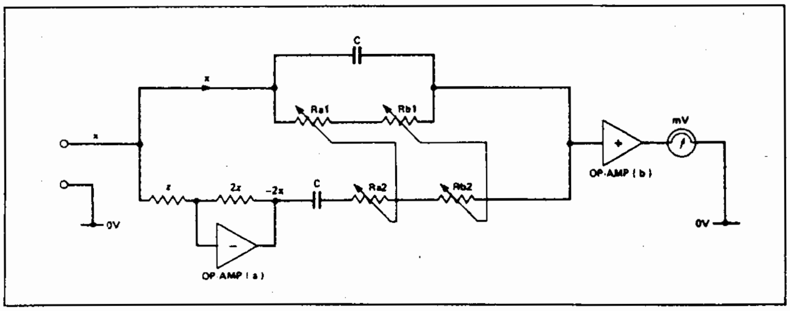

Fig. 1 The configuration of the Wien bridge used by the author; it has advantages over the more common differential version.

Distortion Meter

The distortion meter is a useful piece of test equipment that can quickly give a circuit a clean bill of health (or not). Here is the first of two parts on building your own.

By John Linsley Hood

THE IDEAL power amplifier, along with other pieces of audio signal handling gear not intended to modify the frequency response of a system, is best described by the old adage "a piece of wire with gain". This implies that the equipment does not modify or impair the signal being handled except to amplify or add muscle power.

However, if this is the specification, how do we check to see how well or how badly this requirement is being met? This is, alas something on which there is very little agreement between audio engineers or circuit designers. So, before we consider the hardware, we need to examine the job we want it to do.

In simple terms, what we want is that the output from an amplifier should be identical to the input, except that it might be bigger or smaller or perhaps one part of the frequency spectrum has been enlarged or diminished. This is an awkward bit, so let's leave that to one side for the moment and just look a the simple flat-frequency response area.

When people first considered this problem, their thoughts turned to the examination of a continuous, fixed-frequency sine wave somewhere in the middle of the audible band, say at 1000Hz. The logic of this was that any distortion of this waveform would lead to the generation of harmonics of the input signal, and these could be isolated and measured.

The problem with this approach is that it is highly artificial. We simply do not listen for enjoyment to steady single tones. Nevertheless, the technique is a useful one, especially if the output from the distortion meter can be examined on an oscilloscope. Quite a lot of information about its defects can then be gained, allowing the affects of changes to be assessed.

The most common of this kind of meter is the simple notch filter which will remove the incoming sine wave and leave only the waveform impurities which have been added by the hardware which we are testing.

The sort of result we would get at the output of the distortion meter is a small waveform which when added back to the distorted output would give us the pure signal with which we started. The waveform of the distortion products may be symmetrical about the zero axis, indicating distortion on both halves of the cycles, or it may be negative or positive spikes, indicating trouble on only one half of the cycle (such as an amplifier clipping on only the negative cycle).

The most conspicuous audible effect of the presence of large amounts of low-order distortion (mostly 2nd and 3rd) is that harmonic tones are added to the signal, making the system sound rather shrill. Those of us with long memories will recall the sound of output pentode power tubes, which caused generous quantities of 3rd order distortion. Triodes were much preferred since they generated mostly 2nd harmonic distortion, and this was lower down in the spectrum and sounded less "squawky".

Also, as one might guess, these low-order harmonics do in fact harmonize with the input signal; once one gets beyond the 3rd in the odd-orders or the 6th in the evens, the tones become increasingly dissonant and objectionable to the listener.

This was one of the reasons why the first transistor amplifiers were so much worse than the tubes they replaced, even at 0.1 percent distortion; the distortion products were 7th, 9th, 11th and other dissonant odd harmonics.

A way of measuring distortion distinct from the notch method is to put in a high-purity sine wave and then display the output of the amplifier as a sweep of the frequency response on a spectrum analyzer. The various harmonic products will be displayed on a vertical log scale, either on a paper printout or a video screen. While the display is very effective, it's a bit hard to read if the distortion is down around 0.01 percent, not to mention the cost of the equipment required.

Notching

The Total Harmonic Distortion meter in this project is the Wien bridge notch type; it produces a sharp notch in the frequency response which removes the fundamental of the test tone being used. Anything left over should consist of distortion products plus hum and noise. The noise can be subtracted by disconnecting the signal source; we'll come back to applications in the second part of the article.

The basic layout of the meter is shown in **Fig. 1** and the circuit diagram in **Fig. 2**. The total circuit consists of the meter, a millivoltmeter, a built-in

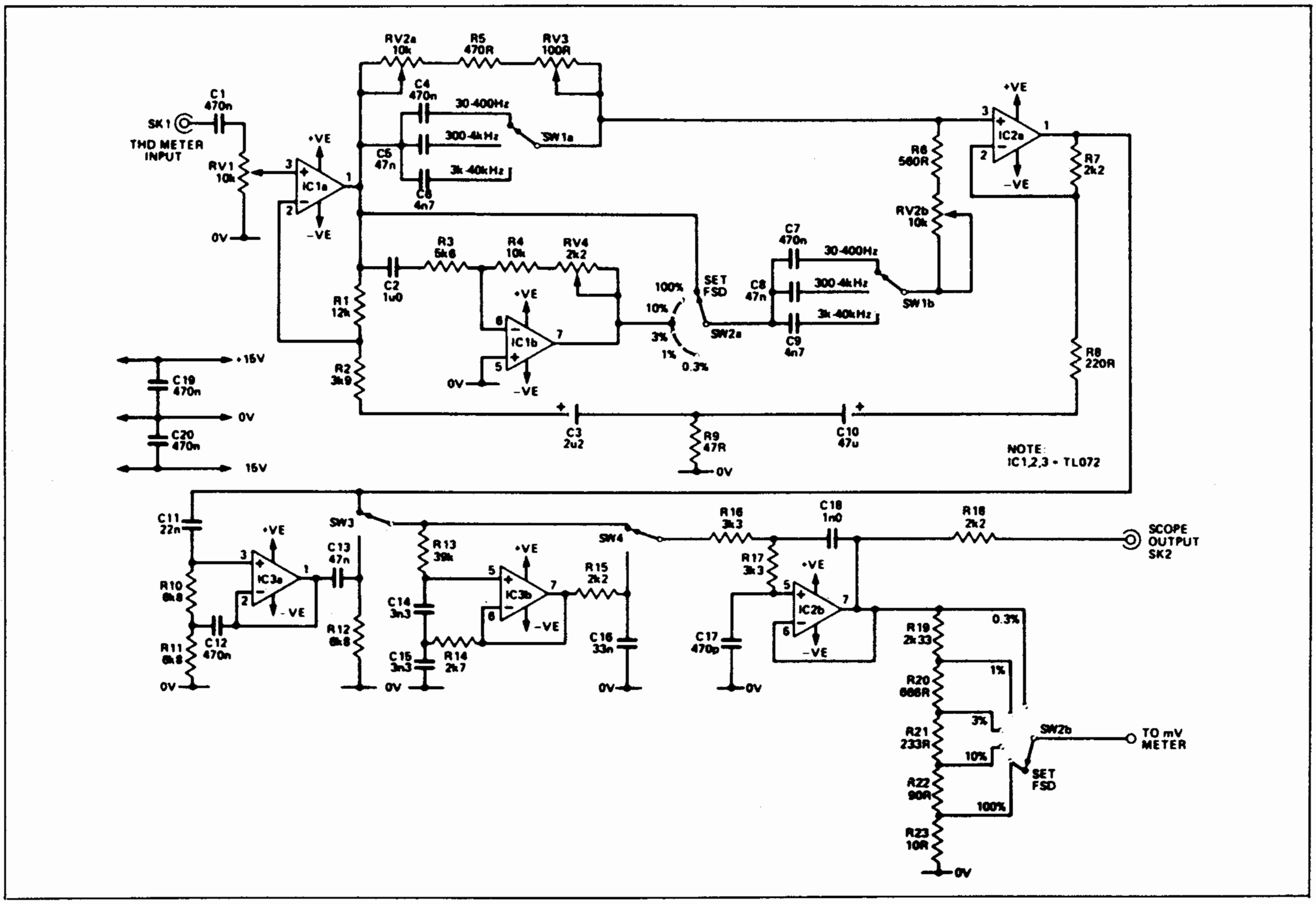

Fig. 2 The final circuit diagram of THD meter.

oscillator, and a regulated power supply. There is also a converter for running the unit from a single battery.

The Meter Bridge

In Fig. 2, RV1 acts as a gain control in the input circuit of IC1a, a buffer stage that ensures that the Wien network is always driven from a low impedance. From the output of this the signal is divided into three paths, the upper RC parallel network, the inverter stage, and a feed to the mode switch SW2, which allows the network to be bypassed for setting the full scale meter reading.

In the other positions of SW2, the two halves of the network are connected to produce the notch characteristic required. For a perfect balance to be obtained, the input from the inverter to the lower section needs to be exactly twice as large as the input to the upper. To arrange this, a 2K2 10-turn pot, RV4, is connected in series with the op-amp feedback resistor so that its gain can be adjusted. This is the Trim control on the front panel.

Ideally, the tuning of this instrument would be done by dual gang pots, Ra and Rb. However, I wanted to keep circuit impedances as low as possible for minimum hum pickup and circuit noise, and 1K dual pots are hard to come by. I have therefore, with regret, because it makes the instrument a little more difficult to use, opted for a single fine-tune pot, the 100 ohm RV3. This means that notching out requires the interaction of RV3 and RV4. If a decent quality low resistance dual pot is available, the other half should be inserted in series with R6, whose value can then be reduced to 470 ohms.

It is necessary to sharpen up the notch a bit to prevent unwanted attenuation of the lower harmonics, and this is done by negative feedback to IC1 from IC2 through R9, R2, and R8.

There are two signal infiltration stages. IC3a is a highpass hum filter with a turnover frequency of 250Hz and a slope of 18dB/octave; a similar lowpass built around IC3b has a similar slope and a turnover frequency of 4700Hz. These two options are selected by SW3 and SW4. The lowpass HF-noise filter allows an instrumental identification of the harmonics associated with crossover distortion, which with a 1KHz signal would be at 7, 9, 11, and 13KHz.

So, if the minimum signal is noted on a test at 1KHz and the lowpass filter is then switched in and the new minimum noted, the amount of high-order harmonics present can be determined by an RMS subtraction of the two values. To distinguish between high-order harmonics and general noise, the extent to which the difference between the filtered and unfiltered signal levels changes when the signal input is removed can be noted.

The final stage of the distortion meter part of the circuit is the buffer amplifier, which precedes the meter attenuator, and from which an oscilloscope monitor signal can be obtained if needed.

An option included is the 50KHz, 12dB/oct, unity-gain rolloff buffer IC2b, which serves as a useful bandwidth limit. If this is not required, the output of SW4 can be sent to the non-inverting input of IC2b and C17, C18, R16, and R17 deleted.

The Millivoltmeter

Since any distortion meter requires an AC millivoltmeter to display its result, and the millivoltmeter is a useful bench instrument, I have decided to make the input to the measuring circuit available separately by way of a switched attenuator, **Fig. 3.**

The circuit is straightforward, with a 100uA meter in a diode bridge in the feedback network of an op-amp. I have used a dual FET amp (TL072 or LF353) in which the first half acts as a gain stage. This allows both high input impedance and a 20Hz-100KHz -3dB bandwidth.

The input attenuator has a resistance of 100K ohms; this can be scaled up to 1M if the constructor takes care to shield it to prevent pickup from other parts of the circuit. Calculating the actual resistors is easily done by using the current flow down the chain. For instance, 100V across 100k gives a current of 1mA. This will develop 10mV across 10 ohms, and hence the value of R32, and so on. Odd resistor values can be made up by paralleling standard values, depending on the accuracy required. For instance, a 6k66 resistor can be made up by putting a 330k and a 6k8 in parallel.

The proper operation of this type of circuit depends on a low impedance from the non-inverting input to ground, so the tantalum beads are bypassed with small non-polarzied types (C22 and C24). The supply lines are also bypassed to ground with 0.47uF capacitors.

The Oscillator

It's a great convenience to have an oscillator actually on the instrument, and from my experience I find that one does not need a continuous spread of frequencies, but rather a few spot points. The reason for this is that if you know how a system behaves at, say, 1KHz or 3Khz, its behaviour at 1500Hz or 3500Hz is unlikely to be anything but intermediate between the known points.

The basic circuit used is the Wien bridge system. The inverting input is fed with two feedback signals through the sections of the Wien network. A positive feedback signal is obtained from the two inverting amplifiers connected in series through the RC element, and the negative feedback signal is fed to the same point from the output of the inverting amplifier.

The gain of the second amplifier is controlled by a thermistor in the feedback path. When the thermistor is cold, its resistance is high and ICb has a high gain. This makes the positive feedback larger than the negative and the system oscillates. The output signal warms the thermistor, lowers its resistance, and increases the negative feedback to lower the gain to just enough to keep the circuit oscillating at a constant amplitude.

Because op amps have a lower distortion in the non-inverting mode (surprising but true), and because the circuit has no common-mode signal which the op-amp must cancel, the distortion produced by this circuit is extremely low. **Table 1** shows the distortion performance of the oscillator. The high distortion a low frequencies is mostly third harmonic, caused by the thermistor resistance actually varying with the waveform amplitude. This is inherent in amplitude-stabilized systems.

The output from ICb is about 600-700mV with an RA53, and the signal level at the output of ICa is about half this. I mention this because ICa is an integrator with a response which decreases with frequency, reducing the third harmonic distortion to about one-third at ICa, making a very low distortion oscillator indeed. However, for a THD meter with a minimum reading of .005 percent, the circuit shown is adequate.

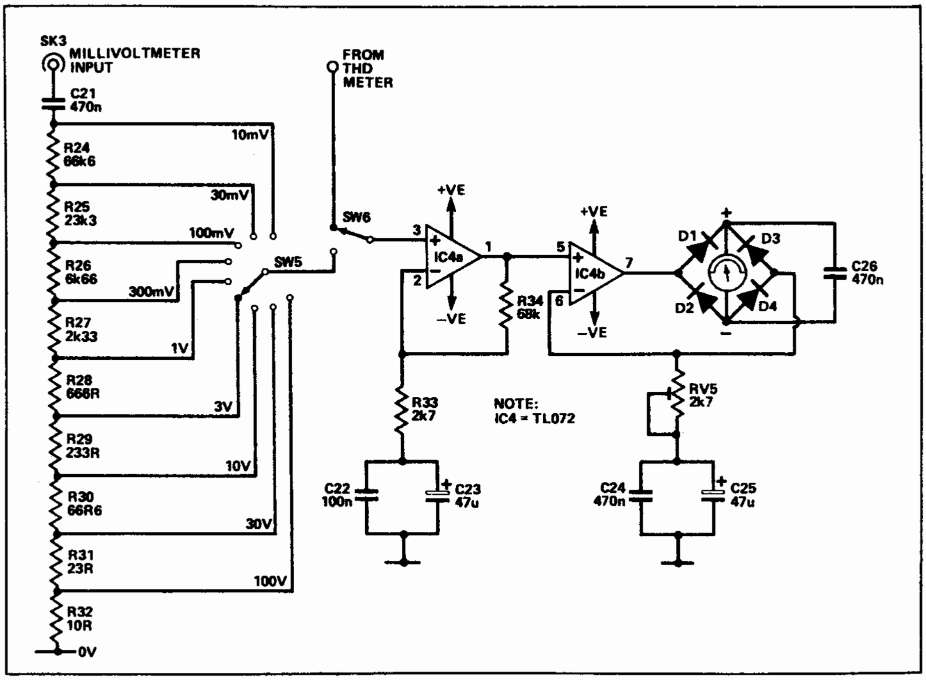

Fig. 3 The circuit diagram of the millivoltmeter.

The final circuit is shown in **Fig. 5.** The value of C is constant and R is changed to alter the frequency; this allows the use of easily-obtained resistors and only two close-tolerance polystyrene capacitors.

A three-stage output attenuator is used in combination with the output potentiometer to give output signal levels of 0-6mV, 0-60mV and 0-600mV. The output can be increased to about one volt by putting a resistor of 500 ohms and 1k5 ohms in series with RA53. This will lower the distortion slightly, but will increase the settling time. On the prototype this is 2000 cycles, about 20 seconds at 100 Hz, but this will vary from one thermistor to another.

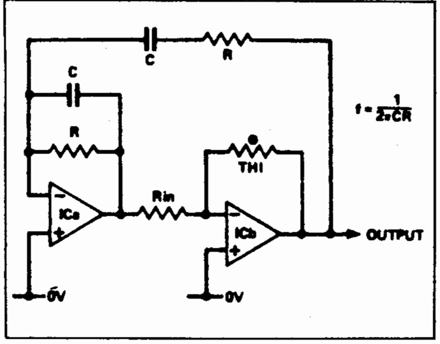

Fig. 4 The basic arrangement used in the spot frequency oscillator.

Power Supply

The total current consumption of the instrument is 18mA at plus and minus 15 volts, which is obtained from a small stabilized supply.

It is possible to make the instrument operate from batteries. Two options exist. The first is use a pair of 6V or 9V batteries, such as the popular 9V radio battery, and switch both supply rails. The second is to use a single 9V battery and use the adapter shown to give plus and minus 4V5. In both cases it is worthwhile substituting TL062s for IC1, IC2, IC3, and IC5, and a TL061 for IC4. This reduces current consumption to 1.5 to 2mA with little performance penalty.

FREQUENCY (Hz)	THD (%)
100	0.02
300	0.005
1k	less than 0.003
3k	less than 0.003
10k	less than 0.003
20k	less than 0.003

Table 1 Measured performance of the spot frequency oscillator.

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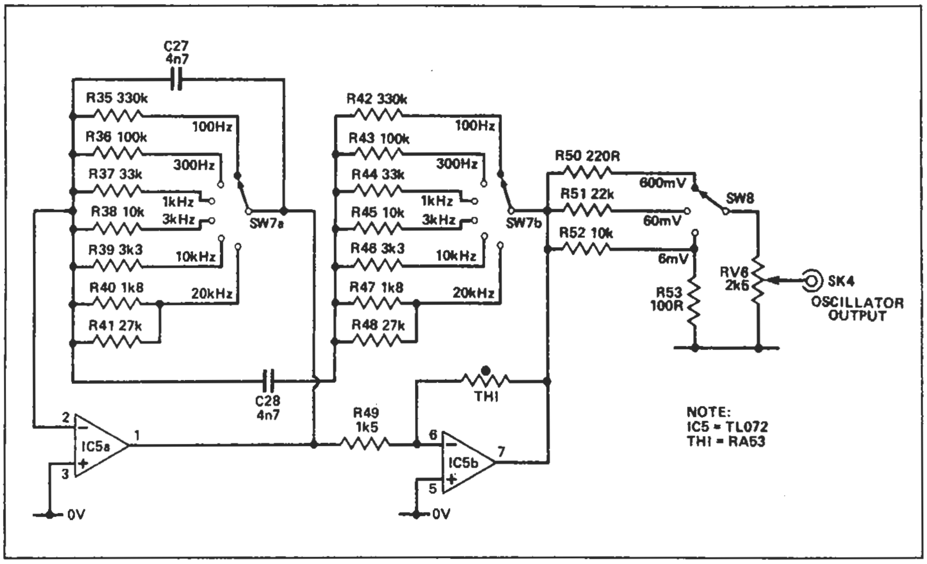


Fig. 5 The final circuit diagram of the spot frequency oscillator.

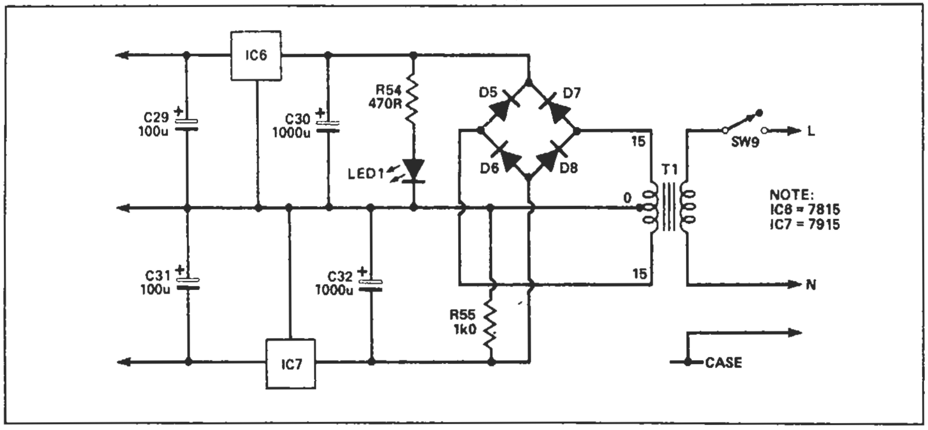
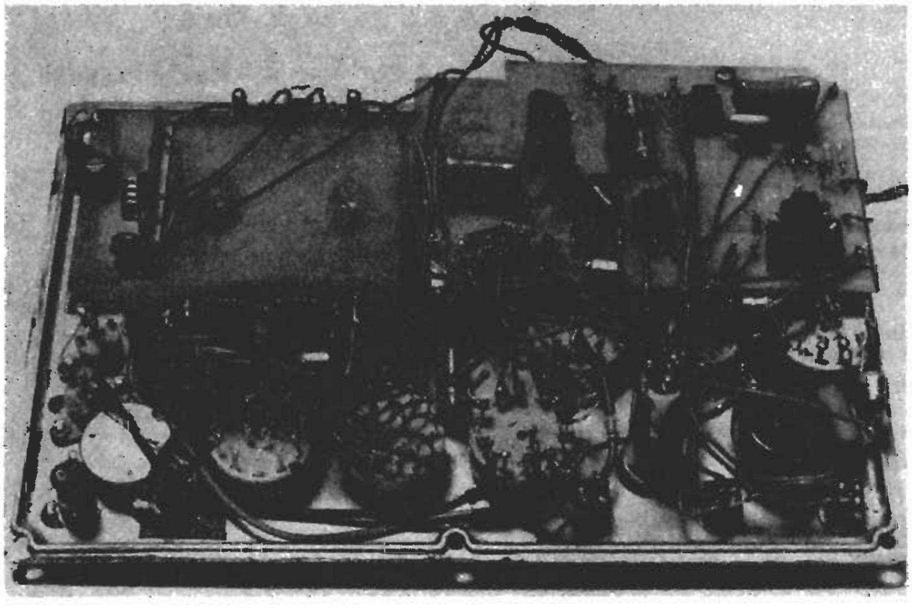


Fig. 6 The circuit diagram of the stabilized power supply.



Internal view of the prototype. A number of modifications have been incorporated in the final version, so don't try and follow this wiring too closely!

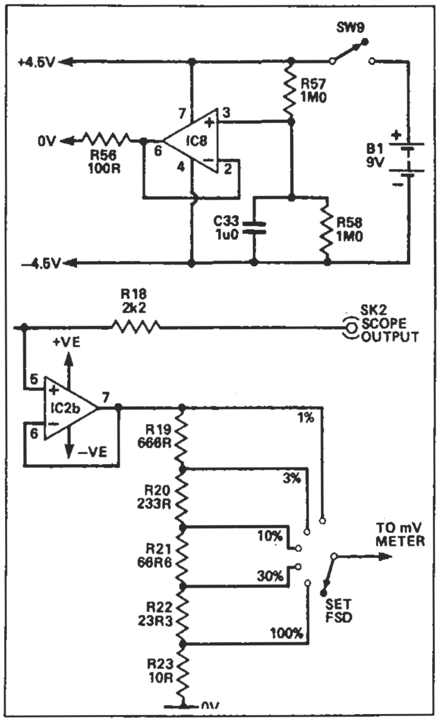


Fig. 7 A dual supply from a battery (top) and changes in the circuit to suit this method.

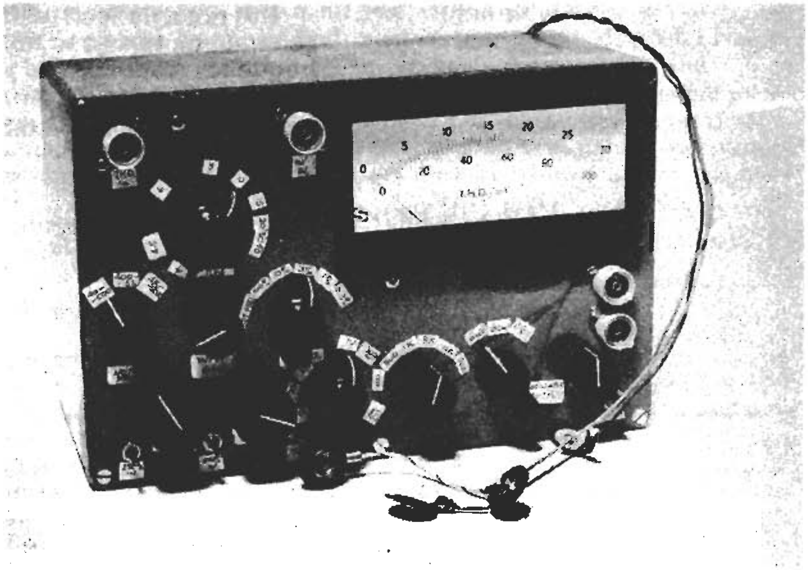
However, if the supply voltage chosen is the plus and minus 4V5, a problem would arise because the notch amplifier circuit would overload at the 3V RMS required from ICs 2 and 3 for FSD on the measuring instrument. It is therefore necessary to downgrade this a bit by cutting out R19 (2k33) so that SW2b is that shown in **Fig. 7.** This gives a minimum sensitivity of 1 percent. This requires only a 1V swing from the notch amplifier.

The Wien Bridge

It is not a difficult matter to generate quite a good notch in a frequency response and tune it to the test waveform, and there are several circuit choices for doing this. Of these, the two most convenient are the RC Twin-T and the Wien bridge.

The interesting thing about the Wien bridge is that it has zero phase shift and an attenuation of just three at one specific frequency. If one makes the resistors adjustable, this frequency can be altered. If the capacitors are not quite the same, the attenuation will not be exactly three, but this can be adjusted by altering the values of the resistors.

In the circuit I have chosen, the amplifier is used to simply invert the phase of the signal and amplify it by 2x. This utilizes the feature of the Wien bridge that the impedance of one leg is twice that of the other when the phase shift produced by each leg is equal. So, if the amplifier applies a signal to the upper half which is exactly twice that of the lower, the output will come to a null at some frequency



The prototype, looking much the way most prototypes do at this stage in their development!

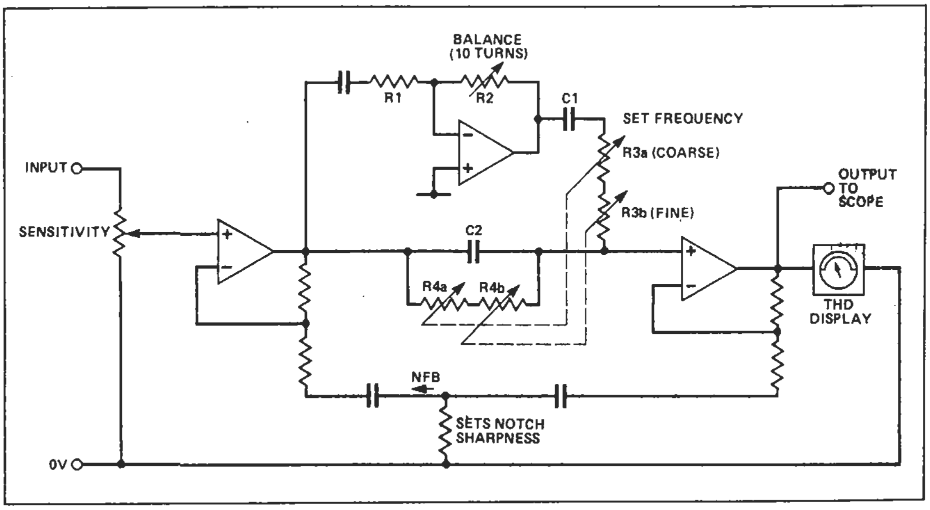


Fig. 8 Wien network with negative feedback to produce a sharper notch.

dependent on the values chosen. This amplifier method eliminates the problem of requiring a very well-balanced differential amplifier.

If we just want to remove the input signal frequency without attenuating the harmonics, the skirts of the notch must be much steeper than those of an ordinary Wien bridge. However, we can sharpen the notch by applying some negative feedback around the bridge.

To tune the notch frequency so that it exactly coincides with the input frequency, we need to be able to adjust either the Cs or the Rs in the network. Since the operating frequency is given by the equation

$$F_o = \frac{1}{2\pi\sqrt{C_1 C_2 R_3 R_4}}$$

the values for C are too large to allow the use of a variable ganged capacitor unless a very high impedance circuit is used. In fact, if the Rs were 10k each, the capacitors would have to be 16nF for a 1KHz notch frequency, and lower frequencies would require proportionately larger values of capacitors.

It is possible to make such a system with an air-spaced twin-gang capacitor, but the necessary high values of R make the whole unit very sensitive to hum pickup. Overall, I think it is better to use variable resistors, which are easier to get and a lot more compact.

The necessary slow-motion adjustment can be obtained by the use of two resistors in series, one ten times the value of the other, when the high value resistors (as ganged pairs adjusted together) can be used as the coarse adjustment and the lower ones for fine trimming. This principle could be extended, of course, to employ three such resistors in series to allow a very fine adjustment indeed.

Since the resistor which adjusts the gain of the Wien amplifier is a single potentiometer, a ten-turn type can be used in this position to adjust the gain of this leg so that a complete notch is obtained with no residues of the input frequency remaining.

The final part of the system will be a wide bandwidth millivoltmeter to display the value of the distortion and noise residues remaining when the input sinewave is removed.

Since we live in the real world and there will inevitably be some hum pickup somewhere in the system we are testing, it is useful to incorporate a 60 Hz filter which can be switched in. Also, while we are doing that, we might as well include some HF filtering options so that we don't measure the THD over too wide a frequency window, with its associated noise components.

Finally, it is very helpful in tests where one is taking the measuring instrument to the gear being tested, to have a built-in signal source of adequate quality.

There are two versions of the above instrument in this project; one a laboratory standard instrument operated from the AC line, and a somewhat simpler version operated from a single 9V battery, which will be somewhat easier to make, if the demands made upon it are less stringent.

I like battery operated instruments myself because they are highly portable and don't cause problems with ground loops. However, if one wants high performance, it is impractical to demand much lower power consumption at the same time. If one then accepts a higher battery drain, say, 10–25mA, it is expensive if one forgets to switch off the instrument after use, while any auto-off circuit may switch it off in the middle of a measurement, which is infuriating.

Hence the two versions of the instrument. I have deliberately tried to make the battery-operated system as economical in use as possible without resorting to exotic ICs, and in both cases I have organized things so that the millivoltmeter is available as a separate input so that it and the oscillator can be used on their own as a means, for example, of measuring frequency response.

PCBs and constructional details will appear next month.

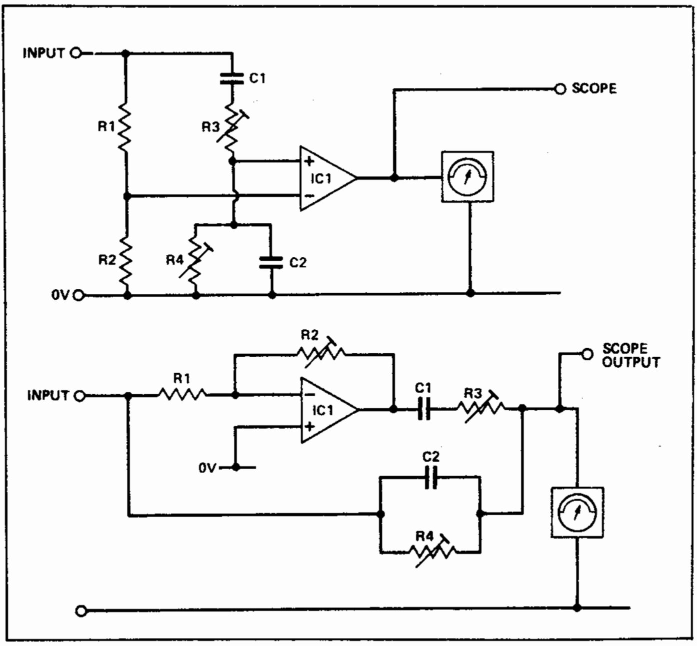


Fig. 9a and b — Two possible arrangements of the Wien network.

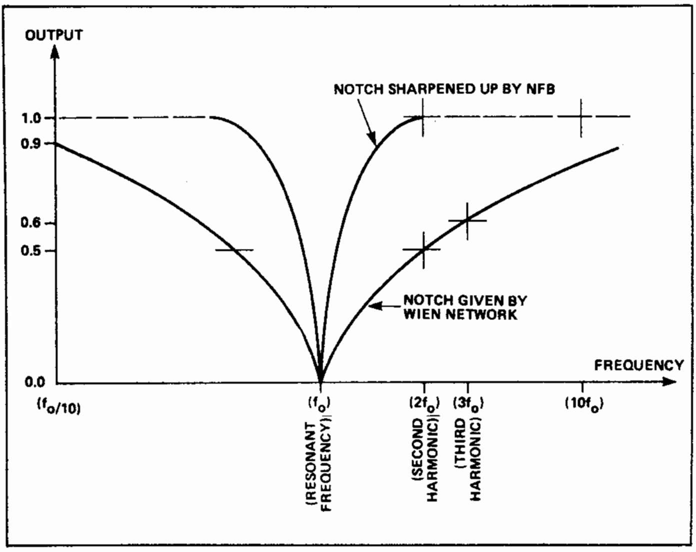


Fig. 10 The notch produced using the arrangement of Fig. 9b.

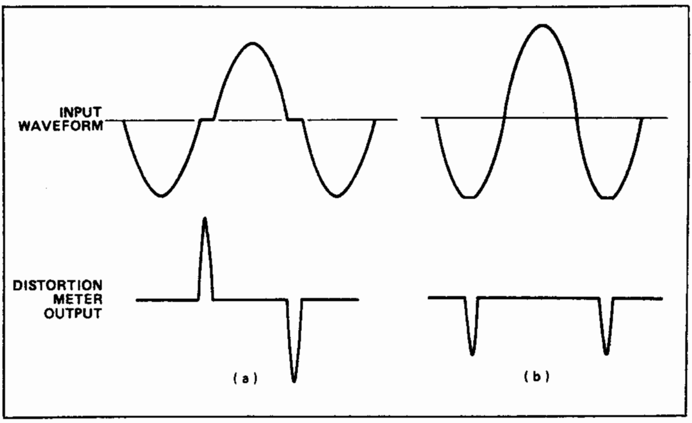


Fig. 11 Examples of the waveforms obtained by using a notch filter on distorted sine-waves.

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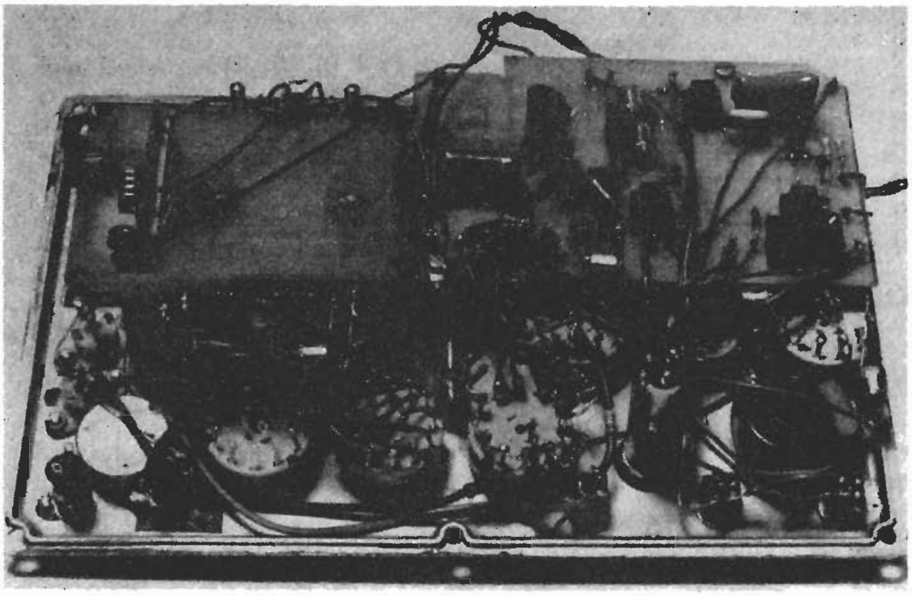

Distortion Meter Part 2

The second and final part, describing the construction and use of the distortion meter project.

By John Linsley Hood

THE THD meter is built on two PCBs, one carrying the circuitry for the distortion meter and the millivoltmeter and the other carrying the oscillator circuitry. A further PCB is required for the regulator or the dual-rail circuit if the battery supply is used. No power supply is required if twin batteries are used.

Assembly of the PCBs should present no problems if the the overlay diagrams are followed carefully, and the only points to watch are the usual ones concerning orientation of ICs, electrolytics, diodes, and any other polarity-conscious components. If you're using IC sockets, these should be soldered on first, followed by the passive components and the insertion of the ICs. If you're not using sockets, insert and solder the passive components first before soldering in the ICs.

The choice of case will be determined by the method of powering you intend to use. The single battery option will fit into a fairly small case, the twin-battery version will be slightly larger, and the AC version will be largest, requiring enough space for the transformer plus adequate clearance between this and the rest of the circuitry to prevent hum pickup. A die-cast box is preferable to a pressed-steel one, and you should not use a plastic box.

The PCBs are mounted below the front panel using stand-off pillars, and the total depth of the finished unit should be about two inches. This allows plenty of room for a metal shield and an AC power supply to be mounted in the base of a suitable box without making the completed instrument unduly deep. Leave yourself plenty of room, however; too tight a construction may lead to capacitive coupling between various parts of the cir-

Parts List — The Meter and Millivoltmeter

Resistors (all ¼W carbon or metal film)

R1	12k
R2	3k9
R3	5k6
R4	10k
R5	470R
R6	560R
R7, 15, 18	2k2
R8	220R
R9	47R
R10, 11, 12	6k8
R13	39k
R14, 33	2k7
R16, 17	3k3 (see text for R16-32)
R19, 27	2k33
R20, 28	666R
R21, 29	R33R
R22	90R
R23, 32	10R
R24	66k6
R25	23k3
R26	6k66
R30	66R6
R31	23R
R32	10R
R34	68k
RV1	10k
RV2	10k dual gang
RV3	100R
RV4	2k2
RV5	2k7

Capacitors

C1, 4, 7, 12, 19, 20, 21, 24, 26	470n
C2	1u0
C3	2u2 electrolytic
C5, 8, 13	47n
C6, 9	4n7
C10, 23, 25	47u electrolytic
C11	22n
C14, 15	3n3
C16	33n
C17	470p (see text)
C18	1n0 (see text)
C22	100n

Semiconductors

IC1-4	TL072
D1-4	1N4148

Miscellaneous

M1	100uA meter
SK1-3	co-axial socket, panel mounting
SW1	2 pole, 3 way rotary switch
SW2	2 pole, 6 way rotary switch
SW3, 4, 6	SPDT toggle switch
SW5	1 pole, 9 way rotary switch
PCB.	

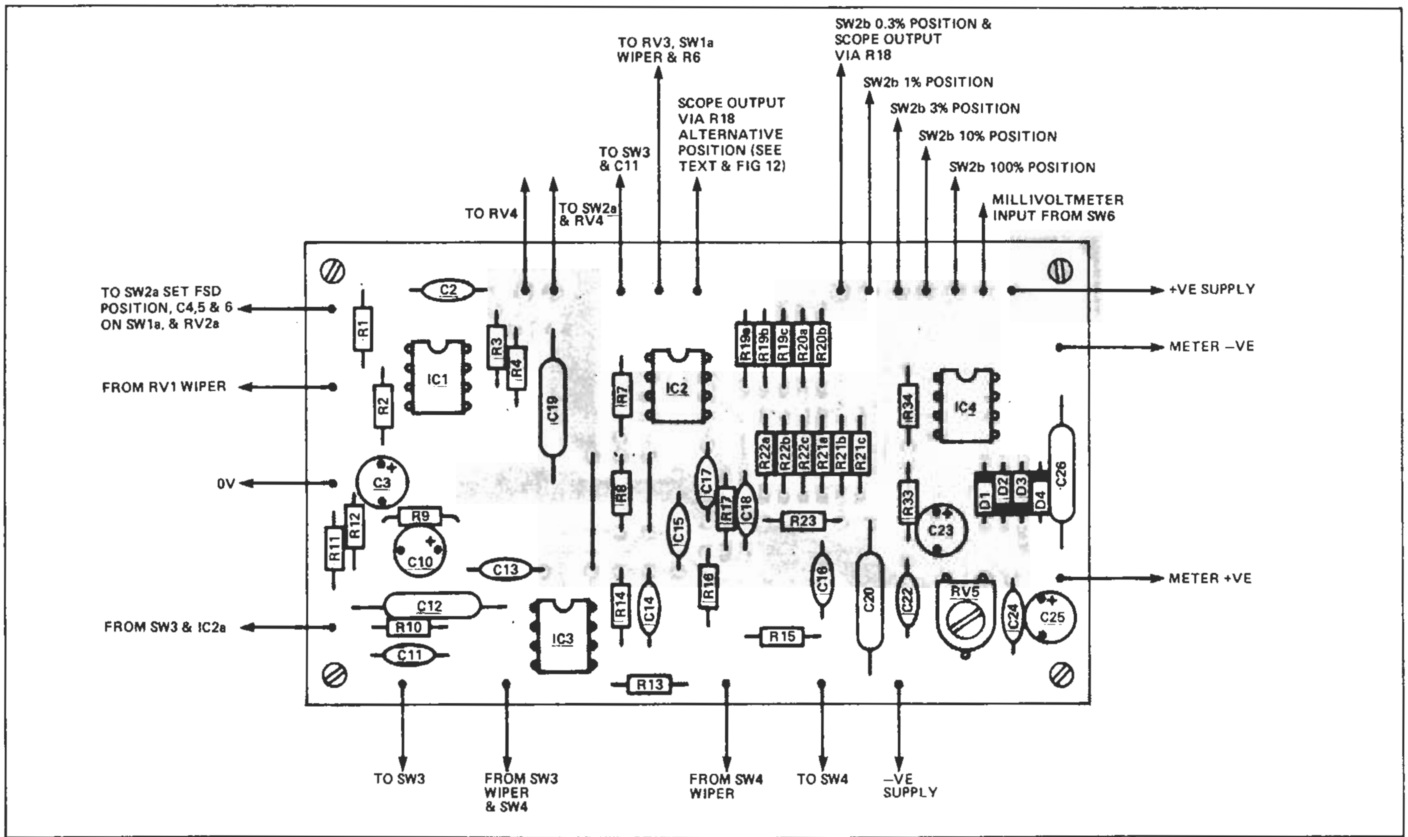

Fig 1 Component overlay of the THD and millivoltmeter PCB.

cuit. One particular example is the effect of coupling the feedback signal from the millivoltmeter into the early stages of the THD meter circuit. This gives rise to a spurious crossover distortion effect which vanishes when the instrument is nulled.

The input attenuator resistors can be mounted between the tags of the rotary switch. If you are using the specified values this arrangement is not too critical, but if you decide to use higher values to increase the input impedance, you may find it necessary to use shielding to prevent pickup. Note that a number of other components are also mounted on switches or pots rather than on PCBs. These include R5, 6, and 18 and C1, C4-9 and C21. R54 and R55 in the power supply must be mounted off the board.

Connecting up the PCBs and controls should present no problems, but don't make the wiring any longer than you have to. This is particularly important with the AC power wiring if you're building the line-powered version.

When the unit has been completed and appears to be working correctly, the sensitivity of the basic meter amplifier should be set to 10mV FSD. If calibration gear is not available, use a small power transformer in the range of 5-20V; connect it to the meter along with a multimeter and adjust RV5 and the range switch until the meter agrees with the multimeter.

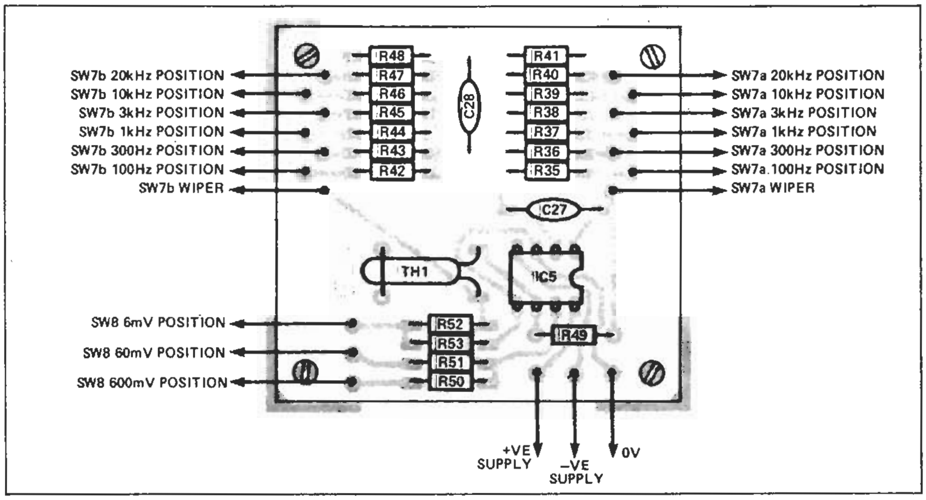

Fig. 2 Component overlay of the spot frequency oscillator PCB.

Parts List — Oscillator

Resistors (all ¼W carbon or metal film)	
R35, 42	330k
R36, 43	100k
R37, 44	33k
R38, 45, 52	10k
R39, 46	3k3
R40, 47	1k8
R41, 48	27k
R49	1k5
R50	220R
R51	22k
R53	100R
RV6	2k5

Capacitor	
C27, 28	4n7
Semiconductors	
IC5	TL072
Miscellaneous	
Sk4	co-axial socket, panel mounting
SW7	2 pole, 6 way rotary switch
SW8	1 pole, 3 way rotary switch
TH1	RA53 thermistor (ITT)
PCB.	

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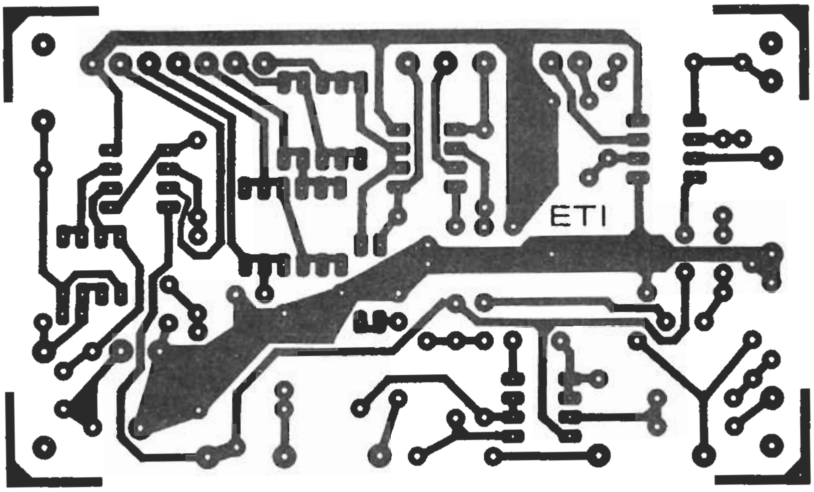
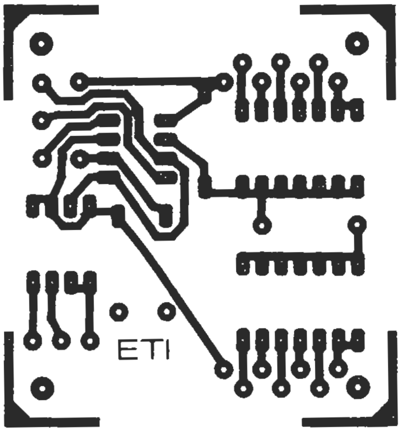


The THD and millivoltmeter board for the Distortion Meter



The Distortion Meter spot frequency oscillator board.

Use

While the major application will be audio amplifiers, for instance setting the quiescent current correctly, there are other uses.

There are three particular applications that are particularly valuable. One is to check that the alignment of a phono cartridge is correct. For this, you need a test record with a track of 1kHz or 3kHz (the higher, the harder for the cartridge) recorded at, say, 5cm/sec. If the cartridge is properly aligned, the THD will probably be in the range of 0.4 to 1.2 percent depending on cartridge quality. A worn stylus will increase these readings rapidly, so a check from time to time can monitor the health of the stylus.

A second useful application is to check the correct recording and bias levels on a tape or cassette recorder. With the latter, on a reasonable machine, the THD should be on the order of 0.3 percent at -5VU. This will worsen with increasing level, becoming perhaps 3 percent just below the recording overload level. This allows the overload level to be determined for a particular tape/machine combination. A reel-to-reel at 7.5 in/sec should have about half these values.

Since the bias level settings on a tape recorder are a compromise between flatness of frequency response and THD, the combination of oscillator, millivoltmeter and THD meter should allow you to check or reset this level if it not ideally chosen.

The final additional use for the meter is in setting up FM tuners. The THD of these depends on the alignment of the IF coils and also upon the setting of the quadrature coil on the demodulator IC. Needless to say, you should have some experience with tuners before twiddling with the coils.

In all of these operations, the method of operation is the same:

1. Set the THD meter input sensitivity to zero and switch out both filter stages.
2. Set the mV/THD switch to THD and set the Mode switch to Set FSD.
3. Connect the input of the meter to the output of the system under test, and gradually increase the sensitivity until the output meter reads full scale.
4. Switch the Mode switch to 100 percent and alter the settings of the Coarse and Fine tune at an appropriate choice of frequency range, set by SW1. Adjust until the best practical notch is obtained with the mode settings adjusted to the 10 and 3 percent settings.
5. Progressively increase the sensitivity given by the mode switch until the highest practical value is obtained, with the fine tune and trim pots adjusted alternately until no lower value of reading can be obtained. Although the use of a single gang pot as RV3 is practicable, it does mean that it is necessary to try trim settings on either side of the apparent minimum position before adjusting the fine tune pot.

PARTS LIST

Resistors

R54	470R
R55	1k0

Capacitors

C29, 31	100u 16V electrolytic
C30, 32	1000u 25V electrolytic

Semiconductors

IC6	7815
IC7	7915
LED1	panel mounting LED
D5-8	1N4001

Miscellaneous

SW9	toggle switch
T1	15-0-15V 3VA transformer
PCB.	

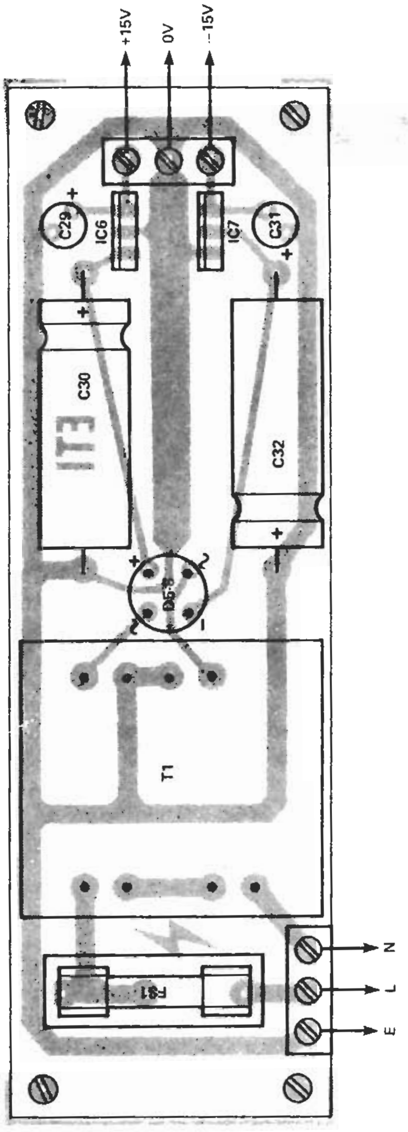
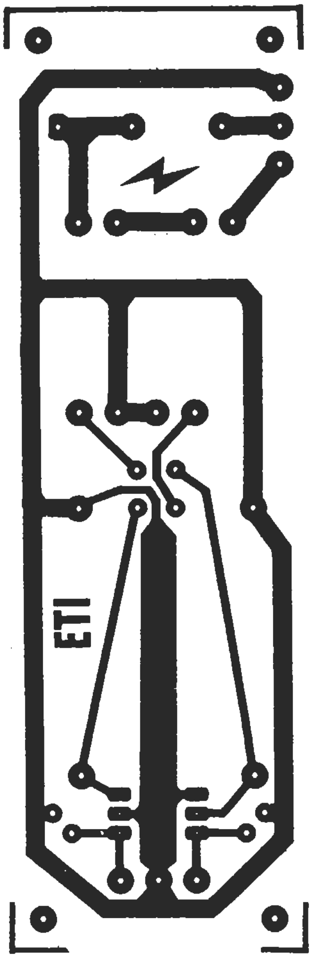


Fig. 3 Component overlay of the AC power supply PCB.



The Distortion Meter AC power supply board.

Interpreting

In spite of all the publicity which attends the introduction of new, very high quality audio amplifiers, and in spite of all the efforts of designers to produce very low distortion systems, I think a lot of effort devoted to getting more zeros after the decimal point is of small value to the user. I do not believe it is possible to hear the difference between nil and 0.05 percent. For myself, I am convinced that if an amplifier doesn't sound good and the THD is less than 0.05 percent, then the problem lies elsewhere, perhaps in its transient response or in incipient stability or overload hangup effects.

I say this to save users from needless anxiety if, in testing a well loved unit, they find it has, say, 0.04 percent or maybe even more. Most of that could be low order distortion which isn't really audible, or even hum and noise. The corollary is also true, that an instrument with a lower THD limit of, say, 0.03 percent will still be a valuable amplifier.

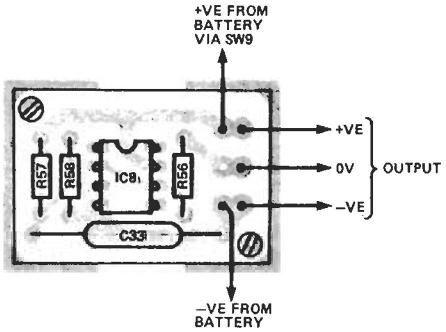
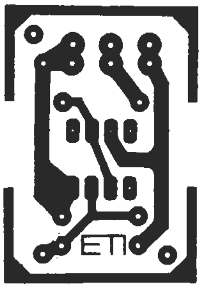


Fig. 4 Component overlay of the single battery supply PCB.



The Distortion Meter single battery supply board.

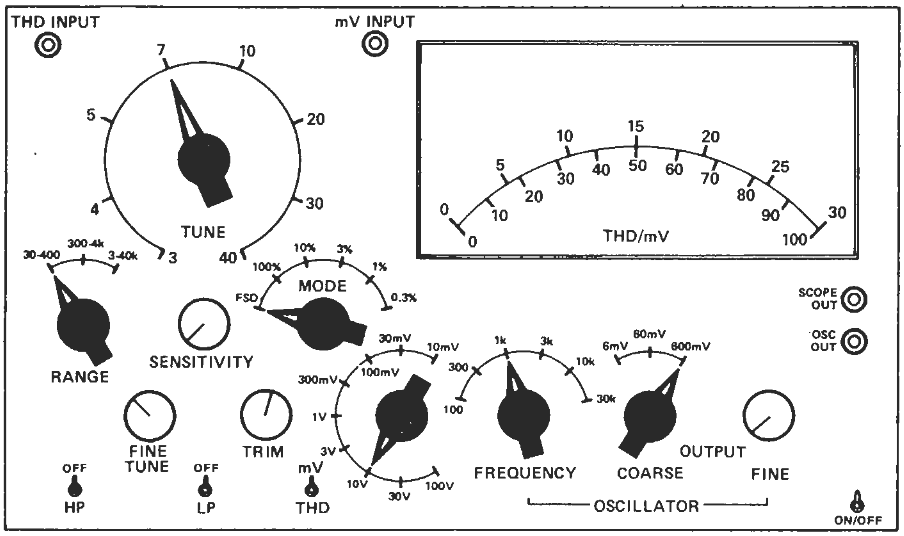


Fig. 5 The front panel layout used in the prototype.

Parts List — Single Battery PSU

Resistors	
R56	100R
R57, 58	1M0
Capacitor	
C33	1u0
Semiconductor	
IC8	TL071
Miscellaneous	
SW9	SPST toggle switch

■