Think of a sinewave, distort it to stabilise the amplitude, take away the harmonics you first thought of, and the answer's a pure sinewave. Not quite that straightforward, but that is roughly what Ian Hickman's latest invention amounts to.

A perfect variable oscillator?

This design more or less materialised by itself – perhaps harmonic serendipity describes it. Low distortion audio frequency oscillators have always held a fascination for me. Several designs have appeared in these pages over the years. Some, like the one described in reference 1, offer a modest performance – around 0.07% THD – while the configuration described in reference 2 improves on this by a factor of 20 or more.

Many low-distortion audio oscillator designs, like the one in reference 3, use a thermistor such as the famous R53, or the R54, for amplitude stabilisation. Though effective, this has certain disadvantages, one of which is the high cost of the device.

The main disadvantage though is a rise in third-harmonic distortion at frequencies below 100Hz, becoming quite marked at 20Hz. This is due to the period of the waveform beginning to approach the thermal time-constant of the thermistor, so that the element tends to cool between each half cycle of the waveform, as it passes through zero voltage.

With this in mind, some years ago I designed a 20Hz-20kHz audio oscillator[4] using diodes to stabilise the amplitude in place of the expensive R53. The advantage here is that the limiting action is totally independent of frequency

At 0.04% total harmonic distortion plus noise over the hole audio frequency range, its performance was good, bearing in mind the low component cost. But in another application[5] even the diodes were dispensed with. Here, the oscillator consisted of a frequency-selective amplifier whose gain was allowed to reach infinity The relationship between oscillators and selective amplifiers was discussed in reference 6 which, though predating op-amps, nevertheless contains some interesting ideas.

Another look at the problem

Being now equipped with an *HP3580A* audio frequency spectrum analyser, I decided it was time to take another look at just how good a low a distortion oscillator could be designed, without recourse to a thermistor for amplitude stabilisation.

As an exercise in making a silk purse out of a sow's ear, that standard low-cost standby of FET input op-amps, the *TL084* was selected I started with the circuit of **Fig. 1**, which, apart from the frequency, is the same basic circuit as in reference 5. This circuit produces an output at approximately 1kHz, the peak to peak amplitude just reaching to the supply rails.

Output spectrum is shown in the upper trace of **Fig. 2** This hows the measured at the output of the second integrator, deliberately plotted with rather a wide IF bandwidth The largest harmonic is the third, being 63dB down on the fundamental or 0.07%. Other harmonics are about 70dB or more down.

Amplitude stabilisation took the form of reducing loop gain at the fundamental component, due to the output hitting the supply rails. In theory, the loop phase shift is exactly 180°, corresponding to a circuit Q of infinity; in practice, the phase shift will be a smidgeon more, due to the inevitable residual phase lag in the integrators, even though this is very small at 1kHz

The output waveforms of all three op-amps in the circuit were substantially similar. All were limiting gently, to slightly different degrees. The obvious next step, therefore, was to confine the limiting to the first op-amp, so that the harmonic distortion products caused by the limiting were attenuated by the the 6dB/octave roll-off of each of the two following integrators.

This was achieved by raising the gain of the first op-amp, so that the amplitude at its output – the high-pass node of the

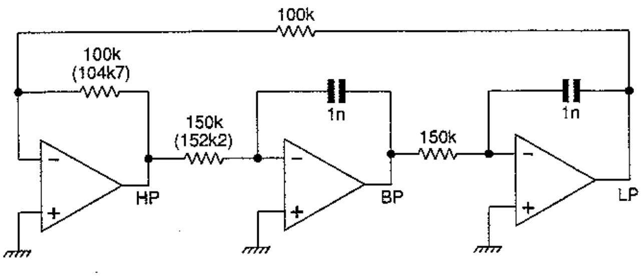

Fig. 1. Simple low distortion sinewave oscillator

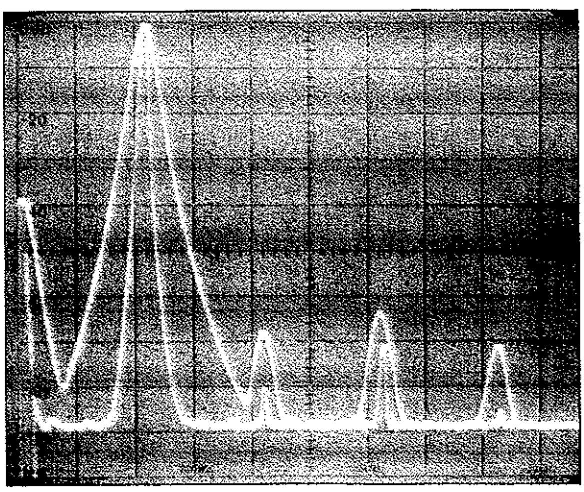

Fig. 2. Upper trace, output of the circuit of Fig 1. Span 0-5kHz, 100Hz resolution (IF) bandwidth, video (post detection) filter off.
Lower trace, as above, but with component values in brackets, resolution bandwidth 30Hz.

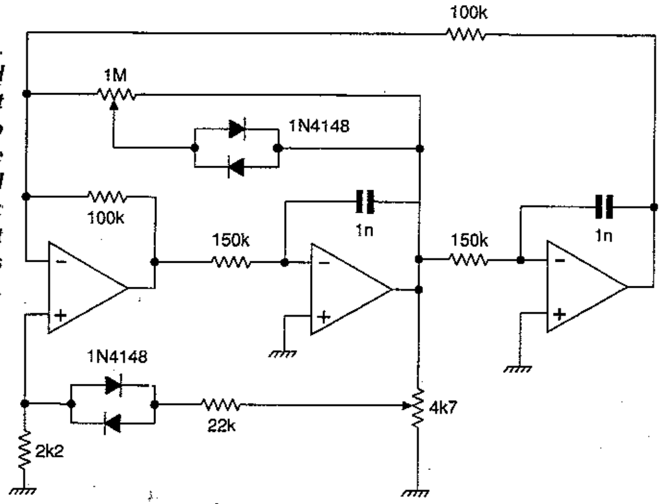

Fig. 3. Modified circuit designed to produce little or no third harmonic component at the lowpass output.

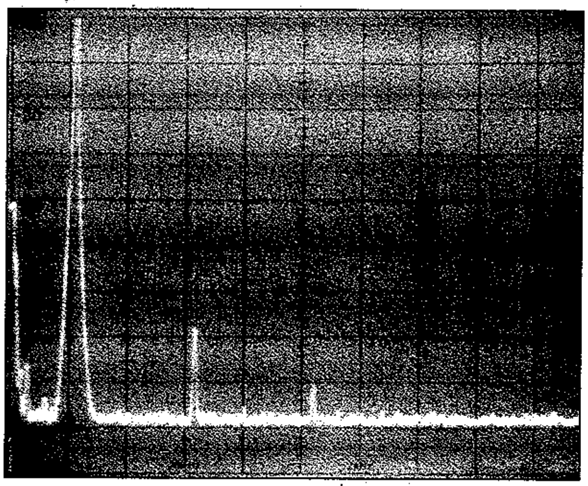

Fig. 4. Output of the circuit of Fig. 3. Span 0-10kHz, 100Hz resolution (IF) bandwidth, video filter off.

filter – was larger than at the output of the second integrator – the low-pass output Its feedback resistor was therefore raised by 4.7kΩ, the integrators between them now providing a gain of 4.7% less than unity

To do this, the frequency automatically adjusts itself up a little. If the integrator components remained the same, the first integrator would still run at a slightly higher amplitude than the second, so its input resistor was raised by 2.2kΩ, giving roughly equal amplitude non-limiting outputs at the bandpass and lowpass output nodes.

The spectrum was now as shown in Fig. 2, lower trace. For clarity, this has been recorded at a narrower IF bandwidth, and the slight increase in frequency is clearly visible, more so at the higher harmonics

The third harmonic is now 70dB down on the fundamental, and others 80dB or more down. Incidentally, the reduction in the second harmonic was not all due to the component changes; the opportunity was taken to tweak one of the supply rails to more nearly equalize the clipping of the positive and negative peaks.

For such a simple circuit, a thd plus noise figure of 0.03% is not at all bad, and it is a very useful and economical arrangement for a fixed frequency oscillator. For a wide-range audio frequency oscillator it is less suitable, since the excess phase shift in the integrators will increase with frequency, leading to a much worse distortion figure at 10kHz and above. So my thoughts turned to the type of oscillator described in reference 4.

Diodes for stabilisation

This circuit incorporated negative feedback of such a value as to set the filter to a Q of 11. Positive feedback was applied from the bandpass output, BP, of a value exceeding the negative feedback, effectively providing the filter with an input derived from itself.

However, as the amplitude of the oscillation builds up, diodes start to limit the positive feedback, so that the fundamental component of it ceases to increase, or does so only marginally.

As the negative feedback continues to increase proportionally with the amplitude of the oscillation, an equilibrium point is reached, where the net loop gain at the fundamental just equals infinity. The circuit was arranged so that this occured at a level well below the maximum possible swing set by the supply rails, with the result that the second harmonic distortion was negligible.

An advantage of an oscillator such as this, based upon the state variable filter, is that the circuit can be used both as an oscillator, and simultaneously as a second-order elliptic lowpass filter. Any third harmonic, due to the limiting action of the diodes, present at the high-pass output will be attenuated by a factor of three in each of the integrators.

Furthermore, as each integrator provides a 90° phase shift regardless of frequency, the third harmonic present at the high-pass output is in antiphase to that present at the lowpass output So by using an additional summing amplifer to combine one ninth of the highpass output with the full lowpass output, the third harmonic sits in a notch.

This results in a signal entirely free of any third harmonic, an arrangement used in reference 4 Meanwhile, the fundamental output is of course also reduced, but only by a ninth.

Handy though this arrangement is, there is a down side to it. While the third harmonic is outphased completely, the fifth harmonic is actually made 5dB worse. But there is still a net reduction in thd, since, due to the fairly soft limiting action of the diodes, the amplitudes of the harmonics at the high-pass output drop off much more rapidly than in an ideal squarewave.

Outphasing the fifth harmonic

It occurred to me that if I could arrange that the amplitude limiting method inherently did not produce third harmonic, then the fifth harmonic could be outphased instead – simply by adding a twentyfifth of the high-pass output to the low-pass output

Reduction of selected harmonics by waveform shaping is a technique long familiar in power engineering. There, it can be used to minimise the filtering required at the output of an inverter, as in for example reference 7 So I experimented with a circuit designed to avoid producing third harmonic in the stabilisation department, permitting outphasing of the fifth

This is shown in **Fig. 3** Oscillation commences since there is positive feedback from the bandpass output via 1MΩ to the inverting input of the first op-amp. Initially, there is no negative feedback via the 22kΩ resistor to the noninverting input, as it is blocked by the diodes.

As the amplitude increases, their forward voltage is overcome, and thereafter the stronger negative feedback increases more rapidly than the positive feedback. This leads to equilibrium at a level which can be adjusted by means of the 4.7kΩ potentiometer. The 1MΩ potentiometer can then be adjusted to feed narrow additional positive feedback pulses at the tips of the waveform.

Following careful setting up, the output spectrum was as shown in **Fig. 4**. The third harmonic at the low-pass output is at –69dB, about as low as the diode-free circuit of Fig. 1. It is also lower – without the benefit of outphasing – than achieved by the circuit of reference 4 with diodes.

But setting up was fairly critical, and performance with tuning and with change of ambient temperature would clearly have been unsatisfactory. Nevertheless, the low level of fifth harmonic was encouraging, so the circuit was rear-

...nged to provide low third harmonic output by means of outphasing.

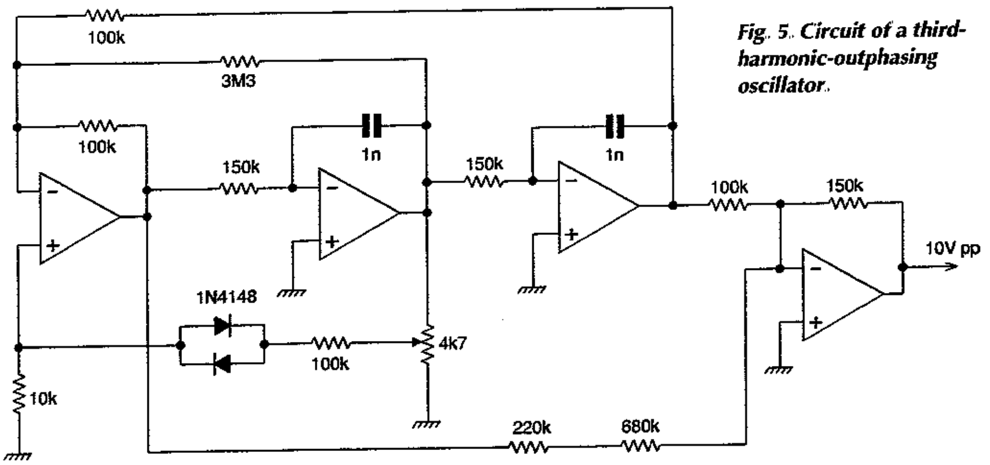

Fig. 5. Circuit of a third-harmonic-outphasing oscillator.

Why not outphase all the harmonics?

This circuit is shown in **Fig. 5**, and its performance in **Fig. 6**. The third harmonic is outphased completely, while compared with Fig. 4, the fifth harmonic has increased by the expected 5dB.

It would be fine though, I thought, if both the third *and* the fifth harmonics could be outphased, and why not the seventh and the others to boot? This led to the experimental arrangement of **Fig. 7**.

Here, the amount of positive feedback is fixed by the 3.3MΩ resistor, the desired amplitude of oscillation being set by the amount of negative feedback via the diodes. Having constructed the circuit as shown, with the 100kΩ potentiometer at mid-travel, on switching on, the spectrum which met my unbelieving gaze is shown in **Fig. 8**.

Where had all the harmonics gone? The following day, they were back again, but only just above the –89dB noise floor of the spectrum analyser. Successive adjustments of the two potentiometers nearly reproduced the previous day's astounding results, but the settings were critical, and the amplitude of the oscillation very unstable. So it was time to don the thinking cap.

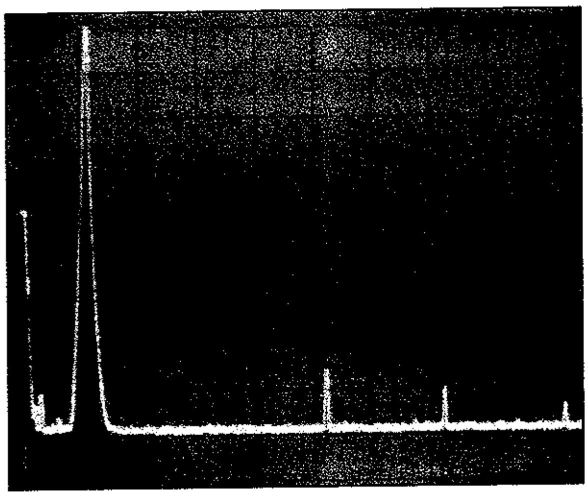

Fig. 6. Spectrum of the 10V peak to peak output of the circuit of Fig. 5. Spectrum analyser settings as for Fig. 4, but with video filter set to 'medium'.

The intention had been to use op-amp IC_4 as a difference amplifier to pick off the harmonics generated by the diodes. These were then fed into the inverting input of IC_1. With the identical harmonics fed also into the non-inverting input as part of the negative feedback signal, the harmonic distortion should be rejected by IC_1 as a common mode signal.

The idea is sound, but it is essential that the harmonics, and only the harmonics, be fed back to the inverting input of IC_1. For if the fundamental component of the near-squarewave appearing across the diodes be fed back as well, the amplitude stabilisation mechanism is defeated. It is the 'dead-space' created in the negative feedback signal by the diodes that ensures oscillator start-up.

Thereafter, when the signal becomes large enough for the diodes to start to conduct, the negative feedback increases with the amplitude of oscillation, faster than the positive feedback increases.

If the fundamental component of the diode drop is now fed back along with the harmonics, via the difference amplifier, to the inverting terminal of IC_1, then regardless of level, the ratio of positive to negative feedback becomes independent of level, and amplitude stabilisation is lost.

So the circuit was modified to make IC_4 a true difference amplifier, as shown in **Fig. 9**. Note that the ratio of the two resistors at the inverting input of IC_4 is equal to the ratio of the resistors at the other input – although these in fact also do double duty as the input divider chain for the negative feedback to IC_1.

With the wiper of R_B at the top of its travel – point B in Fig. 9 – IC_4 is a classic difference amplifier, with a near squarewave output representing the voltdrop waveform across the diodes. This, however, is not quite what is wanted; it contains the missing fundamental component of the negative feedback as well as the harmonics, as shown in the upper trace in **Fig. 10**.

The waveform input to the diodes is shown in the upper trace of **Fig. 11**, and note that the upper trace in Fig. 10 is in antiphase to this. Thus the voltage applied via the diodes and resistors, as negative feedback to IC_1, is as shown in Fig. 11, lower trace. Note the dead-space, rather like an underbiased class B output stage.

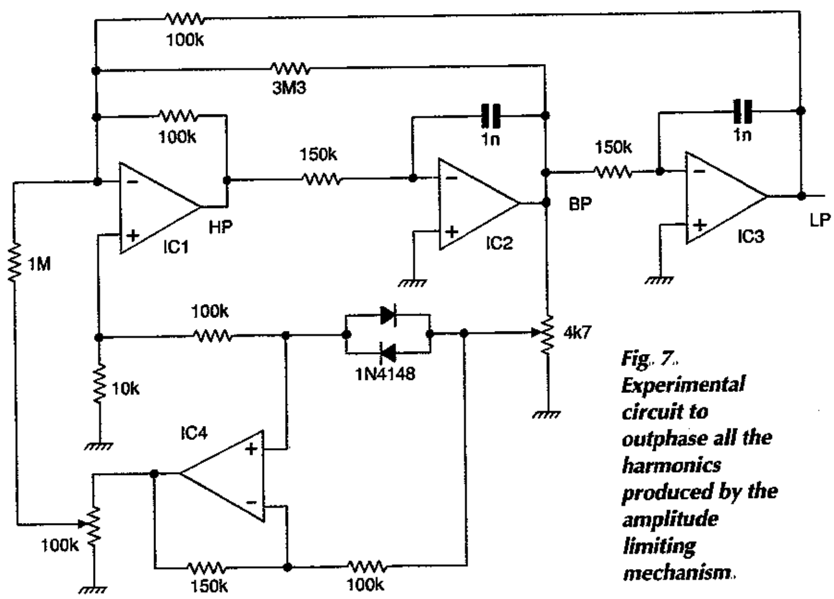

Fig. 7. Experimental circuit to outphase all the harmonics produced by the amplitude limiting mechanism.

This illustrates an important point. When any mechanism introduces harmonic distortion onto a pure sinewave, the amplitude of the fundamental component of the distorted waveform will differ from that of the original.

To ensure outphasing of the harmonics by common mode cancellation in IC_1 without upsetting the amplitude stabilisation, the waveform fed to that op-amp's inverting input should consist of the harmonics only.

These only exist at the downstream side of the diodes. The fundamental component of the near-square waveform across the diodes represents the amount by which the fundamental input to the diodes exceeds that at their output. The difference amplifier IC_4 can be arranged to see a slightly smaller sinewave at its inverting input.

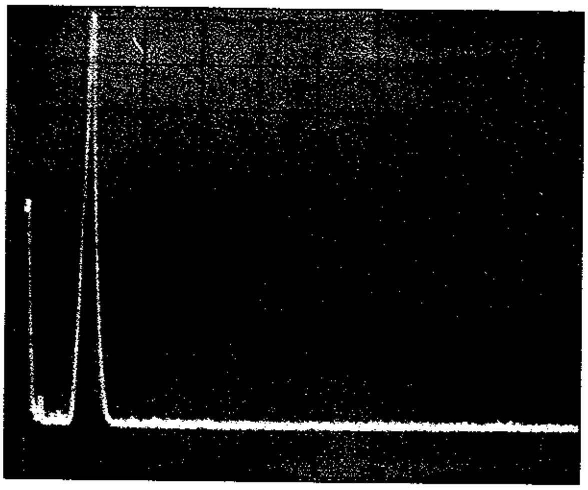

Fig. 8. Output of the circuit of Fig. 3. Span 0-10kHz, 100Hz resolution (IF) bandwidth, video filter off.

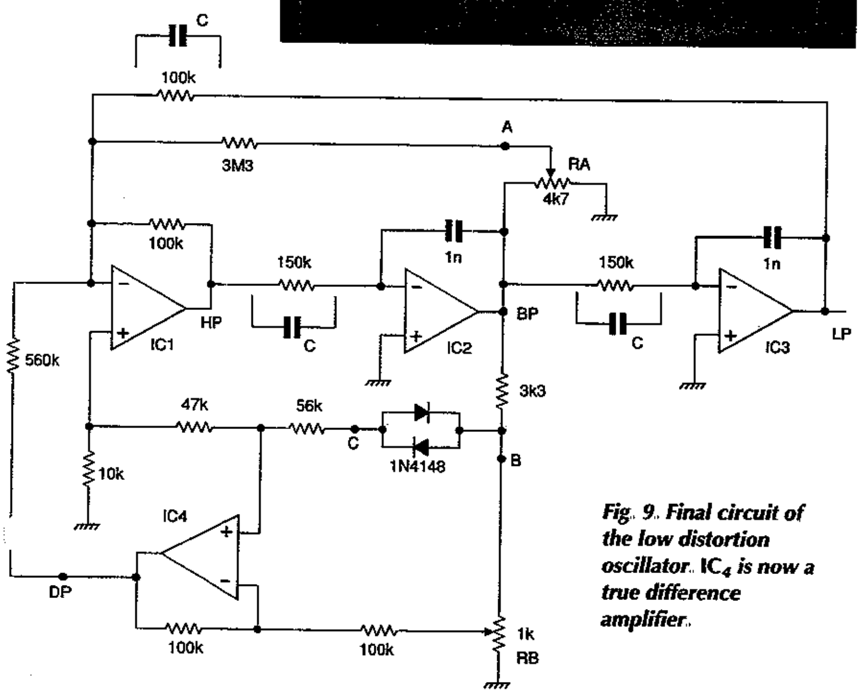

Fig. 9. Final circuit of the low distortion oscillator. IC_4 is now a true difference amplifier.

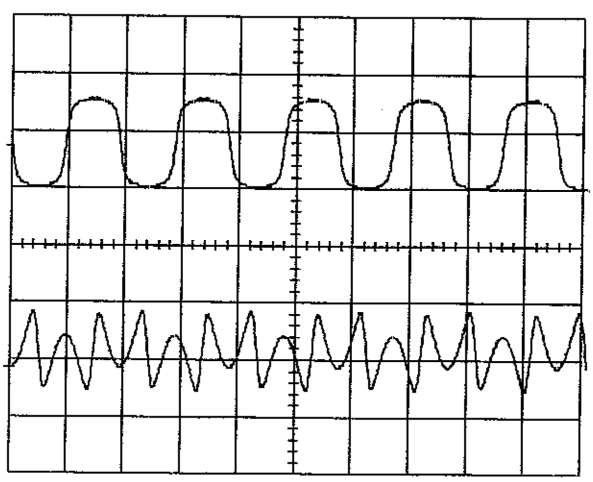

Fig. 10. Upper trace (1V/div), the waveform appearing across the diodes contains a component at the fundamental frequency. Lower trace (0.2V/div), as the upper trace, except with the fundamental component removed. Horizontal: 500μs/division.

Resistor R_B in Fig. 9 allows this to be adjusted to equal the amplitude of the fundamental component of the negative feedback signal shown in the lower trace of Fig. 11. The result is that the output of the difference amplifier IC_4 then contains the harmonic components *only*, as shown in Fig. 10, lower trace.

This adjustment is very easily carried out, by displaying the spectrum of the waveform at the distortion products measuring point DP in Fig. 9, on a spectrum analyser, and adjusting R_B to minimise the fundamental component displayed.

Measuring the results

Output of the circuit of Fig. 9, measured at the point LP, displayed a third harmonic component just visible above the spectrum analyser's noise floor, with higher harmonics not visible at all.

To increase the measurement range, a twin-tee network was made up, using four 15kΩ, 1% metal film resistors and four 10nF, 2.5% polystyrene capacitors. Figure 9 used 2.5% 1n polystyrene capacitors, and 1% metal film resistors throughout by the way.

Response of the twin-tee was plotted, using the spectrum analyser's internal tracking generator, and is shown as the upper trace in **Fig. 12**. With no adjustment, the twin-tee notch reduced the fundamental of the oscillator by 45dB, permitting the input level to the spectrum analyser to be increased by 40dB without overloading.

The measurement noise floor was now about 120dB below the oscillator's output, as can be seen in Fig. 12, lower trace. Allowing for the residual attenuation of the notch, the third harmonic is seen to be at –88dBc, and the fifth at –104dBc, while the second and fourth are lost in the oscillator's phase noise sidebands.

Some practical extensions

While the circuit has not to date been developed into a complete 20Hz to 20kHz audio oscillator, some initial tests were carried out to see if this would be practicable.

To test the performance with change in ambient temperature, an electronic thermometer was used in conjunction with a hair-dryer. The thermometer probe was placed adjacent to the diodes, and the hairdryer at a fair distance, so that the whole circuit was bathed in the same air stream, and left to reach equilibrium.

The temperature was thus raised from 20° C to 30°C. The oscillator's output level rose by roughly 2dB, but the distortion figure remained unchanged.

Next, the circuit was modified to operate at 10kHz by changing the two integrator 150kΩ resistors to 15kΩ. As expected, amplitude control was lost, due to the increased residual phase shift in the integrators. This was largely corrected by fitting three 1.8pF capacitors shown as *C* in Fig. 9.

Some re-adjustment of R_A was still necessary, but thereafter, the distortion was, as far as could be determined without another twin-tee filter, similar to that measured previously.

The exact value required for the compensating capacitors *C* will depend upon layout, and may well be 1.8pF or even less with a good pcb design – the experiments were carried out using, for speed, *Experimentor* prototyping plug-board. This exhibits a fairly high stray capacitance between adjacent points, rendering it completely unsuitable for rf work.

Even at audio, the strays can, as here, pose a problem. Bandswitching and fine frequency control, to cover 20Hz to 20kHz, can be implemented as in reference 4.

Figure 13 shows some simple additions which could be accommodated with an additional quad op-amp. In theory, IC_5 should outphase even the residual third harmonic distortion visible in Fig. 12 – but don't expect perfection. After all, the typical thd of the *TL084* used in all the circuits illus-

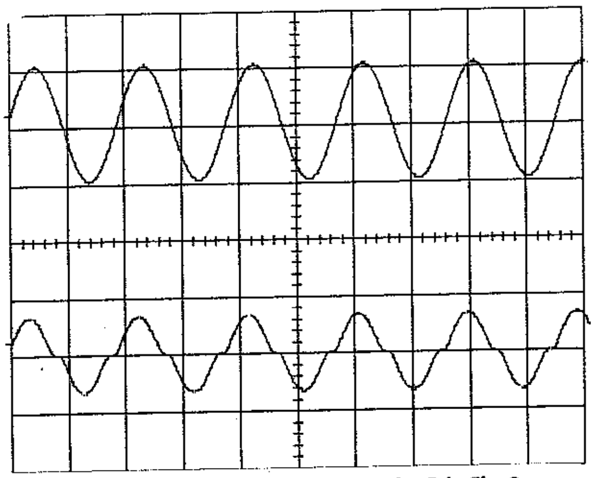

Fig. 11. Upper trace, the waveform at point B in Fig. 9. Lower trace, the waveform at point C in Fig. 9. Both traces, 2V/division vertical, 500µs/division horizontal.

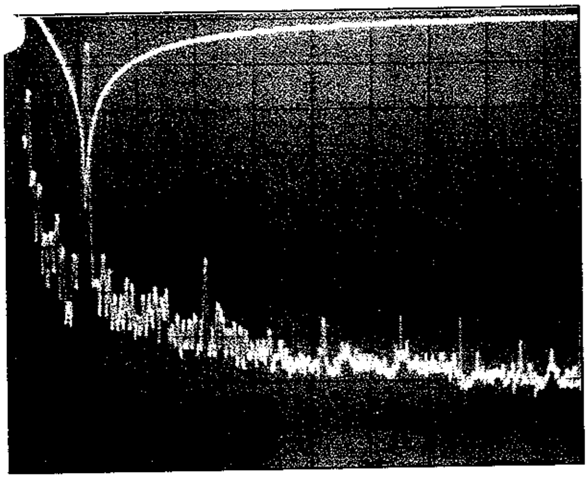

Fig. 12. Upper trace, the response of a 1kHz (nominal) notch filter. Lower trace, the LP output of the circuit of Fig. 9 with the fundamental in the notch, and the sensitivity of the spectrum analyser increased by 40dB. Span 0-10kHz, 30Hz bandwidth, video filter at 'medium', 20s/div sweep speed.

trated, is listed as 0.003% or –90dBc.

Together with IC_5, IC_6 provides a choice of a 600Ω output, or a variable voltage source for driving high impedance loads. Amplitude monitoring is provided by IC_7, enabling any output level variations with temperature to be trimmed out, by adjustment of R_A.

The value of R_m is determined by the sensitivity of the meter used, while another resistor R_p, of suitable value, may be included if desired, for meter protection in the event of overload.

Finally, IC_8 provides a means of adjusting R_B so that the output of difference amplifier IC_4 contains zero contribution at the fundamental. As R_B is adjusted, the sudden complete disappearance of the fundamental is very obvious, no need for the aid of a spectrum analyser

A switch to turn the stage off once the adjustment is complete, is clearly a good idea. Resistors R_A and R_B should preferably be multi-turn types, and for convenience can be made adjustable via the oscillator's front panel.

Setting up

Setting up the circuit for optimum performance is very straightforward, and no special equipment is needed. The sequence is as follows.

Disconnect the 560kΩ resistor from the point DP and connect it to ground instead. This isolates the effect of R_B, preventing it interacting with the next step, while ensuring the effective positive feedback ratio is unchanged.

Set R_A to give the desired output level. Assuming 15V supply rails, 10V peak to peak is a suitable value.

Using the audio monitor of Fig. 13, adjust R_B for zero fundamental component in the output of IC_4; this is conveniently carried out at 1kHz.

Disconnect the 560kΩ resistor from ground and reconnect it to IC_4's output. Check that this does not alter the level at the LP output ■

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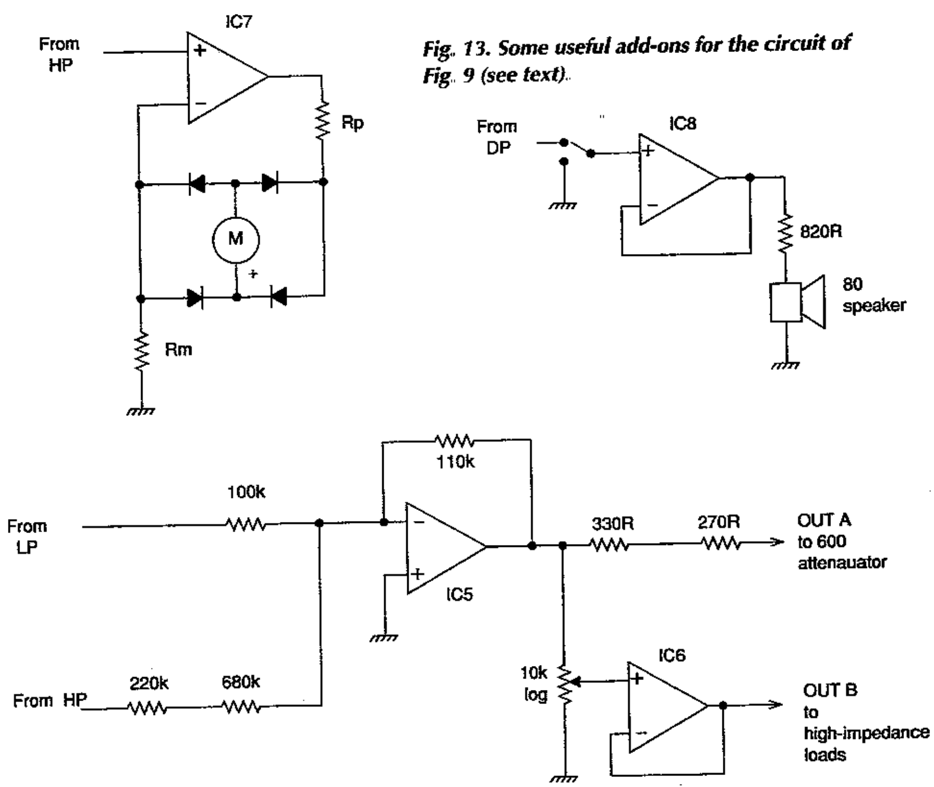

Fig. 13. Some useful add-ons for the circuit of Fig. 9 (see text).