LOW DISTORTION AUDIO OSCILLATOR

Part 2

Last month we told you the principles and compromises in designing this impressive audio oscillator. It was such a comprehensive discussion we had to split the project into two parts. Here we resume with a guide to construction, circuit details and testing advice.

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SO MUCH FOR all the reasons for the eventual circuit last month. Now for how to use it.

Construction

I chose to use a plastic instrument case available from Geoff Wood, Jaycar or Altronics. I think just about every electronics store will stock one that's OK. The plastic boxes are neater but the metal ones do make the oscillator less prone to hum pick-up. You pays your money and makes your choice!

If you want to do your own layout and make the board fit a different case, the most important thing of all is to keep the RC parts of the oscillator *as far as possible from the power transformer.* Power transformers radiate 50 Hz fields and these are entirely too easy to get into the oscillator. If you look at the layout of the board, you'll see that they are on opposite diagonal corners of the board and I still had some trouble. For the same reason (hum pickup) I chose to use the miniature Bourns trimpots to minimise board area used by the selective components in the oscillator. These are also available from Geoff Wood and were, in fact, a lot cheaper than the normal cermet trimmers. On the subject of trimmers it's *absolutely essential* that good quality cermet trimpots be used as the cruddy old carbon film ones really aren't stable enough. All the trimpots are in frequency determining networks and if an older type is used, the output frequency would be all over the place like a dog's breakfast. Similar remarks apply to all the fixed resistors. Ideally they should be ±1% metal film resistors not so much for the ±1% as for the stability with time and temperature although in the prototype they were mainly ±2% and seemed to work OK.

The capacitors used in the frequency determining networks are all metallised polyester and are encapsulated in plastic cases. The types that're suitable are ERO (Roederstein) type MKT1817 or MKT1826 or Wima type PR21 or RS21 or some fair dinkum equivalent. If you do decide to go for a rock bottom budget unit and use greencaps let me know how they work (by mail — not in person!). The point about the capacitors I specified is that they have a known temperature characteristic which only gives a ±0.5% change over the normal operating temperature range.

The safest way to get the board layout is to copy the one given or buy a mask from ETI (if you put any value on your time this is really far cheaper). The board is made from single sided 1/16 inch epoxy glass board. I don't recommend using paper phenolic type boards as their leakage performance is a bit sus. If you are doing your own layout take particular care to get the spacing right for the switch banks pins (they're *@#!! not on 0.1 inch centres).

Etch and drill the board normally and start assembly with the power supply. Assemble only the power transformer, rectifier, diodes, filter electrolytics and voltage regulators. I VERY strongly recommend using printed circuit terminals to get 240 volts onto the board as I have been bitten far too many times.

NEXT COVER ALL THE TRACKS THAT CARRY MAINS VOLTAGE WITH INSULATING TAPE. If you don't you'll probably kill yourself. Also there are two solder pins that carry mains that stick out from the side of the little Ferguson transformer. Tape them up too. I missed them and my CRO earth clip brushed across them on the prototype (BANG!! palpitate!).

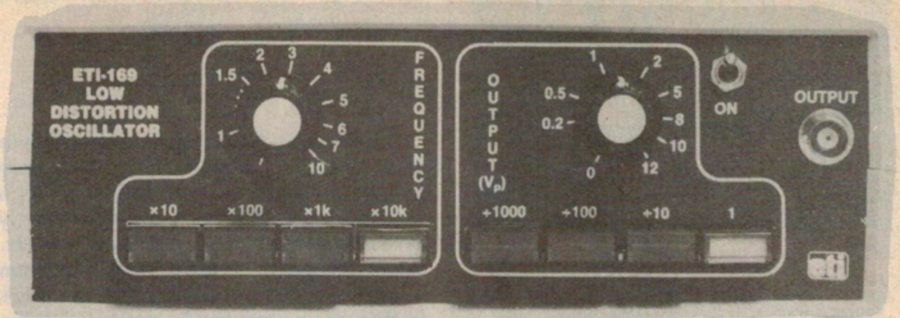
Next create for yourself a death machine — that is a length of 2 or 3 core flex with a mains plug on one end and the other end with bare wires. Connect the wires to the input terminals on the board then power the beast up. Check that you have plus and minus 15 volts coming out of the regulators. If all is well remove the plug from the mains, remove the bare ends from the terminals and lock the damn think away in a safe or something. Now that you know that the voltage regulators work you can carry on with the rest of the assembly with some confidence that the whole thing won't go up in flames when you turn it on.

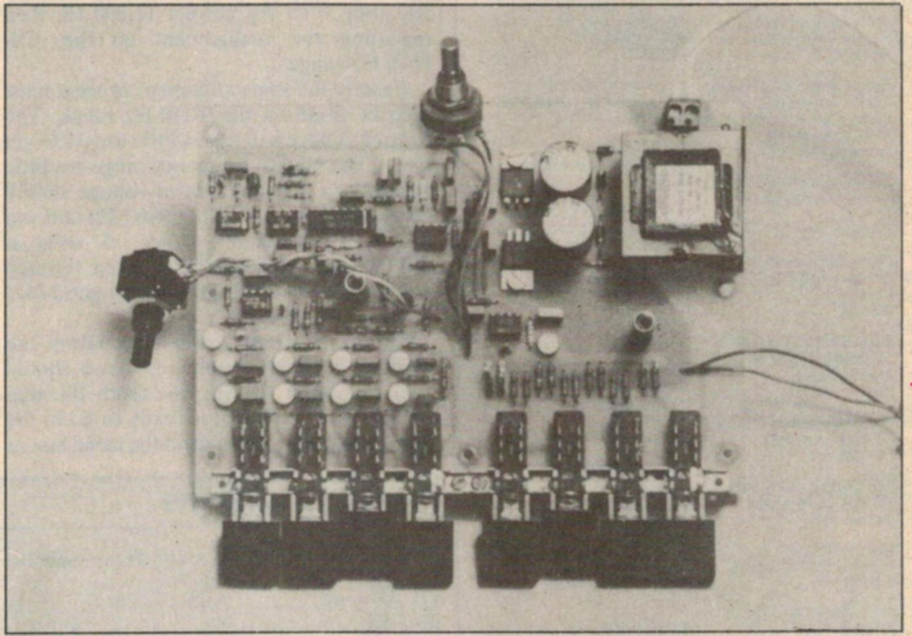
As always make sure that all the ICs are in the right way and also the diodes. It's particularly important that the leads be neat and short around the oscillator (mains hum again). In the prototype I used two 1M and two 200k resistors to make up the 1.2M needed for the −60 dB attenuator as this gives the exact value. There are three wire jumpers that run just behind the frequency select switch which should be as short and straight as possible — resistor leads that've been cropped off do just fine. The last components that should go in are the two switch banks.

Testing and alignment

Before you try to mount the oscillator in the box it's a good idea to do a preliminary alignment and make sure all the ranges are working. Once the board is completely assembled reconnect the death machine to the power terminals and turn the unit on. When I do this to a brand new board I normally run my hands lightly over the components for 30 seconds or so to see if anything is getting too hot too fast (that's another reason to check the power supply first). Next check that the supply rails are still sitting at ±15 volts. If this is right then you're ready for the fun bit.

To set up the pots you really need a counter although a CRO will do in a pinch. The purpose of this adjustment is to remove the ±10% or so tolerances in the oscillator





components and it can't be done properly if you can only measure frequency to ±20%. You can certainly make sure that everything is working but the frequency scale on the front panel won't be worth much.

Given that you've got, begged, borrowed or whatever a counter with a 1 second timebase at least (10 seconds is better) connect it to the output and select the 100 to 1000 Hz frequency range and the 0 dB attenuation range. Connect the frequency adjustment potentiometer temporarily to its appropriate holes and tack a piece of wire across the level adjust pot holes so you get full output. Turn all nine trimpots full clockwise and turn the beast on. If all is normal the output should go up against the rails and stay there. Set RV10 (the frequency select pot) for minimum resistance or maximum frequency then start winding RV9 anticlockwise while monitoring the output. Bring it back to about mid position then start winding RV3 counterclockwise. Somewhere around mid position oscillation should start and it should be at around 1000 Hz. If this is OK, everything is looking good and you can start checking out the level control circuitry.

First check that the squarer IC2 is working. Pin 6 of IC2 should have a square wave on it which is in opposite phase to the sine wave input. The output should show no sign of oscillation during transitions. The input to the squarer on pin 2 should show the input sine wave during positive half cycles and should be diode clamped to about −0.7 volts during negative excursions. The output from the squarer should appear on pin 10 of IC5, the CD4053. C14 and R25 should differentiate the squarer output and a very narrow negative going pulse should appear on pin 9. Finally pin 11 of IC5 should be sitting near ground. Momentarily stop the squarer by shorting its output to ground and pin 11 should rise to about 12 volts if you're using a 10M input impedance CRO probe.

Next comes the peak detector. Check that the sine wave output from the oscillator appears on pin 3 of IC3. Next check the signal on the negative input pin 2. It should be sitting at a dc voltage equal to the peak positive swing of the oscillator with a negative step occurring every time the input signal crosses zero volts going positive. If the oscillator is not being properly level controlled due to other problems then the peak detector output may not be able to get as far positive as the oscillator input but the step should still appear every time pin 9 of IC5 is pulsed negative. If this is what you get it's time to proceed to the integrator IC4.

Integrater IC4 is just a simple inverting operational amplifier with a rather messy RC network in the feedback circuit. Check that pin 3 has +6.8 volts on it and that pin 1 of IC5 has the peak detector output on it. As the analogue switch in IC5 is turned off when the peak detector is reset the negative step doesn't appear on pin 1. If the oscillator output level isn't being controlled and is swinging up against the rails then the output of the integrator IC4 pin 1 should be far negative and the output of the inverting amplifier following the integrator should be hard positive. If the level control circuitry is working (that is if the oscillator has been adjusted so it has enough control range) the integrator output will probably be sitting at a few volts positive, and the output of the inverting amplifier, a few volts negative.

Last of all check that the control voltage on the gate terminal of the FET is at one half the voltage of the inverting amplifier, and the control circuitry should be OK. If the oscillator output is giving bursts of oscillation there is probably a short in the RC network around the integrator. As a final check on the level control try adjusting RV3 again until the level control circuit can take over. You should see a beautiful clean sine wave with a 6.8 volt peak swing on the oscillator output. Pretty — isn't it?

Now back to setting up the oscillator frequency. When the level control is working it's a lot easier to adjust the oscillator as monitoring the control voltage out of pin 7 of IC4 tells how the adjustment is going. Connect a voltmeter there and adjust RV9 until it reads about −4 volts. The next step is to adjust R7 until the oscillator output frequency is 1100 Hz and the control voltage is at −3 volts. To do this, it will be necessary to adjust both RV3 and RV4 to keep the control voltage where it's wanted. You will find that rotating RV3 clockwise lowers the control voltage, and rotating RV4 clockwise raises it. Leave RV3 in the mid position and start adjusting R4 clockwise to raise the control voltage, adjusting RV9 counterclockwise to raise the output frequency until it reads 1100 Hz. Repeat until the correct frequency is obtained with a control voltage of −3 volts.

Next set the frequency pot to lowest (highest resistance). Leave RV9 alone and adjust both RV3 and RV4 until the output frequency is 90 Hz and the control voltage is steady at −2 volts. You will find that rotating RV3 counterclockwise lowers the frequency and raises the control voltage. Rotating RV4 counterclockwise raises both the voltage and frequency. It's easy to adjust one against the other to get the required result. Return now to the maximum frequency setting on RV10 and check that it is still 1100 Hz. If necessary readjust RV9 to the correct 1100 Hz. Return to the lowest frequency setting and reset RV3 and RV4 for 90 Hz. Repeat until it's perfect, but it should only take two or three tries. That's the first range setup completed and you can move on to the 900-11,000 Hz range. ▶

For starters adjust both RV5 and RV6 to mid position and select the lowest frequency setting on RV10. Adjust RV5 and RV6 until the oscillator starts; then adjust exactly as before except that you want 900 Hz. When this is right adjust RV10 to maximum frequency and check that it reads 11,000 Hz. It may not be exact and if the difference is too big for you to live with try adjusting RV9 for correct 11,000 Hz then repeating the realignment on the 100-1000 Hz range.

Exactly the same alignment process must then be done on the 9-110 Hz range. The control voltage will take a little longer to get there. The highest frequency range is a little different in that the control voltage should be adjusted for −1 volt at 9000 Hz and will go down to about −4 to −5 volts at 110,000 Hz. Once you've slogged through this lot you should have a pretty good idea of what you've built.

Finally check that the attenuators are working correctly (each step down should give an output voltage one tenth the step before) and the board is ready to go in the box. Assuming you've used the same box as I did, proceed as follows.

First locate the board in the box and note the plastic mounting pillars that will actually support the board. Next attack the box bottom with a large pair of side cutters and remove the pillars that aren't wanted. There must be about 15 pillars there and only seven are needed. Next carefully mark off exactly where the holes are needed to allow the switch banks to come through the front panel and cut the holes. As this is the front panel it pays to take a little care: if you make a mess of it your mistake will be staring at you for years!

Mark off where you want the frequency and level pots to come through and drill the holes. The same applies to the power switch and output terminals. Assemble all the components on to the front panel then slide it into the box bottom. Solder lengths of wire into the board suitable for connecting the level and frequency pots. At this stage in the assembly of the prototype, a major problem reared its ugly head.

When the board was powered up in the box with all the mains wiring in place, I found that a *large* amount of mains hum was ▶

PARTS LIST — ETI-169

Resistors .... all 0.4 W, 2% unless noted

R1 to 9	5k1
R10, 13	750R
R11	6k2
R12	5k6
R14	1k5
R15, 21, 53	1k0
R16, 17, 26, 28	1M0
R18	220R
R19, 20	100k
R22, 23	33R
R24	5R1
R25	10k
R27	2M2
R29	220k
R30	330k
R31	470k
R32, 33	4k7
R34	100R
R35	3k3
R36, 37, 48, 49	1k2
R38, 39	12k
R40	680R
R41	33k
R42, 43	120k
R44	620R
R45	27k
R46	1M0
R47	1M5
R50, 51, 52	10R
RV2, 4, 5, 8, 9, 13	2k0 trimpot cermet*
RV1, 3, 5, 7	5k0 trimpot cermet*
RV10	100k pot freq set Allen Bradley 72J1N056S104B
R11	100k trimpot cermet*
RV12	2k linear law pot level set

* *Bourns type*

Capacitors

C1, 2	1µ ±10% 50 V met poly*
C3, 4, 13, 15	100n ±10% 63 V met poly*
C5, 6, 17, 31	10n ±10% 63 V met poly*
C7, 8	1n ±10% 63 V met poly*
C9, 24	10p ±5% ceramic plate
C10	47p ±5% ceramic plate
C11	22p ±5% ceramic plate
C12, 18	47n ±10% 63 V met poly*
C14	220p ±5% ceramic plate
C16	2n2 ±10% 63 V met poly*
C19	220n ±10% 63 V met poly*
C20, 21	470µ 25 V RB electro
C22, 23, 24, 25, 27, 28, 30	100n ceramic monolythic
C26	33p ±5% ceramic plate

* *see text for types suitable*

Semiconductors

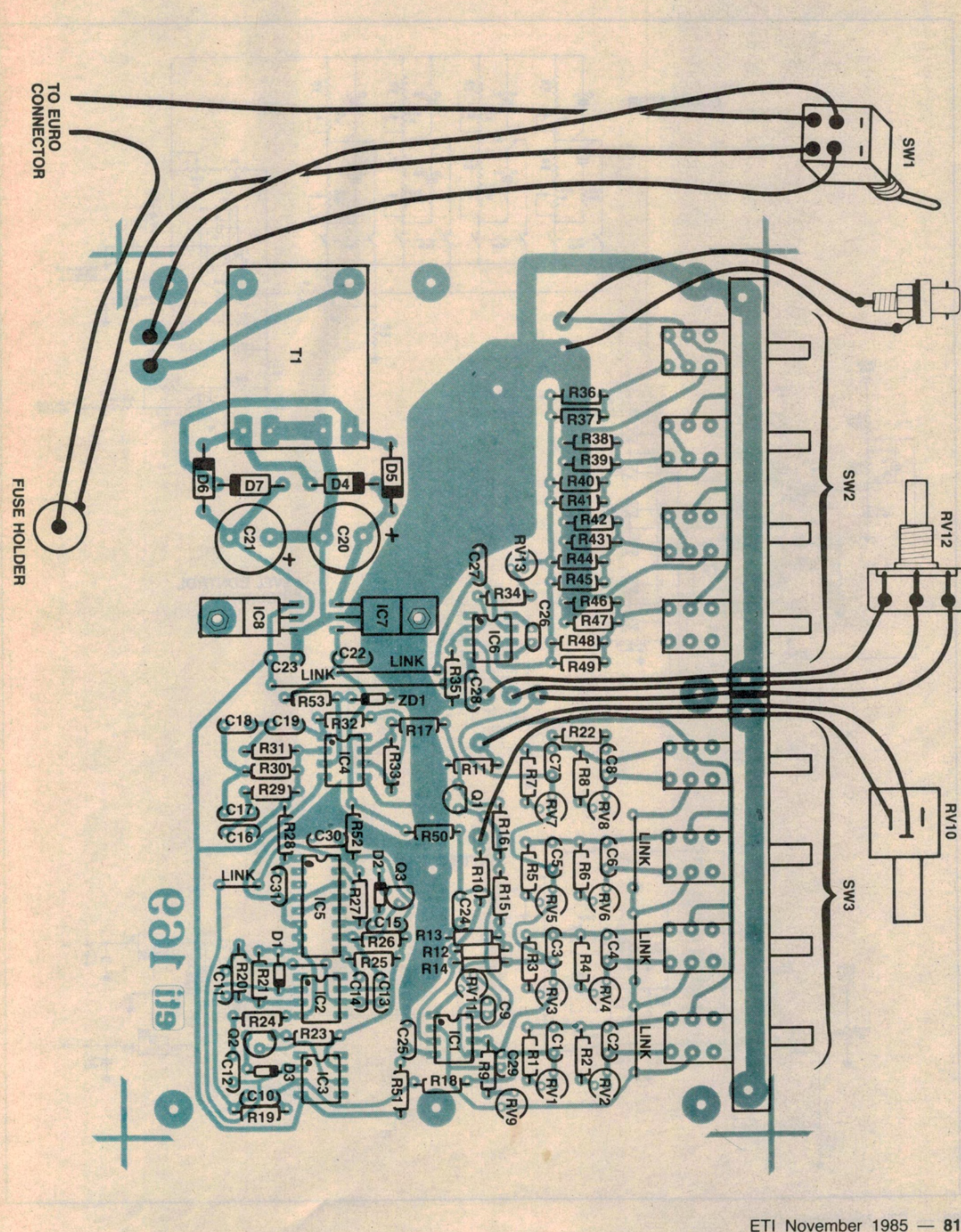
IC1, 6	NE5534
IC2	RCA CA 3130
IC3	LF357
IC4	RCA CA 3240
IC5	RCA CD4053BE
IC7	7815 + 15 V reg
IC8	7915 − 15 V reg
Q1	2N5485
Q2	BC337
Q3	BC327
D1, 2, 3	1N914
D4, 5, 6, 7	1N4004
ZD1	BZX79 C6V8

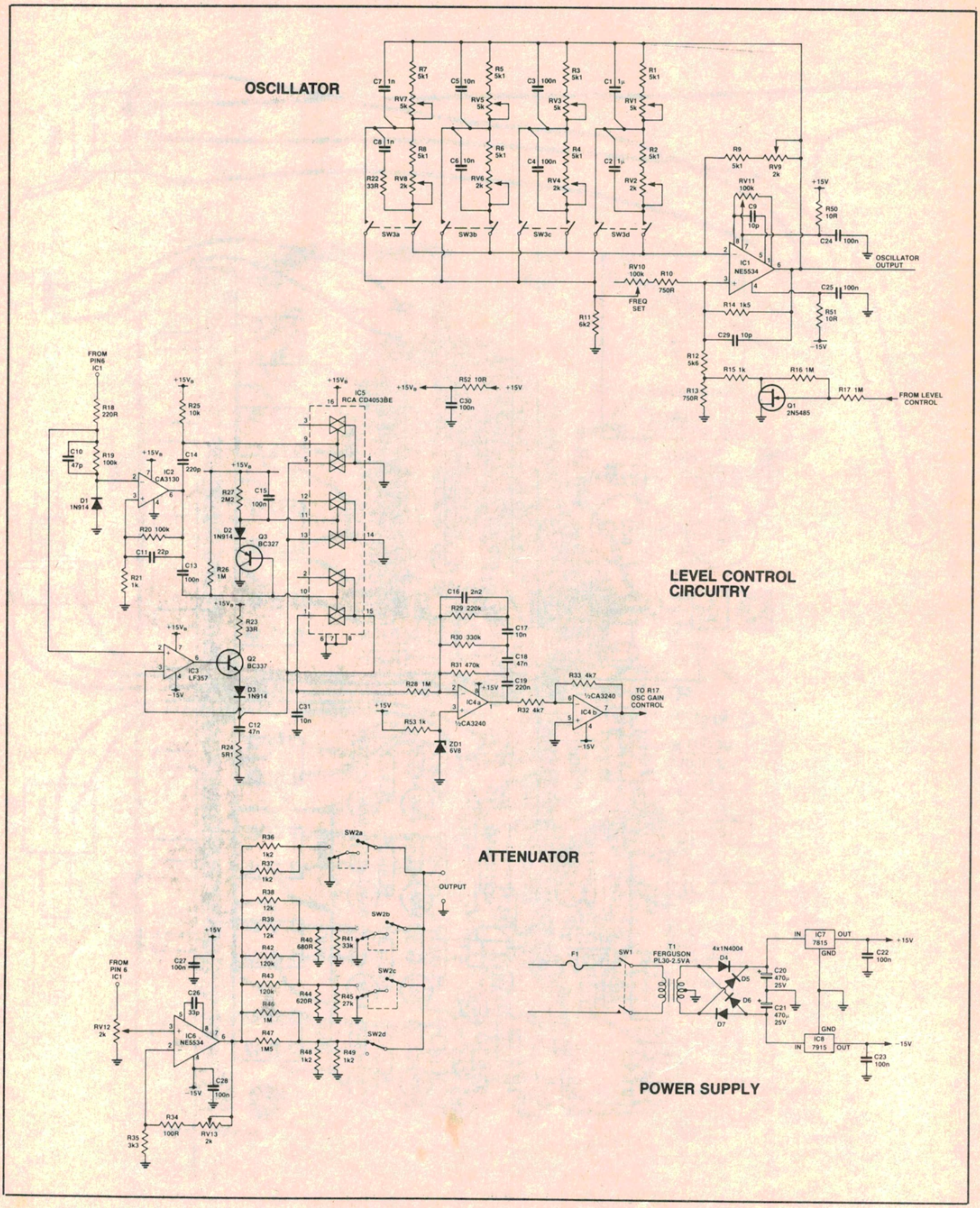
Miscellaneous

T1	Ferguson PL30/2.5 VA
SW1	DPDT mains toggle switch
SW2, 3	4-way pc mount switch bank and knobs
F1	350 mA 2AG fuse

ETI-169 pc board; 90 x 60 mm piece sheet copper; 120 x 170 mm sheet aluminium; Euro connector; 2AG fuse holder; 2 knobs for pots; 2 x 25 mm pc board spacer tapped at both ends; BNC panel mount socket; 200 x 160 x 70 mm plastic instrument case; Scotchcal front label; mains hookup wire; light hookup wire; assorted nuts and bolts.

Price estimate: $99.50


TO EURO CONNECTOR
FUSE HOLDER
SW1
OUTPUT
RV12
RV10
SW2
SW3
T1
LINK


OSCILLATOR
OSCILLATOR OUTPUT
FREQ SET
FROM LEVEL CONTROL
LEVEL CONTROL CIRCUITRY
TO R17 OSC GAIN CONTROL
RCA CD4053BE
ATTENUATOR
OUTPUT
POWER SUPPLY
FERGUSON PL30-2.5VA
4x1N4004

HOW IT WORKS — ETI-169

The audio oscillator can be separated into four main areas:

(1) the power supply;
(2) the oscillator;
(3) the output buffer and attenuator; and
(4) the level control circuitry which may be further broken down into
  (a) the peak detector;
  (b) the squarer; and
  (c) the integrator — loop filter.

The power supply is a conventional mains operated ±15 volt integrated regulator. The transformer TR1 is mounted on the printed circuit board and has a centre tapped secondary with outputs of ±15 volts ac. With this brand of transformer the secondary is designed to give rated voltage under full load so in the oscillator the voltages on the two filter capacitors C20 and C21 are at about ±24 volts. The current to charge C20 and C21 is provided from the full wave rectifier bridge D5 to D8. ICs 7 and 8 regulate the output from the filter capacitors to provide a clean ±15 volt supply for the oscillator.

The oscillator is based on an NE5534 operational amplifier with both positive and negative feedback. SW1, the frequency band switch, selects one of four RC networks to provide frequency dependent negative feedback through two resistors and two capacitors. The two resistors associated with each of the four networks are made adjustable to make up for the fact that only 10% tolerance capacitors are used. Direct negative feedback is also provided via R9 and RV9, and RV9 allows compensation for the fact that the frequency select potentiometer, RV10, is also only ±10% tolerance.

Negative feedback to preserve the correct conditions for oscillation is provided via R14. R12, R13, R15 and the level control FET, Q1, also form part of the negative feedback network. R16 and R17 ensure that the voltage on the gate of the FET is exactly one half of the gate-source voltage. This minimises distortion introduced by the FET and results in predominantly third order distortion.

RV10 is the frequency adjust pot and by varying its value from 100k to 0 ohms a frequency range of 0.9 to 11 can be achieved. As this frequency variation is proportional to the square root of the resistance it is necessary to use an inverse log law pot to avoid the frequency change being bunched up at one end of the pot rotation.

Both C24 in the negative feedback path and R34 in the highest frequency band select network are to compensate for stray capacitances around the loop and ensure that the correct conditions for oscillation are maintained.

The level control circuitry is fed from the output of the oscillator via R18 which is included to provide some isolation of high frequency spikes generated in the level control circuit. The oscillator output is squared by the squarer IC2 and its associated components. R20, R21 and C11 provide positive feedback for the squarer, which is really only an op-amp operating open loop. As IC2 and the circuitry it drives is CMOS it is necessary to only power it from +15 volts and ground. The op-amp will not tolerate large negative swings on its input under these conditions so R19 and D1 clip the negative swing at the op-amp negative input. C10 provides phase correction at high frequencies.

The output of the squarer drives a CMOS analogue switch CD4053. This switch has three sections, one of which is used to switch the error signal to the loop integrator and the other two are used to control the peak detector reset function.

The peak detector is formed by IC3 and its associated circuitry. IC3 is used as a non-inverting voltage follower with a transistor-diode in the feedback path. To understand how the peak detector works, first consider that C12 has no charge on it. This means that the voltage on the negative input of IC3 is zero volts. As the voltage on the positive input is taken positive by the oscillator output, the output of IC3 will also go positive turning on Q2 and forcing charge into C12 via diode D4. D4 is only included as the reverse bias breakdown of a transistor emitter base junction is normally only 6 or 7 volts and in theory could be left out (in practice it can't). Thus feedback is provided around the op-amp through the transistor and the negative input is held at the same voltage as the positive input. In the process C12 is charged to the same voltage as the positive input. R24 is included in series with C12 so the op-amp doesn't have to drive a purely capacitive load which makes the loop unstable.

When the input from the oscillator reaches its peak value and starts to swing negative again the transistor-diode prevents charge being removed from the capacitor and C12 is left charged to exactly the peak value of the oscillator output. The capacitor is left charged while the oscillator output swings through the complete negative part of its cycle and starts to come positive again. When it passes through zero volts positive going the squarer output IC2 pin 6 switches negative. This sharp edge is differentiated through C14 and R25 to produce a narrow negative spike on the input of one of the analogue switches. This turns on the analogue switch IC5 pins 4 and 5 and partially discharges the peak detector capacitor C12 ready for the next peak detection cycle.

The resultant voltage on the peak detector is thus a dc voltage equal to the peak ac value of the oscillator output with small negative steps every time the oscillator output crosses zero positive going.

A second section of the analogue switch is driven directly from the squarer output such that pins 1 and 15 are on during the negative half of the oscillator output and off during the positive half. Thus when the peak detector output is stable the analogue switch is on and when it is being reset it is off.

One problem that exists with this type of level control circuit is that it is possible for the oscillator to stop running because the gain control is set too low. If the peak detector has been charged to a high voltage by a transient then, as the oscillator is not running, no reset pulse is generated from the squarer output and the oscillator cannot start. To prevent this C15 is continually discharged to ground by the squarer output if it is running by Q3 and D2.

If the squarer stops running or fails to start then R27 charges C15 to the positive rail and turns on the analogue switch pins 13 and 14. This completely discharges the peak detector. At the same time the squarer input to the analogue switch (pins 1 and 15) is ac coupled through C13 and R26 and thus under no signal conditions IC5 (pins 1 and 15) is turned hard on. This ensures that the oscillator will always get a 'kick start' if it fails to start normally.

The loop integrator is formed by one half of IC4, a MOS input op-amp. The input to the integrator is from pin 1 of the analogue switch which is at the peak detector output voltage for half the time and open circuit for the other half. The positive input of the op-amp is set to a reference voltage by the zener diode, ZD1, biased by R29.

A rather complex feedback network is formed around the op-amp by capacitors C16, C17, C18, C19 and resistors R29, R30 and R31. All these components are necessary to preserve the correct gain/phase conditions for all oscillator frequencies and conditions. The most important feature of the network is that C19 has no resistor in parallel with it and hence for low frequencies the amplifier acts as a pure integrator. This means that given sufficient time the dc voltage at the peak detector output will be adjusted by the loop to be exactly equal to the reference voltage no matter how other conditions in the loop vary.

The output of the loop integrator is inverted by the second half of IC4 with resistors R32 and R33. This is because the FET, Q1, requires an increasing dc voltage to reduce the gain and preserves the correct dc operating conditions.

The output buffer amplifier is formed by IC6 and is a simple non-inverting amplifier with adjustable gain so the correct output level can be set. RV12 is the level adjust potentiometer on the front panel which allows the oscillator output to be adjusted from maximum to nothing and RV13 in the feedback is the fine adjust to preset the amplifier gain. The output of IC6 drives three 'L' pad attenuators and a series resistor in parallel to generate four outputs, all of which have a 600 ohm output impedance and output levels of 0, −20, −40 and −60 dB referred to the output of IC6. One of these four outputs is selected by SW2 and connected to the output terminals. SW2 is connected in a 'T' configuration with the centre of the off switches connected to ground to minimise capacitive coupling of the higher level outputs to the low level output.

being coupled into the output. There were three ways that this could occur. The first was that there was hum on the power supply lines but as the crud in the output was 50 Hz this tended to rule it out. Any unfiltered and regulated grot on the rails would be at 100 Hz (full wave rectifier bridge). Also a quick check showed the rails were as pure as the driven slush.

The next way was through some capacitive coupling from the mains area to the oscillator circuit. As the problem seemed to occur only for the lowest frequencies where the frequency set pot has its highest resistance, this seemed most likely. Capacitive coupling is a high impedance effect which is, praise be, easy to stop. By holding my hands around the oscillator I found that I could snuff the coupling with ease. It appeared that I was getting capacitive hopover from the mains wiring to and from the ▶

switch and the high impedance oscillator circuit. Annoying but not disastrous. If it had been stray magnetic fields from the transformer it would have meant deep trouble; an electrostatic field will be stopped by almost anything but a magnetic field takes kilos of iron.

To fix it I cut a piece of sheet metal to fit in the bottom of the box so it covered the complete area under the oscillator. This must include the area under the switch bank right up to the front panel. It should extend from the centre of the box right to the left hand edge. I then completely removed what was left of the unwanted mounting pillars with a hammer and sharp wood chisel and fitted the screen to the case. I connected a piece of wire to the screen and brought it out so I could earth it and reassembled the oscillator. About a 10 dB improvement but still not nearly good enough!

I found that holding my hands over the oscillator part of the circuit still had a very marked effect so a screen above the circuit was needed too. I mounted two 1" spacers off the board in grounded areas and cut a piece of aluminium so it completely covered the top of the board, with a notch out of one corner to clear the transformer and filter capacitors. When I screwed it down there was considerable improvement but still not good enough.

If a piece of metal was held down the left hand side of the box near the oscillator frequency select elements, it helped a bit so I bent up a small bracket to protrude down 25 mm from the top screen, extending from the front edge of the screen to the centre of the side where there is a major mounting pillar. This was easily attached with two of the self tappers that hold the board down. Another test and almost good enough!

After a few more magic gestures with my hands the last culprit was found. The field was coupling into the frequency pot itself which is visible above the screen. A bit more quick work with sheet aluminium and a little box was screwed in place around the pot. In case you have some trouble getting the sheet aluminium, I used a cheap oven baking tray that was on special for a dollar — it seemed to be pretty good stuff too! This completed the screening and got the hum down to acceptable levels. Even if you chose to use a metal instrument case it would still be necessary to do the top part of the screening as the mains wiring and the oscillator are inside the same box.

After you've gone through all the hassles of making screens as above it should be a snip to screw the board in place. Wire up the frequency select pot *using as short a wire as possible,* the output level pot and the mains wiring to the switch. The mains connection on the rear panel was through an IEC socket so if some oaf trips over the mains cord it just pulls the plug rather than ripping the cord out by the roots. Both the mains IEC connector and fuse are mounted off the rear panel and holes have to be cut for them. It's a good idea to cut the fuse-holder hole just the right size and cut the locating notch in the side so it cannot rotate. *All mains wiring connections should be securely made by looping the bared end of the wire through the terminal tag then soldering it.* All connections should be completely insulated as you'll be the one to cop it if they aren't. The final result should look pretty much as shown in the photo. If this is all OK, remove the top screen and the unit's ready for final test.

More alignment and testing

Final alignment follows almost exactly the same routine as laid out in the preliminary testing except that it's a bit easier as the oscillator is working. You'll probably notice things need a bit of tweaking as the stray capacitances have changed. If the FET control voltage is allowed to go much further than −2 volts then the third harmonic distortion will start to rise. It will also be noticed that when the frequency pot is rotated from one extreme to the other a dc offset will appear in the output. To remove this adjust RV11 next to the oscillator op-amp until there is no discernible shift over the entire range.

The only adjustment left to be made is to set the output level. To a certain extent this is a matter of choosing the units you like to work in. My choice was to terminate the output in 600 ohms then set the level pot so the maximum level out was +12 dBm or just a shade over 3 Vrms. 0 dBm is a very commonly used reference level in the audio industry and is exactly 1 mW into 600 ohms or, in volts 0.775 Vrms. The oscillator is capable of putting out up to 4 Vrms or +16 dBm.

At this stage the top screen can be screwed into place and the small cover screwed over the pot. It has to be put on afterwards but I imagine you've discovered that already! Screw on the top cover, attach knobs to the two pot shafts and the unit is ready to have the front panel marked. To calibrate the frequency pot set the knob on the pot so the knob pointer's rotation is symmetrical about the vertical axis, then set for far counterclockwise. Select the 900-11,000 Hz range and connect the output to your counter. The counter should read 900 Hz give or take. Mark this point with a pencil and label it. Then proceed up the scale in 1000 Hz increments marking and labelling each point. You will probably want finer calibration points between 1000 and about 4000 Hz but above that the scale starts to close up. The number of points you plot is largely a matter of taste and how you want the front panel to look.

Exactly the same procedure is followed for the level pot except that a level meter (or, at a pinch, an oscilloscope) is connected. If you're calibrating in dBm don't forget to terminate the output in 600 ohms. You can then permanently mark the front panel with an engraving tool or dry transfer lettering to give the unit a completed look. The switch banks also need to be labelled in some way too. When this is all done you've added another weapon to your arsenal of electronic weaponry! ●

Below. Bottom of the box showing the piece of sheet metal covering the area beneath the oscillator. Insulation tape is used to prevent shorting of tracks. **Right.** Aluminium completely covering the top of the board with a small bracket protruding down from the top screen stops the electrostatic field. (View from rear of box.)