signals. **Fig. 5**

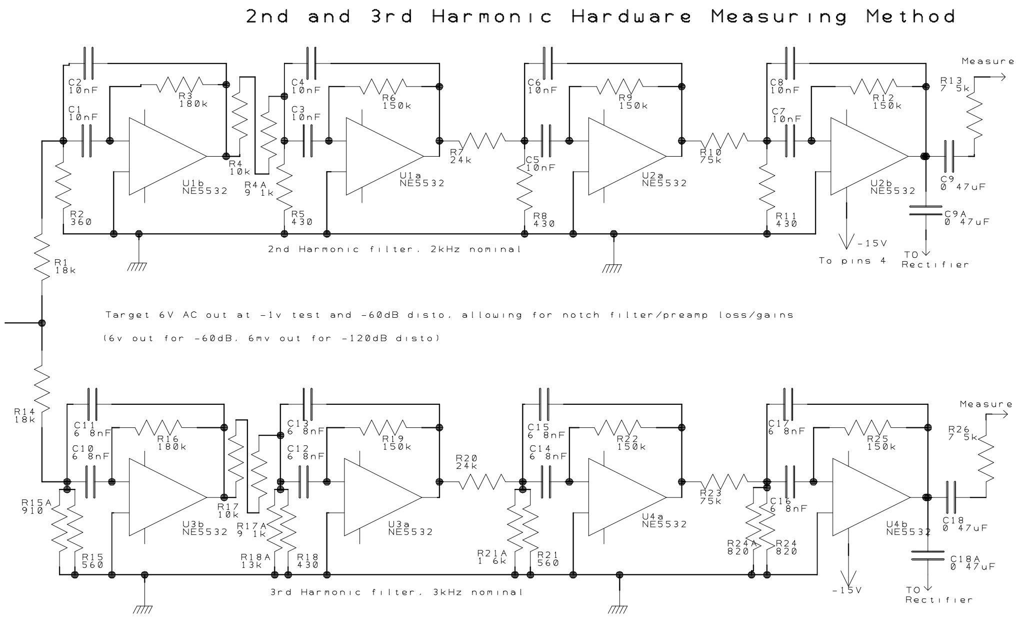

Figure 5) MFB second and third harmonic filters have low noise, low distortion and high rejection of unwanted signals, responding accurately to distortions down to -120dB, in the presence of the much larger fundamental test frequency.

To accommodate differing levels of capacitor test voltages, from 0.5 volt to 5 volt, I assembled a switched gain preamplifier to maintain consistent input signal levels into both the 2 kHz and 3 kHz bandpass filters, when switched to correspond with the test signal used.

LED Display Rectifiers.
To accommodate the peak voltages without incurring excessive diode and op-amp currents, three matched 2k2 resistors and matched pairs of BAT86 Schottky diodes are used with a low cost NE5532, TLE2072 or similar IC. The design being loosely based on the fullwave design used for my RF millivoltmeter published in the April 2000 issue which produces a balanced rectified output. A low cost INA126 in-amp is used to convert this balanced output to un-balanced and scale the rectified level to the 10 volt DC full scale output needed to represent -60dB distortions and drive the LM3915 LED driver to full range.**Fig. 6**

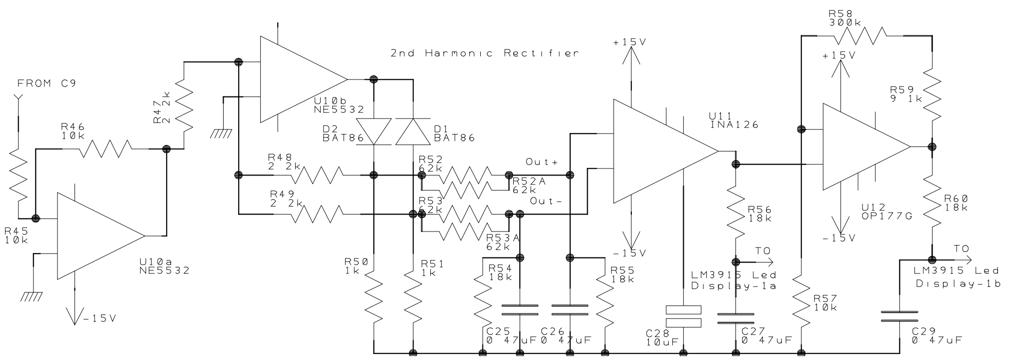

Figure 6) The full wave rectifier used to drive 10 volts DC to an LM3915 for -60dB full scale distortion, is driven from a low source impedance, unity gain inverting buffer.

The right most IC is the +30dB gain stage for the second LM3915 IC for -90dB to -120dB distortion components.
The Figs 1 & 2 top trace voltages were taken from C27, the output of U11.

This 0 to 10 volt DC output was used to record changes in distortion levels with time and DC bias voltage, for figures one and two, using two Coline M12SW oscilloscope probes feeding into my Pico ADC100. One probe displaying second harmonic distortion by monitoring the voltage across C27, the second probe was used to monitor the actual DC bias voltage across the test capacitor. To separate the DC bias from the AC test voltage, this probe was isolated via a 100 kΩ series resistor and decoupled using a 10 nF Polystyrene capacitor to ground.

A single LM3915 IC with 10 LEDs provides a 30dB display range, each LED indicating a 3dB change. To cover our 60dB range, two LM3915 IC's are chained in series driving 20 LEDs. Each LM3915 was set for full-scale with a 10 volt maximum input drive. The first LM3915 display was driven directly from C27, the output of the INA126, for the -60dB to -90dB range display.

Smaller voltages are amplified by 30dB to drive the second LM3915 for the -90dB to -120dB signals. Combined these two drivers provide our target 60dB dynamic range. The LEDs draw significant current so can introduce switching transients on the display board ground and supply rails. For accuracy it is essential this 30dB gain pre-amp has a very small, stable DC offset. An OP177G is mounted on the main printed board, rather than on the display sub boards with the LM3915s. To adjust for any residual INA126 offset also any rectifier unbalance, a small adjustable voltage, derived from two LED stabilisers, is provided.

As can be seen from the schematic in fact all distortion voltages are passed into the +30dB OP177G pre-amplifier, which clips around +14 volts output when overdriven. The two LM3915 Ics are connected so that the -90dB to -120dB display LEDs are turned off while this IC is overdriven, ensuring a contiguous display. By linking pins on the LM3915s, either a dot or bar display graph can be arranged.

DMM Display Rectifiers.
The AD536 IC is a true RMS to DC converter so provides it's own internal rectifying stages to produce two outputs. A DC voltage output at DIL package pin 8 which corresponds to the AC input voltage and a dB related current output from DIL pin 6. This dB output is temperature sensitive so must be compensated using positive coefficient temperature sensing resistors R38 / R42.

The DIL package version of the AD536 integrated circuit plugs directly into the printed board. The less expensive Maxim TO-100 package seen in the photograph, can be used but having different pin numbers and pin assignments, its leadwires must be pre-distorted before inserting to the board. While not essential, I found this alignment was facilitated by pre-forming the leads and soldering onto a low cost DIL header. This header then plugs into the PCB DIL socket. Note other numbered versions of the RMS DC converter chips should not be used, the AD536 version either in the DIL or TO-100 packages, is essential for this design. **Fig. 7**

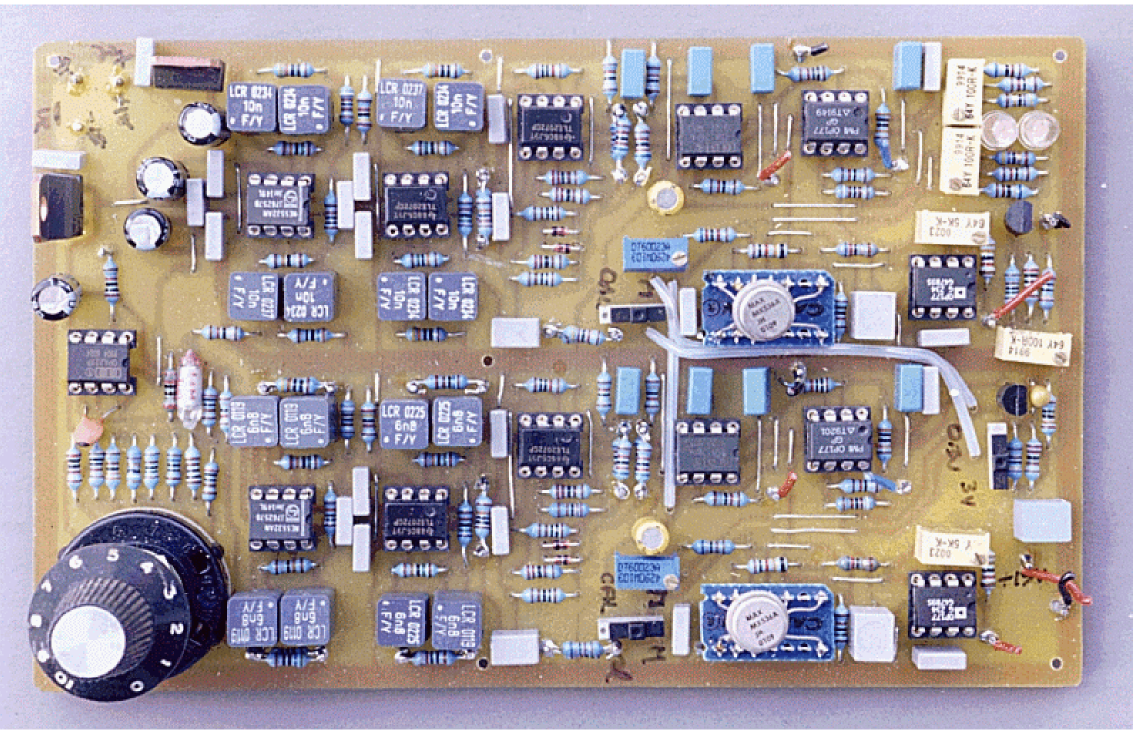

Figure 7) The completed prototype shows how the lower cost Maxim AD536 IC's leadwires can be pre-formed to fit the socket designed for the more expensive DIL package.

The three insulated wire links should be fitted last, after other components have been soldered.

Ideally the temperature sensing resistors R38 / R42 should exhibit a positive 3500 ppm characteristic, not easily sourced in UK. Farnell stocks a near alternative, having a positive 3000 ppm characteristic **REF.5**. This reduction in TC is partially compensated by using the minimum practical value for VR1 also VR4. Cermet pre-set resistors have a relatively high TC, so are used with much larger value low TC 1% metal film resistors. With the circuitry mounted in a case to shield from room drafts and allowing a 15 minute warm up, this compensation worked well producing stable, repeatable and consistent readings.

The dB related current output from pin 6 of the AD536, is then converted, amplified and scaled to 100 millivolt/dB, using another OP177G amplifier.

Unlike the RMS DC function which is factory pre-calibrated, this dB scaled output is not, so must be calibrated using known DC voltages. An LP2950CZ-3 IC provides a 1% precision and stable 3 volts to input a balancing current into AD536 pins 5 and 7. Adjusted using VR1 also VR4 to produce a 0 volt output from U6/U9 when this 3 volt calibration voltage is also input to pins 1 of the AD536.

To calibrate the desired 20dB scaling factor, an accurate 0.3 volt DC is needed. A 10:1 potential divider, R86/R87 provides this second calibration voltage from our stable 3 volt supply. With this 0.3 volt input to pins 1 of both AD536, VR2 also VR3 are adjusted to set the outputs from the OP177G ICs U6/U9, to exactly -2 volt, displaying a -20dB change in reading on a panel meter, set for 20 volt full-scale but with decimal point set for a 2 volt range.

Three PCB C/O switches are provided, two switch the AD536 inputs between calibrate/measure, the third selects between the 3 volt and 0.3 volt calibration voltages.

To offset the DMM readings to display the desired -60dB to -120dB range, a stable 6 volt supply is provided by U16, an LM317L adjustable voltage stabiliser, both DMM ‘low’ inputs are connected to the positive of this 6 volt supply. With the DMM set to read 20 volt full scale but with decimal points set as for 2v, each DMM then displays -60 to -120dB range. **Fig. 8**

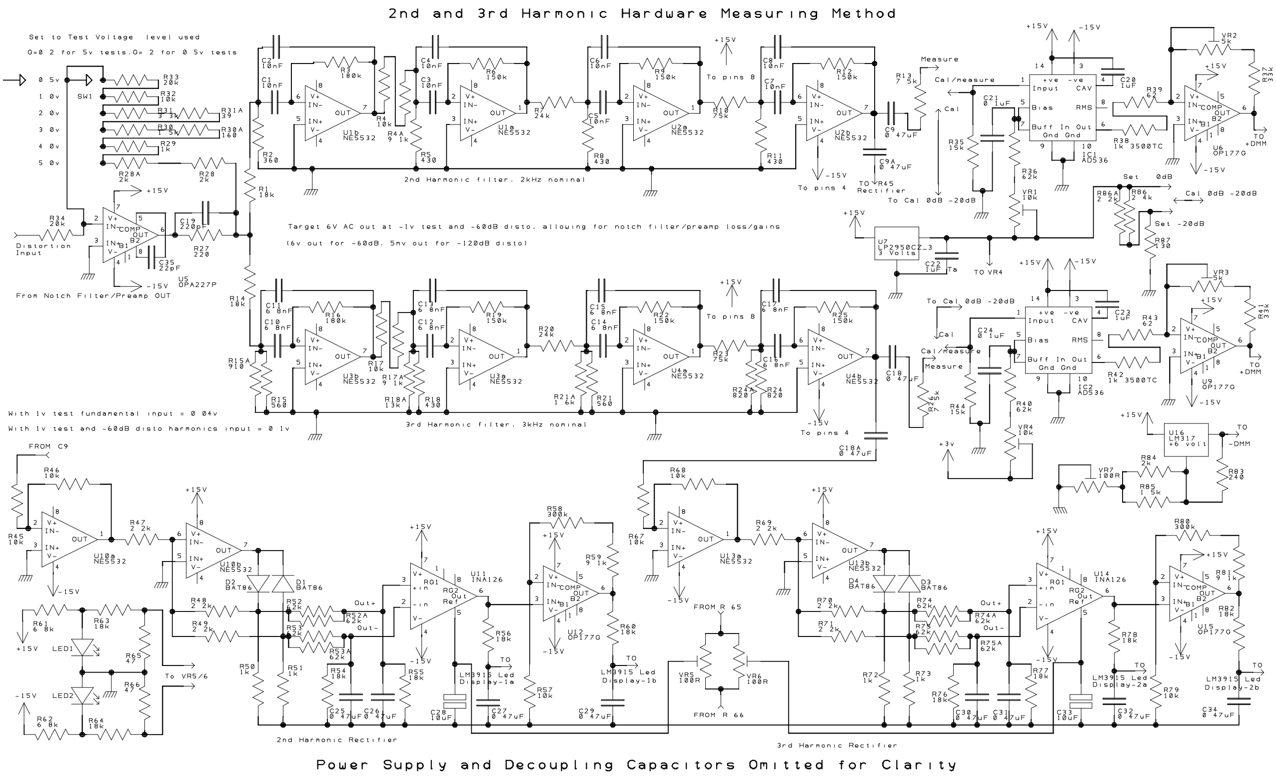

Figure 8) The schematic of the prototype assembly, less supply and decoupling capacitors omitted for clarity.
Six Rubycon 100 µF 25 volt YXF electrolytics with twenty three BC Components 0.1µF 63 volt type 470 metallised PET, decoupling capacitors and two 15v stabilisers were used.

Diode Matching.
Select two close pairs of BAT86 diodes by chaining together 5 to 10 diodes in series together with a 15 kΩ current limiting resistor, and apply 15v DC. Adjust voltage to pass 1 mA through the diode resistor chain, easily monitored by measuring the voltage drop across the 15 kΩ resistor. Allow to stabilise for a few minutes, then using a DMM measure and note the voltage drop across each diode.

Reduce current to 100 mA, allow to stabilise and re-measure voltages. Reduce current to 10 uA and repeat. Select two closely matched pairs, having particular reference to best matching at the lowest current. Insert and solder matched pairs in place.

Assembly. To simplify assembling this design, standard 1% metal film resistor values are used, two resistors either in series or parallel provide non-standard values. When two parallel resistors are needed, to save PCB space, mounting pads accepting a pair of Vero pins are provided.

A number of wire links are needed, all but three can be un-insulated. These three insulated linkwires must be installed last, after all other components have been soldered. All IC's were mounted in low profile Harwin turned pin sockets. **Fig. 9**

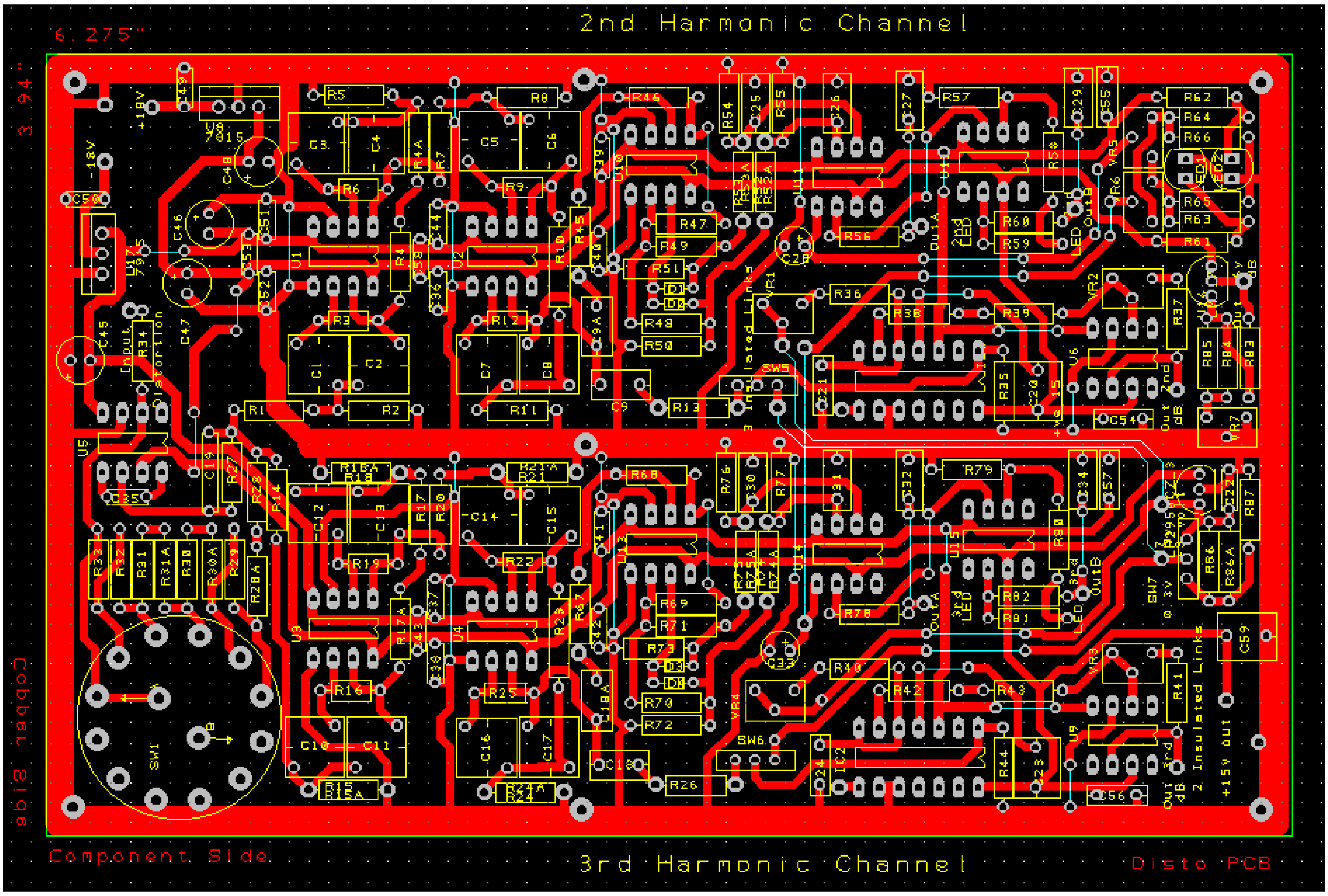

Figure 9) The main PCB used for the prototype assembly shown. This board houses the complete real time distortion measurement system but the forty display LED's and their LM3915 logarithmic display drivers were located on two small, low density, panel mounting PCB's.

Prototype Performance.
With no signal input, all displays are off scale, below -130dB. With a distortion free, 10 times normal, 1 kHz input all displays still show less than -120dB. With a distortion free, normal full scale input signal at 2 kHz the 3rd harmonic display reads -130dB, input with 3 kHz the 2nd harmonic display also reads -130dB, confirming more than adequate isolation between measuring the harmonics and the fundamental test frequency.

The 2 kHz bandpass filter measured -1dB at 1960 Hz and 2015 Hz, the corresponding 3 kHz filter frequencies being 2950 Hz and 3025 Hz. Both bandpass filters are able to accommodate several Hz frequency error in the 1 kHz fundamental test signal.

My next article explores in detail the affects test capacitor voltage coefficient and the much more significant dielectric absorption, have on capacitor sound distortions, by measuring distortions of test capacitors over time, with and without a DC bias voltage, using test capacitors carefully measured and pre-selected for voltco and DA, using a range of DC bias voltages.

References.

1) Capacitor Sounds. C.Bateman. Electronics World, July, September 02 - January 2003.

2) Capacitor Sounds part2 C.Bateman. Electronics World, September 2002.

3) Reference Data for Radio Engineers. H.Sams & Co. Inc. New York.

4) Measure AC Millivolts to 5MHz. C.Bateman. Electronics World, April 2000.

5) Temperature Sensing Resistor. Part 732-278. http://www.farnell.com.uk

Box **Calibration.**

Initial tests.

Insert IC's U1 through U5. Apply ±18 volts, set switch SW1 to 1 volt position. Allow some minutes warm up then check all IC's output offset voltages. Should be near 0 volt.

Apply 0.1 volt 2 kHz test signal to R43 input Vero Pin, and ensure filter output at junction R45/C9A does peak very close to 2 kHz. Reset frequency to 2 kHz and measure voltage at junction R45/C9A, it should approximate 6 volt AC. The exact value will vary according to the actual gain of your chosen IC's and can be corrected later. At this stage, check for correct function.

Repeat above using 3 kHz, measuring at R67/C18A junction.

LED display drivers.

Insert U10, U13. Insert both INA126 IC's and allow the assembly to fully warm up.

With no input signal, adjust VR5 to zero DC at the Vero Pin **OutA 2 kHz**. Repeat using VR6 for 3 kHz channel. If unable to attain zero, try replacing U10/U13 which should be low offset types. If this is not successful, diode matching should be improved.

Reapply 0.1 volt 2 kHz signal. Voltage at **OutA 2 kHz** should read 10 volt ±0.1 volt DC, if less add shunt resistor across R45 to compensate. Repeat using 3 kHz and **OutA 3 kHz** adjusting R67.

Install U12, U15. These must be very small offset types, OP177G worked well in my prototype. Reapply 0.1 volt 2 kHz. Voltage at **OutA 2 kHz** should be as above, voltage at **OutB 2 kHz** should be clipping around 13-14 volts. Reduce signal by 20dB to 0.01 volt. **OutA** should now read 1 volt, **OutB** still clipping. Reduce another 20dB to 0.001 volt. **OutA** should read 0.1 volt, **OutB** should read approx. 3.1 volt. Repeat using 3 kHz and **OutA and B** for 3 kHz

DMM dB displays.

Insert both AD536 also U6 U9 and allow to fully warm up. Set switches SW5 and 6 to measure. (Slider towards AD536). With no input signal, DC voltage at both Vero pins adjacent to pins 8 of both AD536 should be close to 0 volt.

Apply 0.1 volt input at 2 kHz to R43 with SW1 set for 1 volt, voltage at Vero pin at IC1 should be close to 3 volt. Input 0.1 volt at 3 kHz, voltage at Vero pin at IC2 should be close to 3 volt.

Set slider of SW7 away from U7. (sets Cal voltage to 3 volt) Check DC output from U7 is 3.0 volt ±1% measured at junction of R86/C22. Voltage at opposite end R86 should be ten times less and close to 0.3 volt. These two calibration DC voltages are used to set the accuracy of the dB measurements.

Set both switches SW5 and SW6 to Calibrate (Slider away from AD536) and set SW7 to 3 volt Cal (Slider away from U7)

Monitor **Out 2nd dB** voltage. Slowly adjust VR2 to attain 0 volt. Monitor **Out 3rd dB** voltage. Slowly adjust VR3 to attain 0v.

This adjustment is quite coarse, to minimise TC effects VR2/3 are the minimum usable values needed for adjustment. Unfortunately the current output from Pin 6 of AD536 is not tightly specified for value only for change of value. Consequently you may need to amend the values of R36 or R40 to compensate your particular IC.

The datasheet shows a much larger value variable used with a smaller value fixed resistor. In practise due to the very much larger TCR of Cermet pots compared to that of 1% metal film resistors, the datasheet values which should work with all IC's, could degrade the dB accuracy over temperature.

Set SW7 to 0.3 volt Cal (Slider towards U7), both outputs should now read -2 volt. If not adjust VR2 and VR3 the 5 kΩ presets which adjust the gains of U6 and U9. Both these gain and offset adjustments interact. If either of the above trimmers needed adjustment, reset SW7 to 3 volt position and repeat above VR2/VR3 0 volt settings. Repeat as needed.

Set -60dB offset reference.

Using VR7 adjust output from LM317, U16, to 6 volt as measured at the **Out +6 volt** dB Vero pin.

Connect positive lead of DMM to **Out 2nd dB**, negative lead to **Out +6 volt** dB and without changing above switches, DMM should now read -8 volt for -80dB. Reset SW7 to 3 volt Cal (Slider away from U7), DMM should now read -6 volt for -60dB. Repeat using **Out 3rd dB**, for above readings.

Set SW5 and SW6 to measure, (Slider towards AD536).

We now only need to compensate for gain errors in the bandpass filters.

Connect DMM negative to ground.

Apply 0.1 volt input to R43 at 2 kHz with SW1 set for 1 volt, voltage at **Out 2nd dB** voltage with respect to earth should now read 0 volt. (for -60dB). If low shunt R13 to compensate. If high shunt R35. Using 3 kHz signal repeat above measurement for IC2, adjusting R26/R44 if needed.

Reduce input signals by 20dB and repeat above. Voltage at **Out 2nd dB** voltage should be -2 volt (for -80dB). Reduce input signals by another 20dB and repeat above. voltage at **Out 2nd dB** voltage should be -4 volt (for -100dB).

Unit is ready for use with dB DMM displays.

LED display PCB.
Apply +15 volt power and allow to stabilise. Apply 10 volt DC input to **In 0 dB** Vero pin. Check that the -60dB LED connected to LM3915 pin 10 (LED22 also 42) is just illuminated. If needed add shunt resistors across the 15 kΩ so as to display with 10 volt drive. The prototype needed 68 kΩ shunt for one board, 75 kΩ for the second board.

Both displays should now illuminate their -60dB LED with 10 volt input to **In 0 dB** Vero pins.