

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

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

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

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

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

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

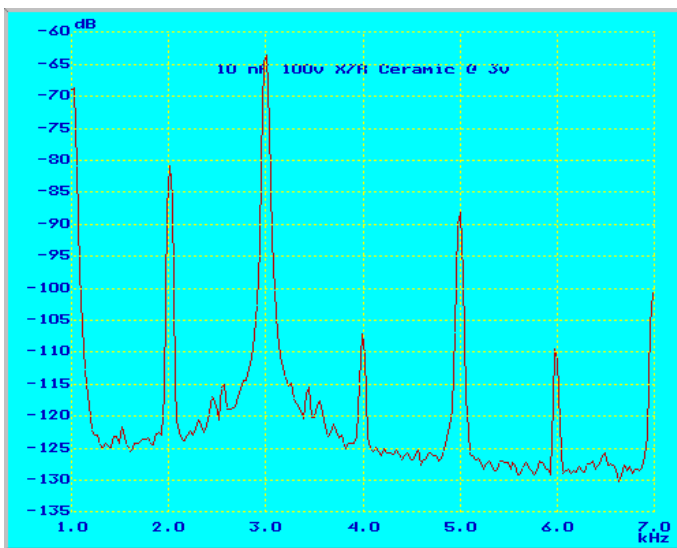
As a result I have regularly received requests for advice about capacitors from readers, who have read the many, often conflicting, subjectivist views, about capacitor types.

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

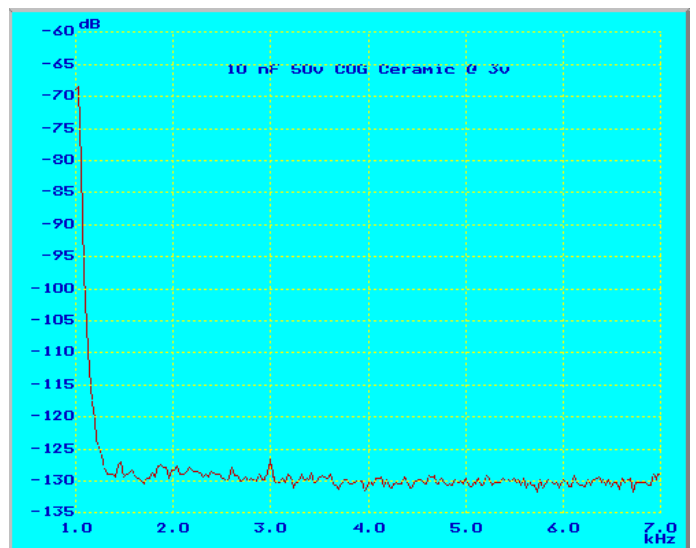
As a long term capacitor designer and measurement engineer, I believe that any truly audible differences must be both understandable and measurable. Understanding should be in terms of the capacitor constructions. Measurements may however require a change in traditional measuring techniques.

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

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



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



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

### Measurements.

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

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

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

### Initial investigations.

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

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

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

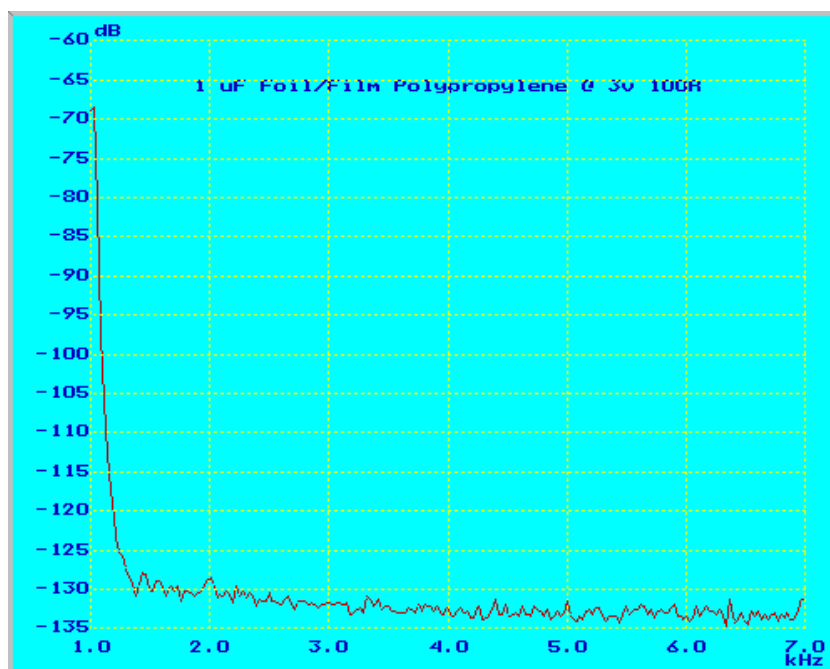
Since few readers would have access to a Spectrum Analyser, performance measurements would be made using more popular equipment. A Pico ADC, such as the ADC-100, once an Electronics World reader's special offer, or a computer soundcard with FFT software, would be much more easily available. Using these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

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

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

### A much better generator.

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



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

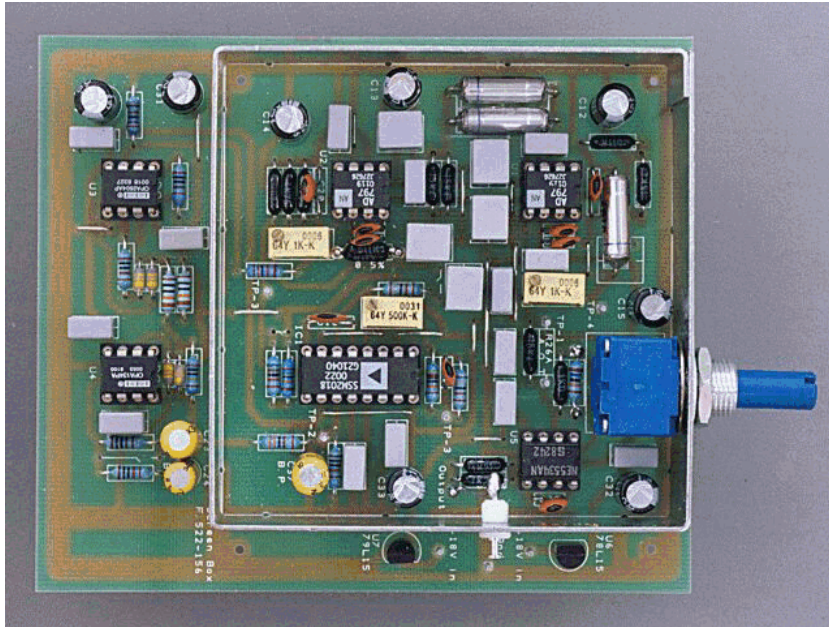
This excellent result depends as much on my output amplifier as on the test oscillator, because even allowing for the 100  $\Omega$  current limiting source resistor, this 100  $\Omega$  / 1  $\mu$ F represents a most difficult load for any low distortion output amplifier.

## Equipment.

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

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

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



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

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

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

## Initial Researches.

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

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

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

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

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

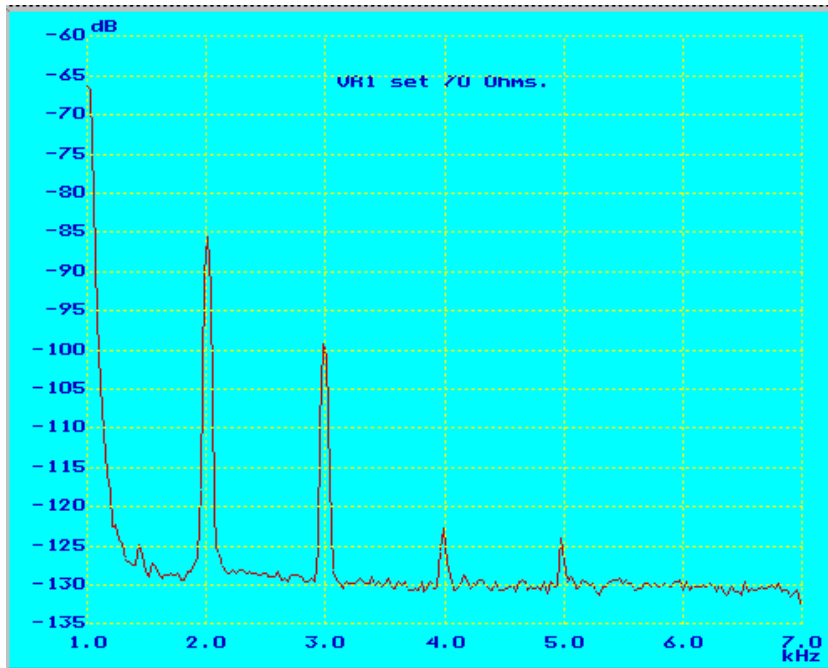
Many oscillators use a thermistor to control oscillator amplitude. Distortion is then mostly third harmonic, which has been blamed on the thermistor. For my needs, at all costs third harmonic had to be minimised. I needed a different amplitude control.

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

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

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

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



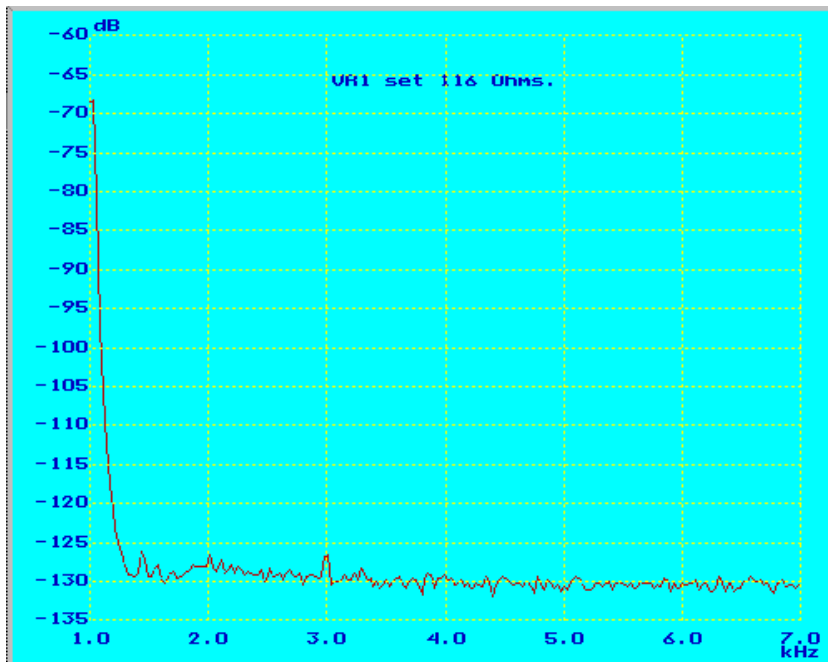
**Fig 5)** Oscillator output with VR1 set to 70  $\Omega$ , well below the optimum value, when using NE5534A IC's. Distortion at 3 volts output measured 57 PPM or 0.0057%.

### Accident or design ?

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

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

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



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

### Why ?

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

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

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

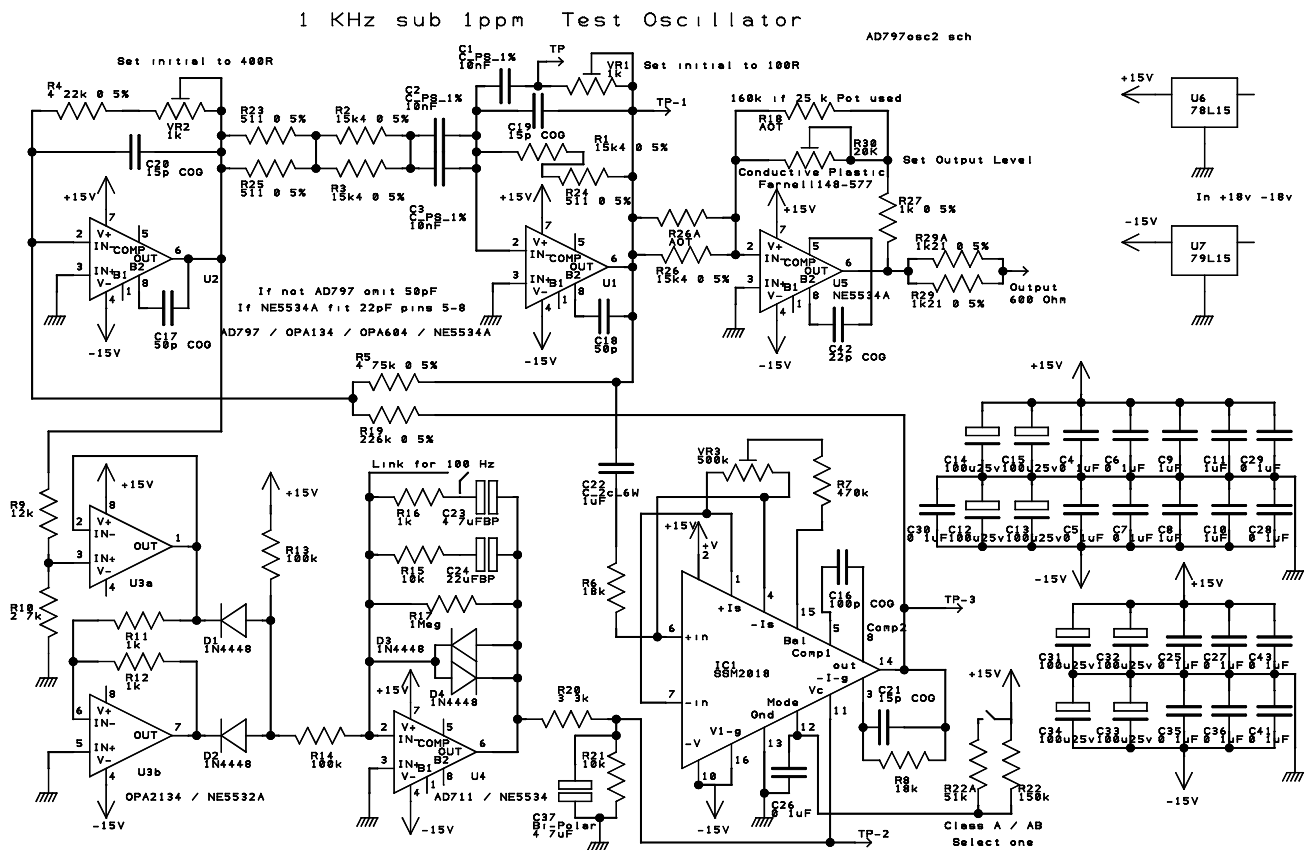
I re-examined the datasheets for the NE5534 and several other IC's I had considered using, but did not find the same recommendation. This added resistor however was found to work well in circuit with my NE5534A and all other IC's I tried in the circuit, virtually eliminating all third harmonic distortions.

**Proving the design.**

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

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

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



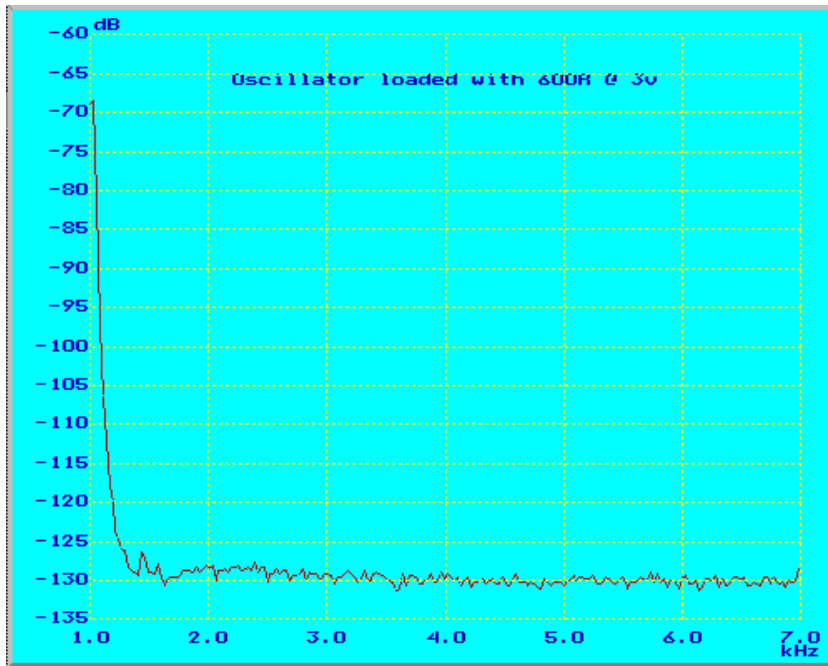
**Level Potentiometer.**

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

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

With a 600 Ω load, distortion was now much lower than I could measure using either the ADC-100, my computer soundcard or Hewlett Packard 331A distortion analyser. Equipped with a passive Twin-Tee pre-notch filter and the above instruments I re-

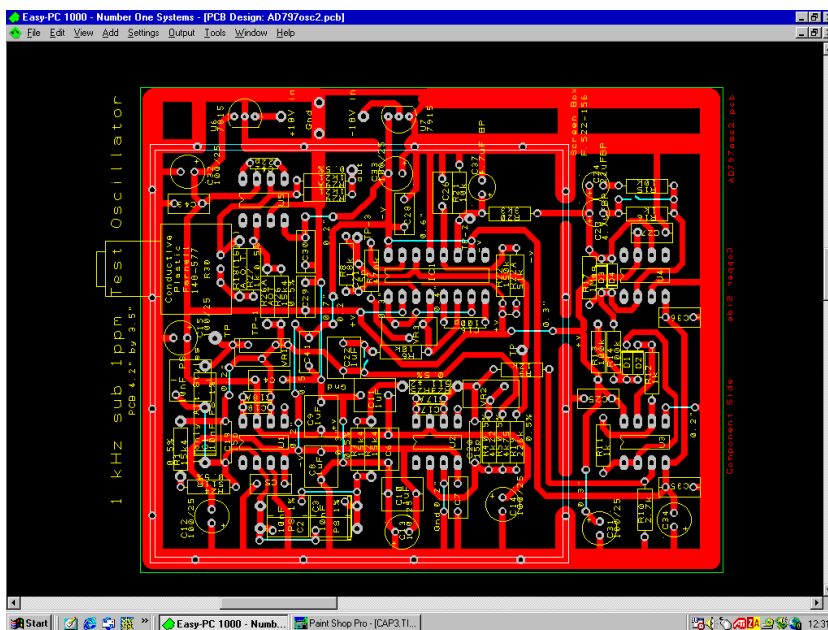
measured the oscillator output. Making allowance for the notch filter's reduction of the second harmonic, I estimated that at 5 volts output, distortion was approximately 1-2 PPM. see **Fig.8**



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

### Final design.

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



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

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

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

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

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

### Box Alternate IC's/Components.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

End of **Box**.

### Final testing.

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

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

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

### Measuring capacitor distortions.

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

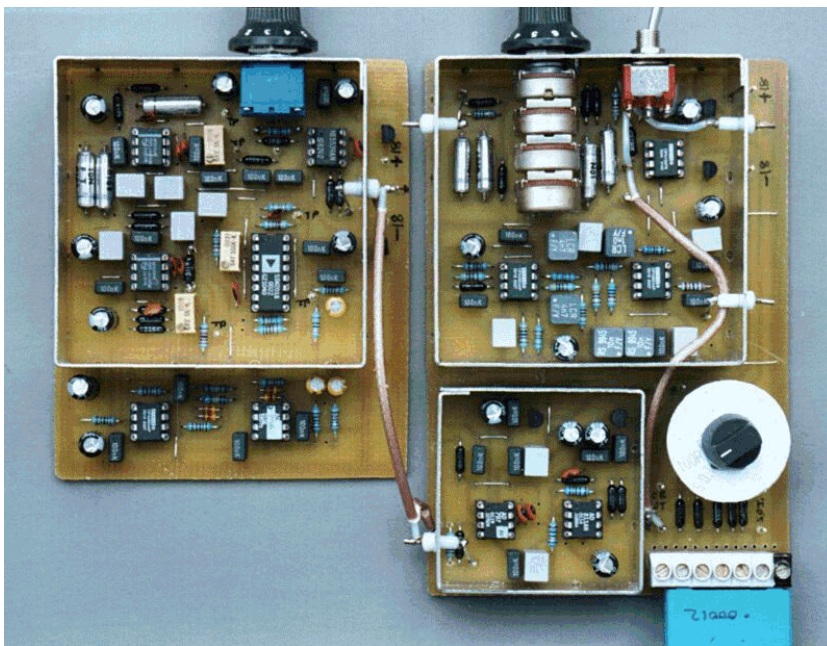
It's nominal input impedance is 10 k $\Omega$ . A high impedance unity gain, low noise pre-amp can be switched into circuit, should this passive notch loading be excessive.

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

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

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

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



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

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

My 1 kHz pre-notch filter/pre-amplifier (top box) and output buffer amplifier (lower box) can be seen in the photograph. Both will be fully described in my next article.

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



### Box Calibration.

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

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

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

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

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

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

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

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

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

Test or select U5.

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

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

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

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

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

**End**

### References.

- |  |   |
|--|---|
| 1) CLT1 Component Linearity Test Equipment data sheet.                     | RE Instruments AS. Copenhagen.                              |
| 2) Trial by three tones. Ivor Brown.                                       | Electronics World February 1991. p.131.                     |
| 3) Wien-bridge oscillator with low harmonic distortion. J.L. Linsley Hood. | Electronics World May 1981 p.51.                            |
| 4) Harmonic testing pinpoints passive component flaws.                     | V.Peterson & Per-Olof Harris.<br>Electronics July 11, 1966. |
| 5) If the Cap Fits. W.Jung and J.Curl.                                     | Hi Fi News & Record Review. April 1986                      |

**CLT1 Component Tester.**

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

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

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

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

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

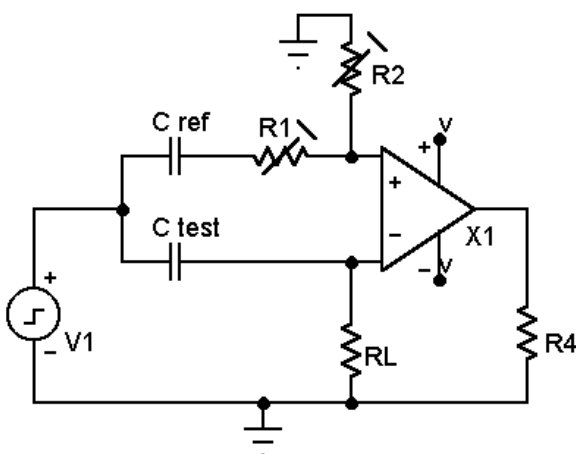
Extremely tight coupling between the test capacitor and the linearity tester is implicit in the CLT1 equipment design. From my early work measuring capacitors, I found it necessary to loosen this coupling in order to clearly reveal anomalies found in many modern capacitors. By trial and error measuring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

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

**Jung-Curl test.**

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

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



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

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

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

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