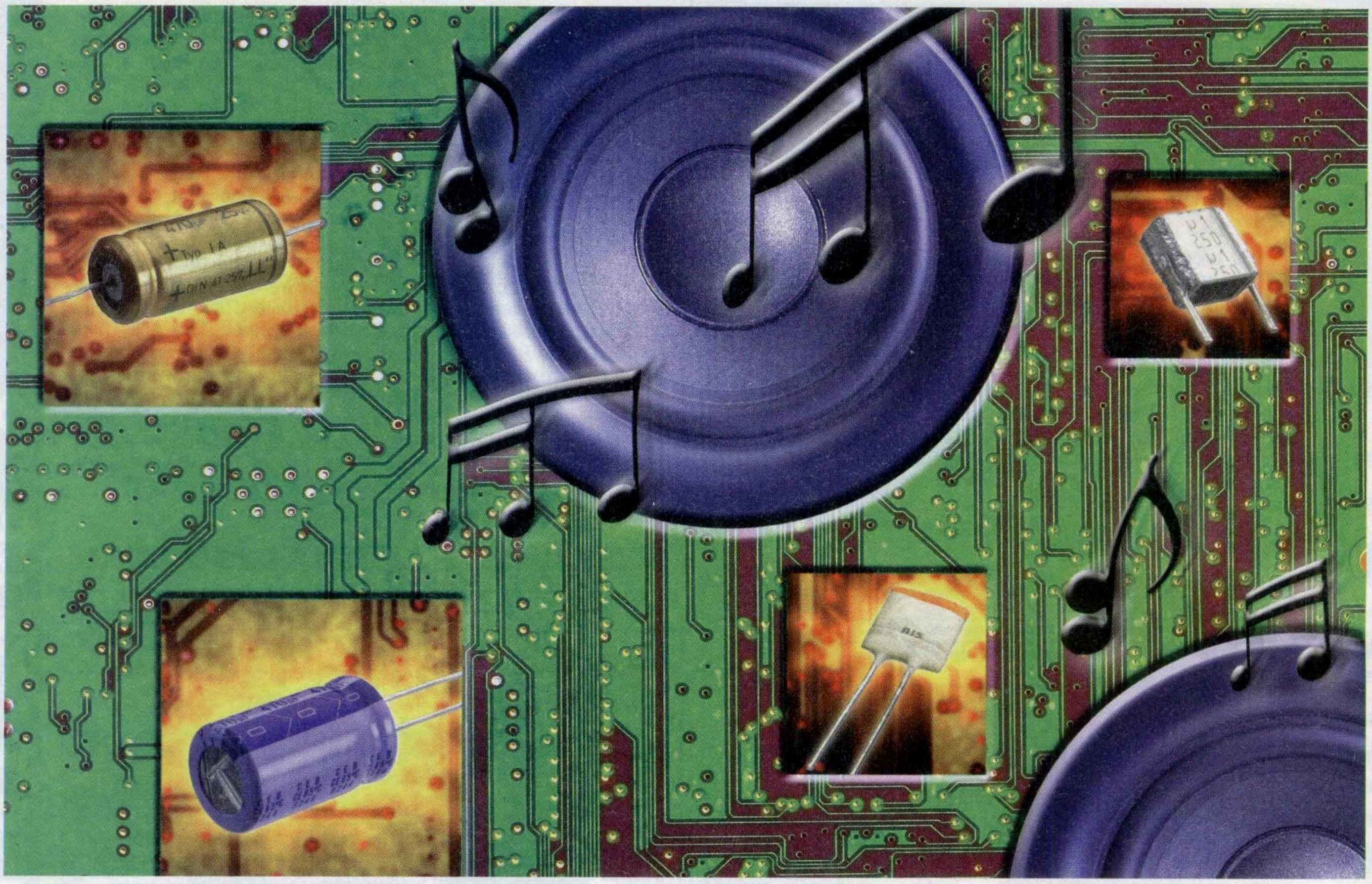


Capacitor sound?

As a first step in breaking new ground in relation to how capacitors can contribute to the 'sound' of a hi-fi amplifier, Cyril Bateman has designed a spot-frequency oscillator with sub-ppm distortion.

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

Most properly designed power amplifiers measure less than 0.01% distortion when sinewave tested at 1kHz. This distortion percentage equates to 100 parts per million. Such small distortions are believed to be inaudible, yet people often claim to hear distortions from these amplifiers when listening to music.

Many authors claim to have identified differences in sound between different capacitor types. These differences have been ascertained not by measurements though, but by listening tests. This has led to a retrofit upgrade 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 writers on this topic even decry measurements, presumably in case such measurements disprove their subjectivist claims.

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 pages have also echoed to disputes between amplifier designers and music enthusiasts regarding capacitor sound distortion. These disputes culminated 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 measuring techniques.

In order to develop suitable test methods, I have measured large numbers of capacitors of many types. From these measurements, I have determined the distortion differences between capacitor constructions.

What I did not expect to to find – and I find this rather disturbing – is that within a small batch of capacitors, some exhibit abnormally higher distortions. These anomalous capacitors typically exhibit some ten times greater distortion than others taped on the same card strip.

In this, the first of a set of articles, I begin to honour my commitment to quantify capacitor distortion.

What the tests involved

Using a scheme involving a test signal at 1kHz, it is possible to differentiate between capacitor types and between good or bad capacitors within a type, **Figs 1, 2**.

In all performance plots, the 1kHz fundamental has been attenuated some 65dB 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 perform measurements using sophisticated equipment, I decided to develop a low-cost method that could be easily replicated by any interested reader. In doing so, I hope to improve understanding of capacitors and reduce the number of capacitor disputes in the letters pages.

Initial investigations

Spectrum analysers capable of measuring small distortion components are prohibitively expensive for most people. I wanted to make sure that performance measurements could be made using readily available test gear like the Picoscope ADC-100 A-to-D converter or a computer sound card with FFT software.

I started by carrying out some initial capacitor intermodulation tests^2. Experiments involving simple harmonic distortion testing revealed easily interpreted differences when testing less good capacitors. Testing good capacitors however confirmed that my existing signal generators introduced far too much distortion.

A much better signal generator...

Having reviewed past low-distortion oscillator designs, I bread-boarded the more promising ones. Using these I tested a number of capacitors but with only partial success.

From these results it became clear that I needed an extremely low distortion 1kHz sinewave. I had to be able to drive at least 3 volts into a 100Ω/1μF near perfect, low distortion capacitive load, and do so without this load distorting my test signal, **Fig. 3**.

To test this near perfect capacitor, measured distortions of my complete equipment needed to be less than 1ppm, or 0.0001%. This is approaching the order of oscillator distortion produced by expensive measuring instruments such as those made by Audio Precision.

So began the design of a suitable test oscillator with a price that would be within the reach of most of you. The design of this oscillator forms the subject of this first article, **Fig. 4**.

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^3. Most Wien bridge oscillators use a single amplifying stage. John suggested a method spreading the capacitor/resistor elements over two stages. This reduced the drive into his first amplifier and thus reduced its distortion.

I ran some simulations that 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 second amplifier having double the voltage output of his first.

I decided to double the capacitance and halve the resistance of the series combination. This would provide equal output

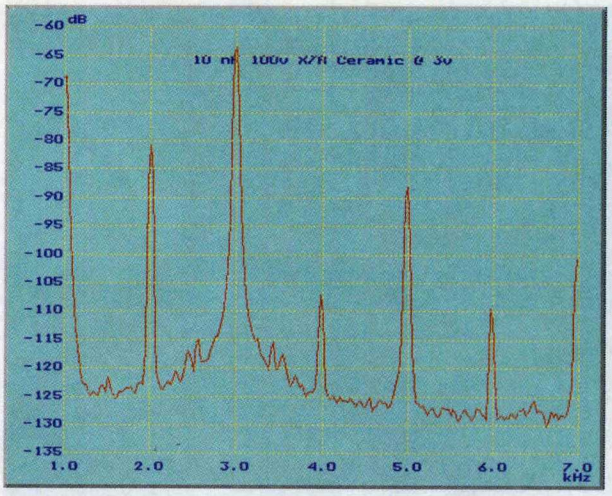


Fig. 1. Some capacitors distort even a pure 1kHz sinewave test signal. This 10nF X7R ceramic was made by a CECC approved, European manufacturer. It was tested at 1kHz and 3 volts, in series with a 10kΩ current limiting resistor. Measurable distortion exists at all voltages down to 0.5 volts – my lowest test voltage.

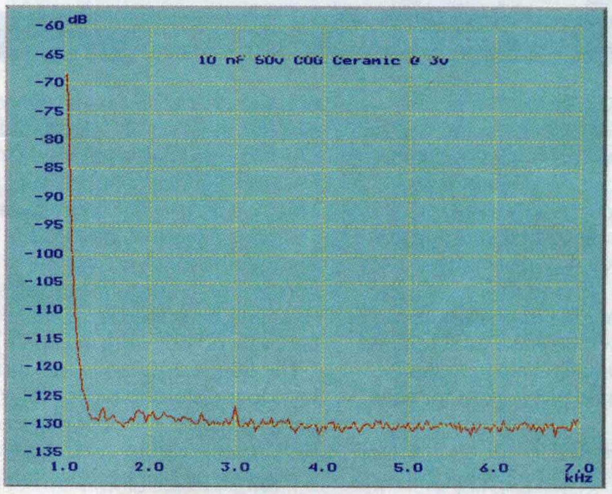


Fig. 2. Some capacitors distort very little. This 10nF COG ceramic was made by the same maker as Fig. 1 and co-purchased from the same distributor. Both were tested at 1kHz under identical conditions, within a few seconds of each other.

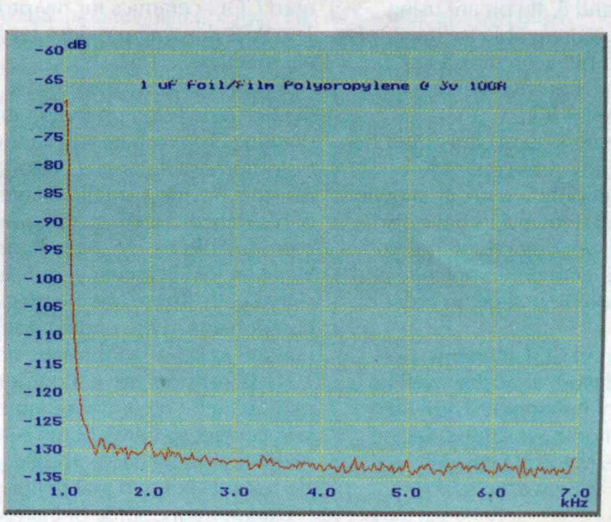


Fig. 3. Plot of a near perfect 1μF foil/film polypropylene capacitor, tested at 3V in series with a 100Ω current limiting resistor. It clearly shows my target test specification has been attained. This excellent result depends as much on my output amplifier design as on the oscillator. Combined distortions of my test system and 1μF load are buried in the noise floor at –130dB.

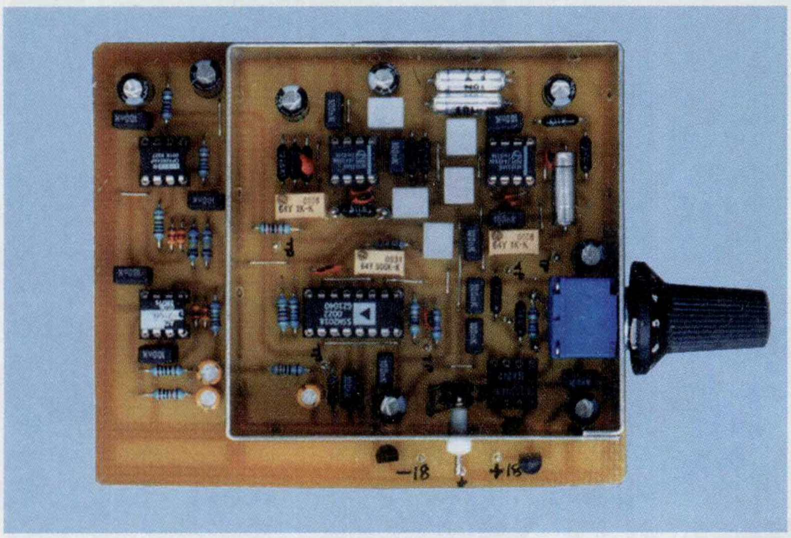


Fig. 4. Final design for the 1kHz test oscillator, with its screening lid removed. Fitted with its lid but no other shielding and with normal fluorescent room lighting, it was used on my bench within 1 metre of the test PC for all measurements.

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.

I needed 200μV drive into the negative inputs of both amplifiers to produce a 3 volts output, and 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, third harmonic had to be minimised as much as possible. 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 1kHz is produced with a 3 volt input and 0dB gain. For 0dB gain, a control voltage a few millivolts above 0V is needed.

Provided that 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 circuit's output.

I bread-boarded the circuit using a manual control voltage and with NE5534A ICs for the oscillator. Encouraged by the

Alternative ICs and components

While I used ultra-low distortion, but expensive, AD797 ICs for U_1 and U_2 when building my final 1kHz oscillator, almost all its circuit development was done using low-cost NE5534A ICs. I found some 6dB difference in distortion between these two IC types in my oscillator.

I have tried other ICs for the oscillator, including the low-distortion OPA134 and OPA604. To facilitate evaluating ICs I used Harwin turned pin sockets for each position.

When using the AD797 for U_1 and U_2, it is preferable to fit a 50pF capacitor between pins 6 and 8. If you are using NE5534A ICs, it is preferable to fit a 22pF capacitor instead between pins 5 and 8. Neither capacitor is needed when using OPA134 or OPA604 ICs.

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 and 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. My PCB provides mountings for a variety of suitable capacitors.

The value of VR_1 needed to minimise distortion will vary depending on which type IC and tuning capacitors are used. I found that only the NE5534A IC provided low distortion when used for the output buffer, U_5. For this low/unity gain position, the 22pF capacitor is essential. Also for its gain control, I found only one satisfactory variable resistor. That was a Bourns 91 series conductive plastic, obtained as 148-557 from Farnell.

Similar types may be OK too, but I have not tried them. Don't use either cermet or wirewound controls for this position though. I have tried several and they certainly do not work acceptably.

The 50pF/22pF capacitors must be low-loss, low-distortion types. Polystyrene parts are preferable, but disc ceramics – COG only – can be used. Similarly for the remaining picofarad capacitors used. I used COG ceramics for my prototypes. 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 in the signal path. These are the black components in the photograph. These are marked as 0.5% on the schematic.

These resistors use plated steel end caps, which I prefer for reliable long term end contact stability. Many subjectivists claim non-magnetic end caps are better. I do not subscribe to that belief.

Undoubtedly, some of the oscillator output distortion is generated inside the three multi-turn Cermet trimmers. For two positions, these trimmers are essential. However the printed board does provide mounting pads for a fixed resistor, which could be substituted for VR_1, once its value has been determined during calibration. So far I have retained use of the trimmer on my versions.

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 are 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 0.1μF value, black in the photograph, I used Evox-Rifa SMR, metallised polyphenylene-sulphide film. I consider this film produces the best, small, low cost, universal capacitor. They were obtained from RS, but unfortunately the company has since stopped supplying them.

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

For the larger capacitors, I used BC Components' 1μF 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 laboratory supply, set to output ±18 volts.

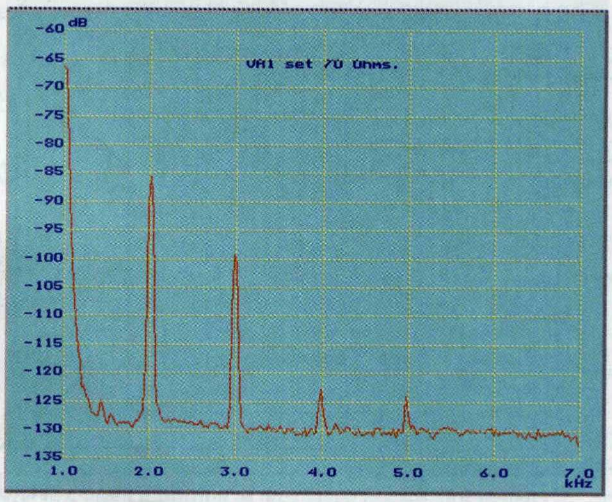


Fig. 5. Oscillator output with VR1 set to 70Ω – well below the optimum value when using NE5534A ICs. Distortion at 3 volts output measured 57ppm or 0.0057%.

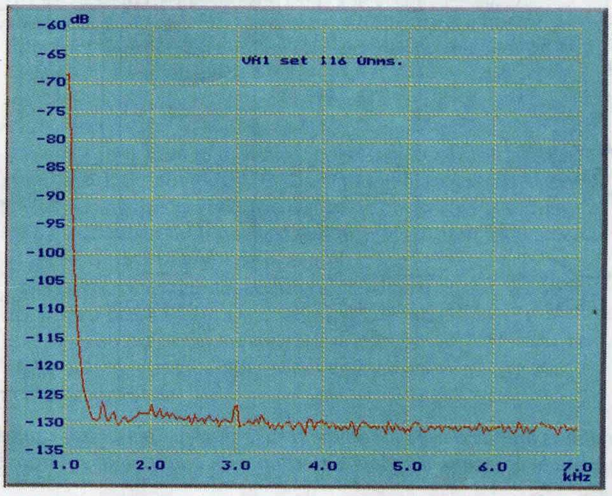


Fig. 6. Increasing VR1 to 116Ω, still slightly below optimum, distortion is now mostly third harmonic and at –126dB is well below 1ppm.

results, I designed a simple rectifier and DC control amplifier and tested the composite assembly.

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

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 device. At some time during my many simulation runs, I had mistyped the entry of this ESR estimate for the shunt feedback capacitor. Instead of 10.0Ω I had input 100Ω. Could this explain my differing results?

Going back to my breadboard, I inserted a 1kΩ ten-turn variable resistor, set to its minimum value. I adjusted it to replicate my typographical error while measuring the circuit. To my amazement, as I increased the resistance value above 100Ω, the distortions rapidly disappeared. Why?

Certain that I had made a mistake, I repeated this adjustment and measurement many times. The results were consistent. Even better, with the variable resistor left above this value, the oscillator could be powered down and restarted, and each time it settled to the new lower distortion output, **Fig. 6**.

I decided to re-read the data sheet for the AD797 amplifier, which I hoped to use in my final implementations. This IC is claimed to have the lowest distortion figures of all the popular audio op-amps, but costing some £7, it is expensive.

After re-reading more carefully, I spotted a paragraph I had previously ignored. This dealt with using a small feedback capacitor 'C_L' in parallel with the feedback resistor 'R_2'. "When R_2 is greater than 100Ω and C_L is greater than 33pF, a 100Ω resistor should be placed in series with C_L".

As one would with many Wien bridge and Sallen and Key filter designs, I was using a much higher feedback resistor of 15911Ω in parallel with a very high feedback capacitor of 10nF. I re-examined the data sheets for the NE5534 and several other ICs I had considered using, but did not find the same recommendation. I found that this added resistance worked well in the circuit with my NE5534A. It also worked well with all other ICs I tried in the circuit, virtually eliminating all third harmonic distortions.

Proving the design

Accidents easily happen when bread-boarding 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 by 75mm PCB solder mount screening can with removable lid. It's available from Farnell. This size could accommodate just the oscillator components. The next size can was much too large. Using the smaller option required leaving my amplitude control components unscreened.

The 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 600Ω load, **Fig. 7**.

Choosing a gain-control pot

Choice of the gain control potentiometer was crucial. I evaluated four types, wirewound, cermet and two different conductive plastic types.

Wirewound alternatives created intolerable distortion; Cermets were better, but not adequate. The Bournes 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, Fig. 4.

With a 600Ω load, distortion was now much lower than I could measure using either the ADC-100, my computer sound card or a 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 1-2ppm, **Fig. 8**.

Final design

Having attained what seemed a satisfactory distortion figure, 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 'adjust-on-test' resistors and links to allow the SSM2018P to be set to either class A or AB operation, **Fig. 9**.

While class AB is the recommended mode and my PCB's default mode, simply linking the free end of R_{22A} to R_{22} 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 50pF capacitor between its pins 6 and 8. For minimum distortion using this amplifier, the 50pF capacitor should be fitted.

If you are using the NE5534A, this 50pF capacitor must not be used. Instead, a 22pF capacitor can be connected

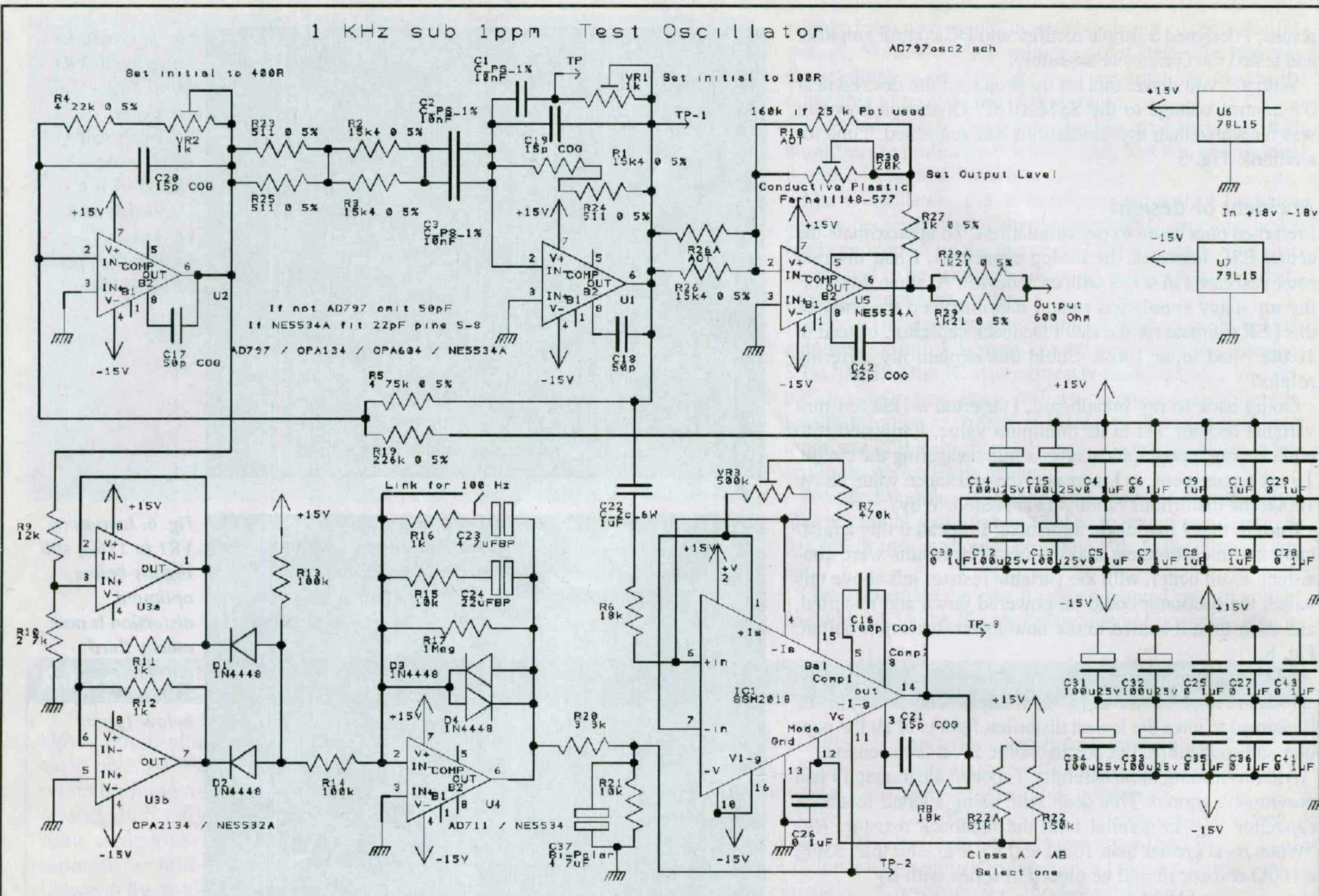


Fig. 7. Full schematic as built and used for all the results shown. This circuit can be used as a stand-alone low distortion 600Ω output test generator. Being capable of maintaining low distortion with output voltages from below 0.2 volts to above 4 volts, it can be used for many test purposes.

Other measuring methods

Early carbon-film resistors were trimmed to their final 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 component failures 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 subjected to a very pure sinewave test signal[4]. Non-linearities were believed to result from badly ground resistor spirals, poor electrical contacts and the use of non-linear materials.

The engineers' original non-linearity detector design produced low-distortion test signals at 10 and 50kHz. Third harmonic distortion generated by the component under test was passed through bandpass filters for measurement. Subsequently the 50kHz test frequency was dropped and a commercial instrument – the CLT1 component linearity tester – was produced by Radiometer of Denmark[1].

To accommodate the range of component impedances and test voltages needed, a low distortion output transformer was used. Having seven adjustable tappings, it was used to tightly couple the instrument to the component under test. Component impedances from 3Ω to 300kΩ 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 quick and easy; however the extremely low impedance of many capacitors at 10kHz requires using extremely small test voltages. Bad and oxidised connections can be discovered. From my work though, 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 voltages. To avoid overstressing the test capacitor or the equipment, 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, Fig. 1.

Using trial and error when measuring known good and bad capacitors at 1kHz, I found that 100Ω in series with a 1μF capacitor provided the best compromise between measuring current and capacitor voltage. This resistance value needs to be adjusted according to the capacitor's impedance at the test frequency used.

between pins 5 and 8. The revised circuit board provides for both options.

Note that it is crucial to use only close tolerance and low distortion capacitors for both these positions. Preferred types are 1% foil/polystyrene or COG disc ceramic.

Final testing

To permit accurate measurements of this oscillator's distortion and facilitate calibration using either the ADC-100 or a sound card, a pre-notch filter is essential. The ADC-100 in its spectrum-analyser mode provides selectable peak input levels up to 20 volts. Its 0dB reference is fixed nominally at 1 volt.

Having 12-bit resolution, the ADC-100's dynamic range is limited to just 70dB. Most sound card a-to-d converter inputs are limited to 2 volts peak or less, but having 16 or more bits, they can provide more dynamic range.

To measure down to –130dB below 3 volts with either of the above, the fundamental should first be reduced by some 60 to 65dB. To minimise the influence of ambient interfering noise and attain a more easily measured signal, this reduced fundamental and the harmonic voltages must be pre-amplified by some 40dB.

Using a 3 volts test signal, this amplified fundamental and distortions results in a measurement voltage of around 0.3 volts RMS. To minimise wideband noise and extraneous pickup from AC mains or your PC, the signal should also be band-pass filtered.

Making measurements

I have designed a second printed circuit board that 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 ±10% from its nominal frequency.

Nominal input impedance of the filter is 10kΩ. A high impedance unity gain, low noise pre-amp can be switched into circuit, should this passive notch loading be excessive.

Four stages of low-noise, low-distortion, amplification and bandpass filtering follow the notch filter. All measurements shown in this article were made using this pre-notch filter/pre-amplifier as the input into my ADC-100 converter.

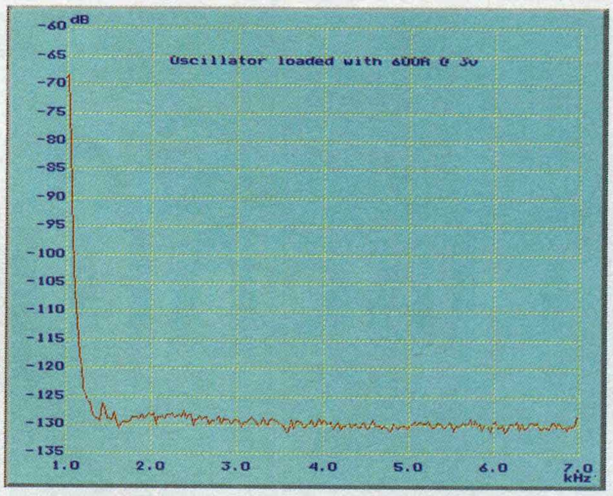


Fig. 8. Output distortion of the complete oscillator design shown in Fig. 7. Outputting 3 volts into a 600Ω load, distortion of this prototype measured using my pre-notch filter/amplifier is buried in the measurement noise floor at –128dB – or less than 0.5ppm.

While I took care 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 600Ω load when built with AD797 ICs, measured less than –128dB, or less than 0.5ppm, Fig. 8.

Less expensive alternative ICs 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 NE5534As. There's more on this in the panel entitled, 'Alternative ICs and components'.

Increasing signal drive

This excellent quality signal driving into 600Ω can be used to measure amplifiers, etc. However a more powerful output buffer amplifier providing increased drive current must be used when testing capacitors.

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[5]. These capacitors were connected in series with each of the instrumentation amplifier inputs, then subjected to a rectangular test wave, **Fig. A**.

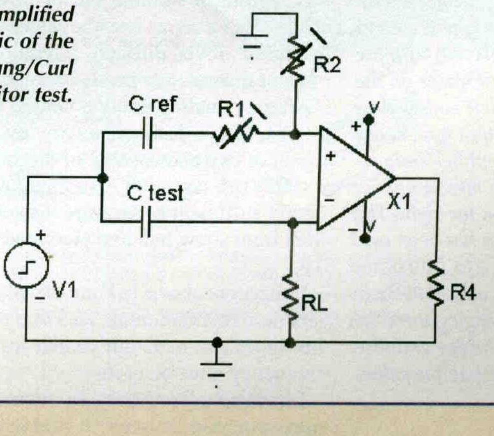
This circuit formed a traditional Wheatstone bridge. Using a sinewave stimulus, a test capacitor was compared with a known reference capacitor. When a rectangular wave test signal is used though, interpretation of the output waveform was impracticable, unless both capacitors were of similar value, dielectric and construction.

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

Differing dielectrics and constructions thus result in small differences in ESR and impedance with test voltage and frequency. The differences 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. A. Simplified schematic of the Jung/Curl capacitor test.



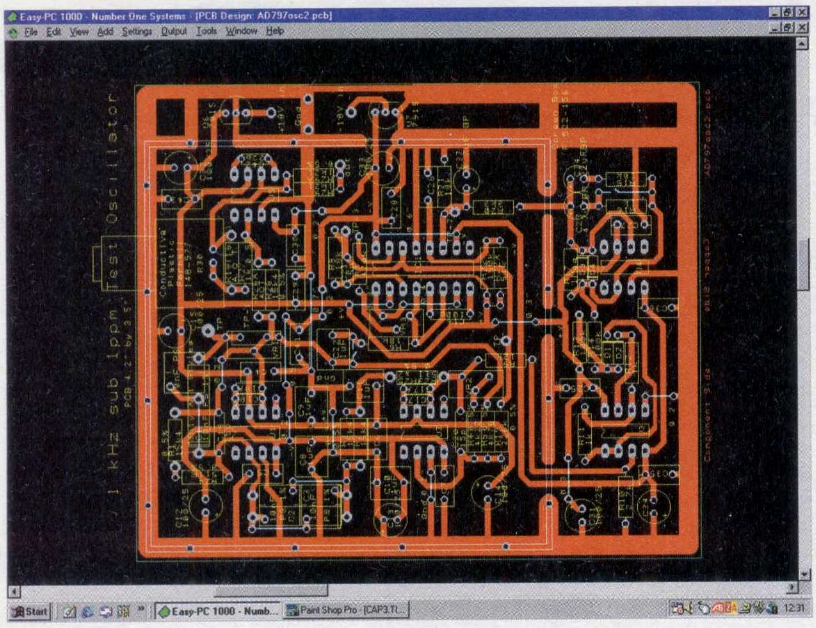


Fig. 9. Version II of the PCB design, as used for this article. The board can be assembled using a variety of oscillator ICs, and is pierced allowing a choice of oscillator capacitor styles and values. The PCB tracks have been arranged for easy one-off PCB etching and assembly.

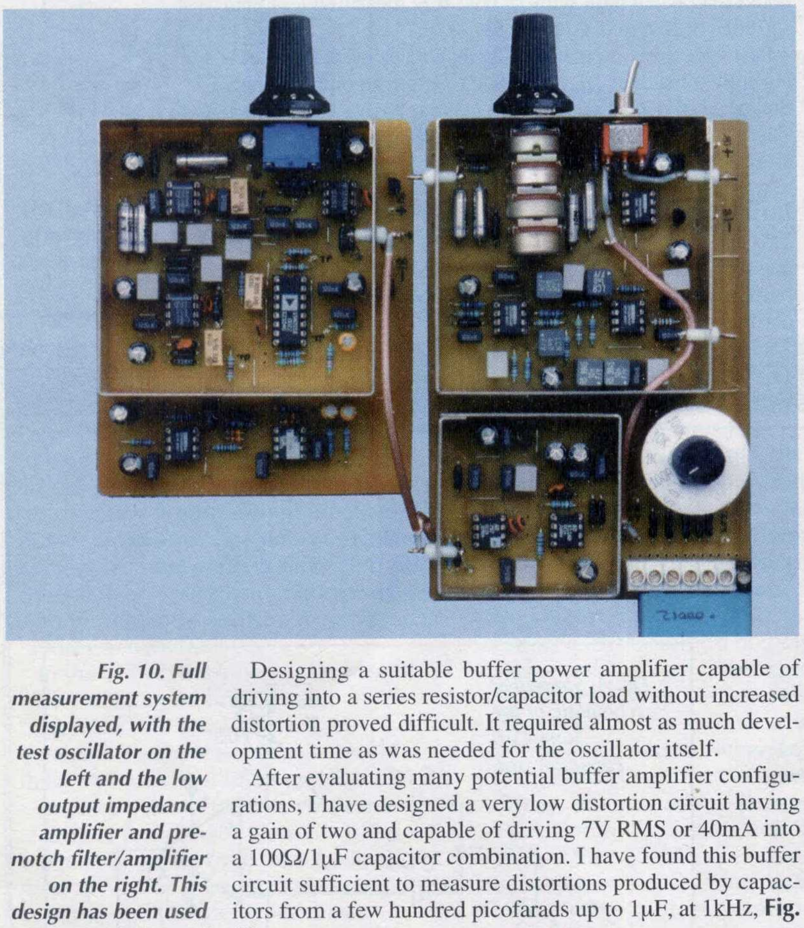


Fig. 10. Full measurement system displayed, with the test oscillator on the left and the low output impedance amplifier and pre-notch filter/amplifier on the right. This design has been used down to 100Hz and up to 10kHz by changing the Wien bridge and filter capacitor values.

Designing a suitable buffer power amplifier capable of driving 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 and capable of driving 7V RMS or 40mA into a 100Ω/1μF capacitor combination. I have found this buffer circuit sufficient to measure distortions produced by capacitors from a few hundred picofarads up to 1μF, at 1kHz, **Fig. 10**.

Capacitors above 1μF are usually electrolytic types, either tantalum or aluminium. To avoid overstressing these capacitor types and maintain similar test voltages, a reduced test frequency must be used.

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

My 1kHz 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.

Calibration

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

Prior to inserting the SSM2018P, trimmer VR_3 should first be set to its mid value. Similarly, prior to inserting U_1 and U_2, trimmers VR_1 and VR_2 should be set to the starting values shown on the diagram. These values give a good starting point and should ensure the oscillator starts reliably. Output at the test point adjacent to VR_1/R_{26} should be around 3 volts.

Monitor test point 2 adjacent to C_{37} using a DC millivoltmeter. Adjust VR_2 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 VR_1/R_{26} using the high impedance preamplifier, you will probably see significant distortion products, Fig. 5.

Slowly increase the resistance of VR_1 and simultaneously adjust trimmer VR_2 to maintain near zero volts on the test point adjacent to C_{37}. This adjustment affects mostly the third and higher odd harmonic components.

Adjusting VR_1 and VR_2 will also slightly change the oscillator frequency. If you are 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 VR_1, Fig. 6.

Relocate your test probe to the test point 3 adjacent to R_8 and adjust VR_2 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 VR_1/R_{26} and slowly adjust all three trimmers as above to minimise distortion. This completes the oscillator calibration, Fig. 8.

Test or select U_5. Attach a 600Ω resistor load to the 'out' test point and adjust the conductive plastic potentiometer to give a 3 volts output. Monitor the distortion spectrum at this 'out' test point, and compare it with that previously attained at the test point adjacent to VR_1/R_{26}. Both should be almost identical. If not replace U_5 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 600Ω, should be considerably less than 1ppm, Fig. 8.

By varying the output potentiometer, the output voltage should range from less than 0.2V to more than 4V. 'Adjust on test' resistor positions have been provided for R_{26A} also R_{18} to ensure attaining this output voltage range. ■

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