BUILD A HIGH PERFORMANCE THD ANALYZER

PART THREE

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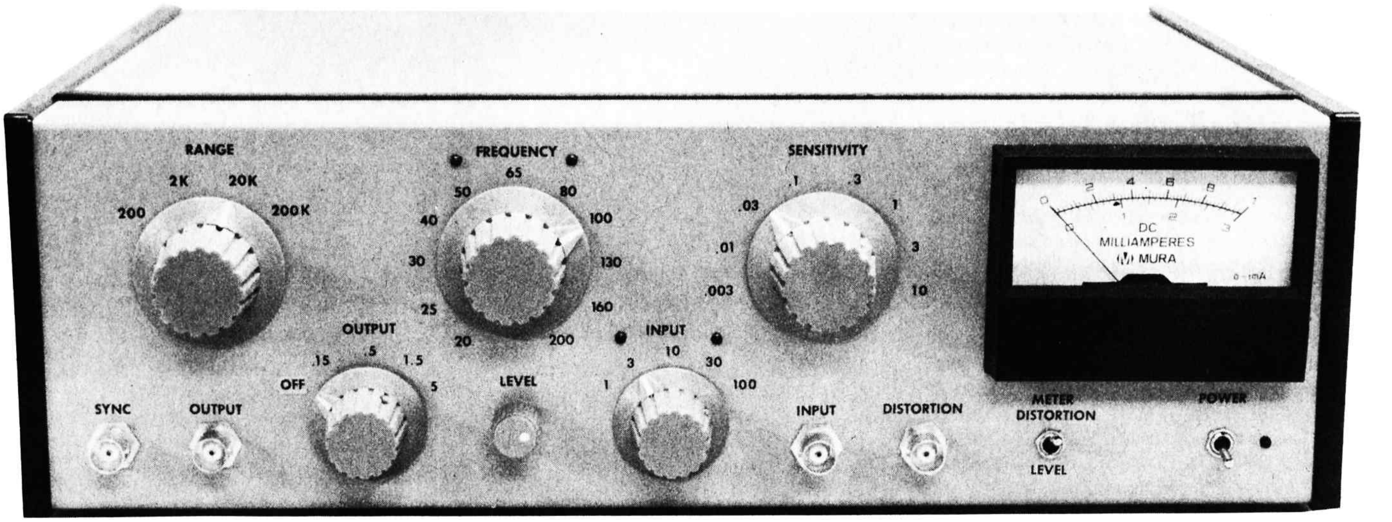
In Parts I and II the theory and operation of all of the THD analyzer circuits were covered. We will now proceed with construction, adjustment, and troubleshooting. It goes without saying that a thorough understanding of Parts I and II will help immensely in troubleshooting.

Circuit Board Assembly

Assembly of the three printed wiring boards should be quite straightforward if the component placement diagrams are followed carefully. Load all of the IC sockets first (socketing is *strongly* recommended); this will make it easier to identify locations of other components. Note that pin #1 of all ICs faces in the same direction *except* for IC38. Next load the off-board connection terminals ("E" connections denoted by large donut lands on p.c. cards), including those for the power-supply leads. Any suitable terminals may be used here, but Vector Type T-18 terminals are a good choice. The boards come drilled with 0.042-inch holes at these locations for maximum flexibility, but will have to be redrilled to 1/16-inch for the T-18 terminals.

Now load all resistors, diodes, bare jumpers, capacitors, transistors, and insulated jumpers — in that order. Take special care to watch polarity on diodes and polarized capacitors. An elongated pad on the p.c. card denotes the negative terminal of most capacitors and the cathode of all diodes. Also take special care in reading the color code on carbon resistors and the resistance code on precision resistors; many different codes exist for the latter. If you have any doubt, use an ohmmeter. Note that the two diode strings on CP2 (D6-8, 9-11) are each prewired and treated as a single component. Prior to installing FETs Q1, Q5, and Q6, it is a good idea to measure and record their pinch-off voltage (V_p) with the simple circuit of Fig. 24. Knowledge of the pinch-off voltage will permit the best adjustments to be made. Use of 22-gauge, insulated, solid wire is OK for the long insulated jumpers. Note that each of these jumpers connects two points on the board labelled with the same letter of the alphabet.

Complete circuit board assembly by installing all ICs in their sockets, taking care to avoid bent pins, which can sometimes be hard to detect. Again, note that pin #1 of all ICs faces in the same direction *except* for IC38.



Circuit Board Bench Test

Because this is a fairly complex construction project which also involves considerable chassis wiring, it is strongly recommended that most of the electrical testing, troubleshooting and adjustment of the three circuit boards be done one at a time on the bench. This will virtually guarantee success upon final assembly.

Before proceeding further, give each of the boards a *thorough* visual inspection, checking for incorrect polarities or values, cold solder joints, solder bridges or other shorts, improper IC insertion or placement, missing components or jumpers, etc. This step should not be bypassed.

A ±15V regulated power supply will be required for bench testing. If you don't have one, you may wish to assemble the analyzer's power supply module now and use it.

Signal Source

Prepare CP1 for bench testing by soldering 0.022-µF, ± 10% polyester capacitors from terminal E2 to E3 and from E4 to E5. Connect 3.9-kilohm resistors from E1 to E2 and from E3 to E4. Connect a 2.7-kilohm resistor from E5 to E6. Strap E5 to E9. Connect a 0.1-µF polyester capacitor from E7 to ground. Center the trimmer pot. Connect ± 15V to the power supply terminals (observe polarity!). Connect a scope to E5.

If all is well, you should see 4.5V p-p sinusoid at about 2 kHz on the scope. In any case, it is wise at this point to check all important d.c. voltages. Table 1 provides a listing of all key d.c. voltages as actually measured in the prototype. "BQ3" means the base of Q3, GQ1 means the gate of Q1, -IC1 means the inverting input of IC1, OIC1 means the output of IC1, IC1-6 means pin 6 of IC1, etc. Values indicated by an asterisk may depend on the input signal, adjustment or something similar, and they may not be close to those listed under certain conditions. All values assume a steady-state condition. A voltmeter with a 1 megohm or greater input impedance should be used. Be very careful to avoid shorting adjacent pins on ICs when probing (especially pin 6 on the 318s). When possible, clip to a resistor connected to the desired point instead. When probing certain sensitive points (like the inverting input of an op-amp), it may be necessary to isolate the meter probe with a 10-kilohm resistor to prevent high-frequency oscillations.

A check of the key voltages for CP1 should reveal any problems at this point and aid in finding the cause. It is worth noting that the inverting and non-inverting inputs of an op-amp properly operating with negative feedback should never differ by more than a few millivolts. If a greater difference is observed, there are three possibilities: First, the stage may be over-driven by the input, which may point to trouble further back in the chain. The second is a bad (or unpowered) op-amp. This is generally the case if the polarity of the input differential is not consistent with the output polarity. If this occurs, the output of the op-amp is usually saturated near one power supply rail. If the output is zero, a short from output to ground may be present. The third possibility is a fault in the associated input or feedback circuitry. In this case, the polarity of the input differential will be consistent with the output polarity. In any case, troubleshooting complex circuits involving many possible interactions requires care, thought, and patience. The key lies in separating cause and effect. Often a particular portion of the circuit can be made to look faulty by a problem elsewhere.

If the signal at E5 is large and clipped, and the gate voltage of Q1 is strongly negative, the fault is probably associated with the multiplier circuit (IC3). If the gate voltage is about +0.5V, the problem lies with the a.g.c. control circuit (IC6,7) or the a.g.c. detector (Q2-Q4). In this case a large positive level (greater than +2.5V) at E7 points to the IC6,7 circuitry. A low level (less than 1V) points to the detector circuitry.

If the signal at E5 is zero and the gate voltage of Q1 is strongly negative, the problem lies with the IC6,7 circuitry. If the gate voltage of Q1 is about +0.5V, something is wrong with the oscillator proper (IC1,2,4).

An unstable or varying level indicates a problem with the IC6.7 circuitry involving a.g.c. loop stability. Check R21, R15, R16, R17, C6 and the capacitor connected to E7.

Now check the main output at E11. It should be three times as great as that at E5 if the output amplifier is operating properly.

Replace the resistors from E1 to E2 and E3 to E4 with 39-kilohm resistors. The frequency should drop to about 200 Hz. Observe the full-wave rectifier sawtooth waveform at pin 6 of IC6. Make sure the signal is full-wave and not half-wave; the latter indicates trouble involving IC5, Q3 or Q4. Adjust R24 for perfect symmetry, i.e., so that adjacent peaks are of equal level. Incorrect and correct adjustments of R24 are illustrated by the 'scope photos in Figs. 25 and 26.

Replace the capacitors at C(KM) and

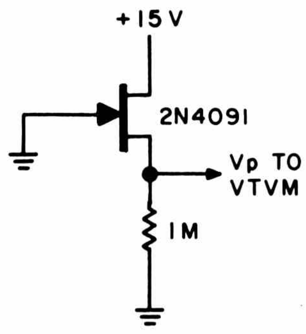


Fig. 24 — Test circuit for measuring J-FET pinch-off voltage.

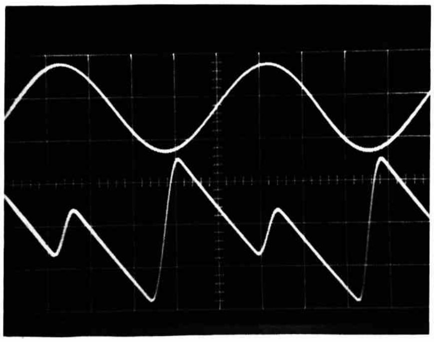


Fig. 25 — Illustration of incorrect adjustment of R24. Bottom trace is from pin 6 of IC6. (Scale: 0.2 V/div.)

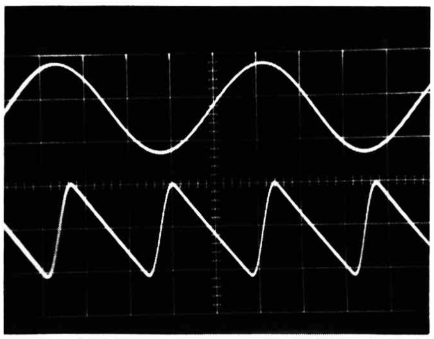


Fig. 26 — Illustration of correct adjustment of R24. Bottom trace is from pin 6 of IC6. (Scale: 0.2 V/div.)

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TABLE 1

CP1	CP2-A	CP2-B	CP3-A	CP3-B
OIC1 +2.9	+IC9 -34	E15 -53	OIC25 +2.5	E29 -10
OIC2 +0.8	OIC9 -101	OIC17 -521	IC26-1 -7.6V	OIC31 -14
+IC3 +0.1	+IC10 -12	+IC18 -15.3	IC26-2 -8.2V	E35 -14
OIC3 -4.3	OIC10 +1.2	OIC18 -153	IC26-3 -8.2V	E36 -0.6
OIC4 +1.0	OIC11 +1.2	OIC19 +5.0	IC26-4 -7.6V	E38 +0.1
OIC5 -4.6	+IC12 0.0	IC20-1 -7.52V	IC26-5 -14.0V	E40 +13.6
BQ3 +602	OIC12 +4.3	IC20-2 -8.19V	IC26-6 +5.6V	OIC35 +110
EQ3 +2.2V	OIC13 +0.9	IC20-3 -8.19V	IC26-10 -2.2	OIC36 0.0
E7 +2.2V	OIC14 -5.6	IC20-5 -13.9V	IC26-12 +5.6V	OIC37 +1.7V*
IC6-6 +13	OIC15 -27.5	IC20-12 +8.59V	IC27-5 +1.3V	IC38-3 +3.3V
E8 -2.5V*	E22 -2.1V*	OIC21 +92	IC27-7 0.0*	IC38-6 -3.5V
GQ1 -2.5V*	E23 -1.5V*	IC22-12 +9.3V	OIC28 +7.2	IC38-9 -2.1V*
		E32 +102	IC29-10 -10.4	IC38-13 -12.1V
		AD5 +450	IC29-12 +5.6	IC38-14 +13.3V*
		E31 +48*	IC30-5 +1.4	E47 +12.8V

Table 1 — Key d.c. voltages as measured in completed prototype analyzer operating at 1 kHz with 1V rms input on the 3V input range, reading 0.0005% distortion on the 0.003% sensitivity range. All voltages are in millivolts unless otherwise noted. The asterisk (*) denotes voltages which depend strongly on operating conditions, FET pinch-off voltages, etc. Keep in mind that many voltages may depend significantly on op-amp input offset voltage or bias current, and may even have the opposite sign in some cases.

C(LN) with 0.22 µF, ±10% polyester capacitors. Connect a 1.0-µF polyester capacitor from E7 to ground. The frequency should now be about 20 Hz, the level should be the same as before, and a stable level should be realized within 15 seconds after power is applied.

Input Amplifier And Bandpass Filters (CP2)

Prepare CP2 for bench testing by connecting 0.022-µF, ±10% polyester capacitors from E17 to E18 and E20 to E21. Connect 3.9-kilohm resistors from E16 to E17 and E19 to E20. Ground E14, E15, E22 and E23. Connect ± 15V to the supply terminals, carefully observing polarity.

Check all d.c. voltages for this circuitry (Fig. 12) in Table 1. Pay less attention to those with asterisks. If problems are found, they should be corrected now. Apply 1V rms at 2 kHz to E12 and check for a 3V rms output at E13. Apply the same signal to the bandpass filter input at E15. Observe the signal at E18. It should exhibit a bandpass characteristic centered at about 2 kHz as the input frequency is varied. Set the frequency for maximum output. Adjust R62 for a level of 1.15V rms at E18. Adjust R59 for a center frequency of 2 kHz and retrim R62.

Observe the signal at pin 6 of IC14. It should be approximately 1.0V p-p and in-phase with that at E19. Temporarily remove the short from E22 to ground and connect E22 to -15V. The signal at pin 6 should now be about 1.0V p-p and inverted from that at E19. Repeat this procedure for pin 6 of IC16 with phase checked relative to that of E21 and changing the voltage on E23 from ground to -15V. The results should be about the same. If either of these procedures reveals a problem, one of the multipliers (IC14, Q5 or IC16, Q6) should be suspected. Note that changing the voltage on E22 should slightly affect the center frequency (about ±1.6%), while changing that on E23 should only slightly affect the amplitude at E18 (about ± 3.5%). Check for about 30mV rms at E24.

Product Amplifiers And Auto-Set Level Circuits (CP2)

Connect a 10-kilohm resistor from E27 to E28 and an 82-kilohm resistor from E26 to E28, and check the d.c. voltages for this circuitry (Fig. 13) in Table 1. Voltage measurements at the pins of IC20 and IC22 should be made through a 10-kilohm isolating resistor at the end of the meter probe to prevent oscillations.

With the 1V rms, 2-kHz signal still applied to E15, sweep the frequency and observe the output at E26. A notch should be observed at the center frequency of the bandpass filter. Try to adjust the generator frequency and the setting of R62 for a deep notch (less than 10mV rms). If R62 doesn't have enough range, connect E23 to -15V instead of ground and try again. Now offset the generator frequency to obtain a 100mV rms output at E26. Ground E25 and observe a level of 1.0V rms at E26. Remove the ground at E25. Check pin 6 of IC19 for a level of 100mV rms.

Now check the auto-set level circuitry. A level of about 1.1V rms should appear at the output of the reference VCA (E32), independent of input level over a ±10-dB range. At the nominal 1V rms input level, E31 should be at about 0V d.c., while plus and minus 10-dB input levels should result in approximately minus and plus 3V respectively at E31. Recovery to nominal output from a 20-dB drop in input level should take about 10 seconds. If the level is too large and E31 is strongly negative, the circuitry associated with IC22 and IC23 is probably faulty. If E31 is strongly positive, the circuitry associated with D5 and IC24 should be suspected. If the level is too low, the opposite polarities at E31 will point to the problem areas above.

Check the distortion product output at E29. A level of 100mV rms should be observed, independent of input level variations over a ±10-dB range about 1V rms. This assumes that there is still 100mV rms at pin 6 of IC19 when the input level is 1V rms.

Auto-Tune Circuits (CP3)

Prepare this portion of CP3 (including IC31, Fig. 18) for bench testing by connecting a 10-kilohm resistor from E29 to ground. Center trimmers R135 and R157. Connect ±15V to the supply terminals of CP3 (observing polarity) and check the relevent d.c. voltages in Table 1. Voltage measurements to the pins of IC26 and IC29 should be made through a 10-kilohm isolating resistor. By offsetting R135 or R157, it should be possible to get the respective integrator outputs at E23 and E22 to drift slowly in a positive or negative direction between approximately -12V and +0.3V.

Apply 100mV rms at 2 kHz to E29 and observe the same signal at pin 6 of IC31. Observe a somewhat softly clipped 1.5V p-p version of the signal at pin 6 of IC25. Briefly short E33 to ground and observe a 1V rms level at pin 6 of IC31 and a 2.5V p-p rounded square wave at pin 6 of IC25. Apply 100mV rms at 2 kHz to E21 and observe a softly clipped 0.8V p-p level at pin 6 of IC28. Increase the input level to 1V rms and observe a hard clipped 1.0V p-p signal at pin 6 of IC28.

Further bench testing of CP3 requires the use of CP2. If any problems remain on CP2, correct them now before proceeding. Prepare CP3 by making interconnections E21, E29 and E32 from CP2 to CP3. Remove the existing connections at E22 and E23 on CP2 and make interconnections E22 and E23 from CP3 to CP2. Center R135 and R157. It is assumed that E25 is open and that the attenuator between E26 and E28 is still in place.

With the 1V rms, approximately 2-kHz signal applied at E15 as previously, check pin 6 of IC25 for a 3V p-p rounded square wave. If the level is very

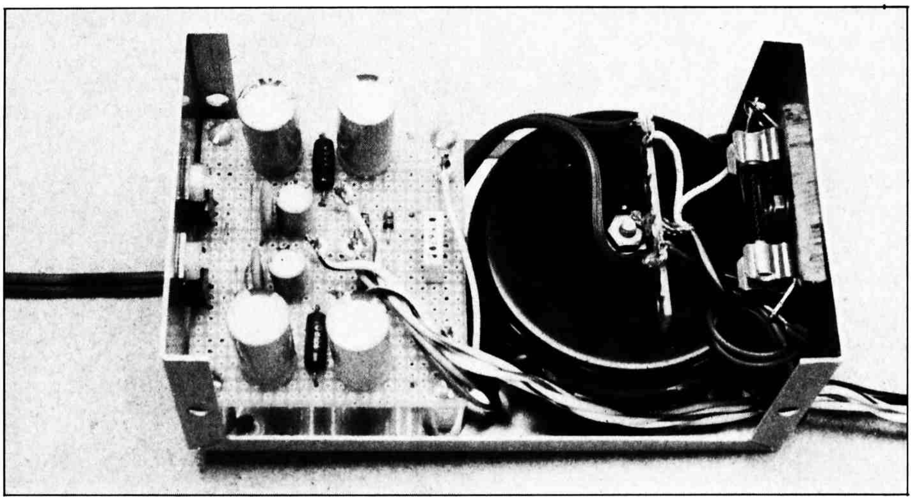

Fig. 27 — Interior of the ±15V power supply module. A torroidal power transformer was utilized in the prototype to minimize hum.

small, the analyzer may have tuned itself. In this case, changing the frequency by about 10% so that it is well out of the tuning range should yield the square wave. Also check for a 1V p-p square wave at pin 6 of IC28.

Adjust the input frequency for a minimal output at E29 and measure the d.c. voltage at E22. Set the input frequency to yield a voltage equal to one-half the pinch-off voltage measured for Q5 (3.5V if you didn't measure it). Now adjust R62 for a d.c. voltage equal to one-half the pinch-off voltage of Q6 at E23. A complete null of the fundamental should now be present at E29, with only distortion and noise visible.

Now place a 100-to-1 attenuator between E29 on CP2 and E29 on CP3; a 100-kilohm series resistor and a 1-kilohm shunt resistor to ground will do. Alternately adjust R135 and R157 for the best possible fundamental null as observed at E29 on CP2. These adjustments should be made slowly, as the time constants in the auto-tune control circuits are long.

Filter, Meter And Status Circuits

Strap E35 to E36 and E40 to E41. Connect a 10-kilohm resistor from E34 to ground. Connect a 1-kilohm shunt resistor from E42 to ground. Center R180 and R192. Apply power and check the relevent voltages in Table 1.

Apply a 300mV rms, 2-kHz signal to E34. Check for 300mV rms levels at pin 6 of ICs 32 and 33. Adjust R180 for about 100mV rms at pin 6 of IC34 and 1V rms at pin 6 of IC35. Drop the input level at E34 to 30mV rms and short E39 to ground. Observe about 100mV rms at pin 6 of IC34 and 1V rms at pin 6 of IC35. Check for 1.4V p-p half-wave rectified signals at the anode of D22 (negative-going) and the cathode of D23 (positive-going). Check for a positive d.c. level of about 1.1V at E42.

Remove the strap from E40 to E41 and place a strap from E24 on CP2 to E41. Apply a 3V rms, 2-kHz signal to E15 on CP2 and check for 1V rms at pin 6 of IC35. Adjust R192 for a +1.1V d.c. level at E42.

Check the status circuits by connecting four LEDs from terminals E43 through E46 to +15V. Remove the strap from E24 to E41 and replace the strap from E40 to E41. Reconnect E29 on CP2 directly to E29 on CP3. Connect a 1V rms 2-kHz signal to E15 on CP2. D26 and D27 should be extinguished, while D24 or D25 should light if the input frequency is tuned above or below the tuning range respectively. They should both be extinguished if a good notch is being observed at E29. Drop the input level to 0.25V rms; D27 should light. Raise the input level to 4V rms; D26 should light.

Bench testing of the circuit boards is

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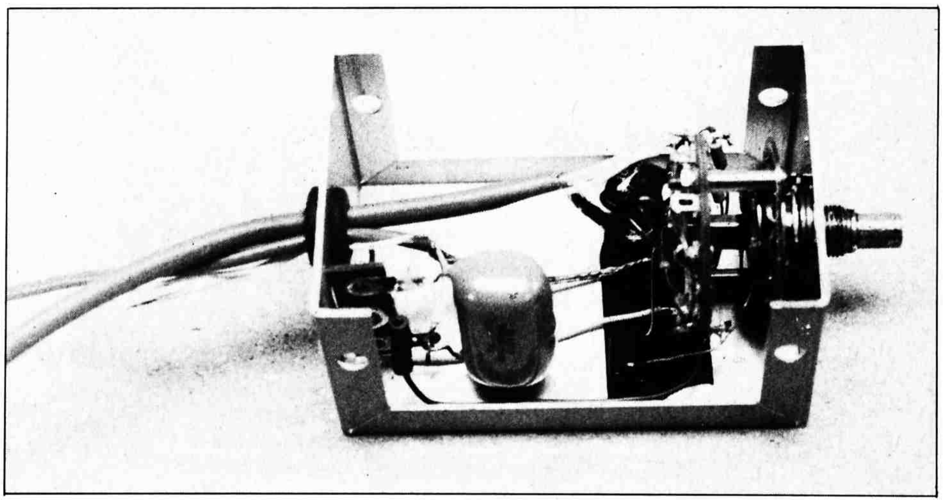

Fig. 28 — Interior view of the input attenuator module.

now complete. If any problems surface after final assembly, they are probably not on the circuit boards.

Chassis Assembly

The first step in chassis assembly is to build the power supply module. It is built inside a 2¼ by 3 by 5¼ inch aluminum utility box. This affords some shielding against 60-Hz hum. Conventional point-to-point wiring is used, employing a perforated board for component mounting. The voltage regulator ICs should be bolted to one wall of the enclosure and insulated with mica washers. Make sure that metal burrs don't cause shorts between the enclosure and the ICs. The power supply module is bolted to the rear of the analyzer enclosure, with the line cord passing through both the power supply and the notched-out analyzer cover. Power leads and switch wiring pass to the interior of the analyzer through a grommet in the power-supply enclosure. A polarized line cord is recommended to guarantee that the power switch is always on the neutral side of the a.c. line so as to minimize hum. The power transformer should be mounted in the module so that it is at the extreme right-rear of the analyzer, far away from CP1 and CP2. A photograph of the power supply is shown in Fig. 27.

Although the choice of the power transformer is not critical, use of a torroidal design (as shown) will assure low induced hum. The Avel-Lindberg 40/3004 used here is available from Sager Electrical Supply Co., 60 Research Rd., Hingham, Mass., 02043 at a cost of about $24.00. In any case, the input voltage to the regulators under the full analyzer load should not be less than 18V (including ripple dips) nor greater than 35V. If necessary, adjust R211 and R212. The 40/3004 transformer does not have much extra current capacity, so be particularly observant of regulator headroom in this case.

The three circuit boards should be mounted on ⅜-inch threaded 6-32 standoffs and placed as shown in Fig. 4 (Part I, July issue). CP1 is placed so that IC1 is closest to the front panel. CP2 is placed so that IC9 is closest to the front panel. CP3 is placed so that IC38 is closest to the front panel. Make all of the power-supply connections and then the connections between CP2 and CP3. Circuit board power and ground should be distributed on a single-point basis from a terminal strip mounted near the input jack (J3).

Two types of shielded cable were used in this project, low-capacitance microphone cable (34pF/ft.) and high-capacitance miniature cable (124pF/ft.). Unless specified, the miniature cable can be used. Use a shielded cable for the E29 interconnection (shield grounded only at E30).

Now mount and interconnect all of the remaining front panel items except the range and frequency switches (S1 and S3). The resistors residing on the output level, input level, and sensitivity switches (S2, S4 and S5) should be wired onto the switches prior to mounting of the switches.

Level control R30 should be connected to E9 through a shielded cable. The shield should connect to E10 and the CCW end of R30. The output attenuator (S2) should receive its ground directly from the single-point ground. R205 will ultimately be suspended between S2C and S11.

As mentioned earlier, the input attenuator should be mounted in a small, shielded enclosure as shown in Fig. 28. Use shielded cable from the input jack and single-point ground to the attenuator. Four ferrite beads are placed on the lead from C21 to S4 for improved r.f.i. immunity. Connect the output of the attenuator to E15 on CP2 with low-capacitance shielded cable. Note that the shield supplies ground to the secondary single-point ground (E14) on CP2.

Selection of the attenuator frequency-compensation capacitors (shown dotted in Fig. 12) will require experimentation, as the required values and even topology (series vs. shunt connection) will depend on particular parasitics. The best approach is to do the compensation before installing the module, using the actual required length of low-capacitance cable at the output looking into a 100-kilohm low-capacitance load (or a 100-kilohm, 100-to-1 resistive attenuator). Use an audio generator and an audio a.c. voltmeter or oscilloscope to achieve a flat frequency response on all ranges with the module's cover in place.

High-capacitance shielded cable is recommended for connection of the sensitivity switch (S5A) to E28. Note that the attenuator receives its ground from E27 via the shield. The "hot" ends of R90 and R94 on S5A can be connected to a nearby unused switch position.

If you have chosen to implement the simple fixed-product filters of Fig. 19 instead of the tracking filters, wire them now. Use shielded cable for the connections to E29 (on CP2), E34, E35, E36 and E38. The filter ground connection should come via the shield of the cable going to E34, which shield can be connected at E37. The shield of the cable going to E29 should be connected only at E30 on CP2. The 510-pF capacitor in Fig. 19 should be made smaller by the amount of the cable capacitance in parallel with it.

Intermediate Check-Out

At this point, prior to the wiring of the range and frequency switches, a moderately thorough check-out of the analyzer is recommended. This can be done if the temporary tuning capacitors and resistors installed for bench testing have been left on the boards. We assume here that the capacitors in place are 0.022 µF and that the resistors are 3.9 kilohm. The 0.1-µF capacitor from E7 to ground and the 2.7-kilohm resistor from E5 to E6 on CP1 should also be in place. If you have chosen to implement the tracking product filters, strap E29 to E34 and E35 to E36. Connect the source output (J2) to the analyzer input (J3).

The analyzer can now be put through a full set of paces at 2 kHz. Note that you may have to adjust R59 and perhaps R62 to get a null and have reasonable FET control voltages at E22 and E23 (say, -1 to -4V). Also check the oscillator a.g.c. FET gate voltage at E8. Check all functions of the analyzer under a variety of level and sensitivity conditions to determine that everything is working properly. Look for evidence of oscillations.

"Distortion" from a separate signal generator can be injected through a 62-kilohm resistor into the connection between the source and the analyzer. If the source is producing 1V rms and the separate signal generator is delivering 100mV rms to the resistor, a 0.1% "distortion" level will result. Check the calibration of R180 and R192. Check for satisfactory tuning time and instrument residual. If any problems are uncovered, correct them now.

Final Assembly

Assembly of the range and frequency switches may require some ingenuity. S1 consists of nine five-position, two-pole wafers if the tracking product filters are implemented. The resulting length will usually require that S1 be assembled with parts from two or more rotary switches. The shaft can be extended by sawing off the shaft from a second switch and affixing it to the shaft of the switch under construction with a standard shaft coupler. The pair of 4-40 screws which hold the switch together can be extended by joining additional lengths of 4-40 screw to them (obtained from the second switch) with tapped 4-40 standoffs. A close-up of the switches assembled in this way is shown in Fig. 29. Alternately, the Centralab switch components specified in the parts list can be assembled into the required switch.

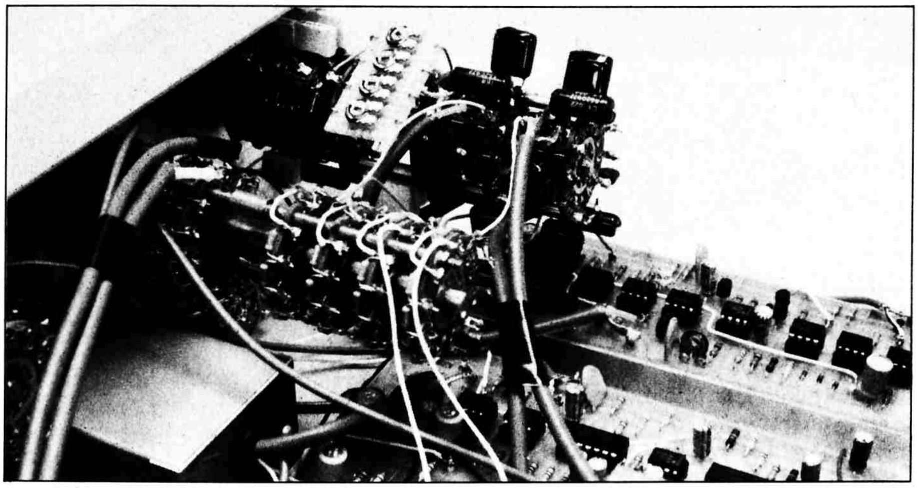

Fig. 29 — Closeup of the specially constructed range and frequency switches.

The capacitors are mounted between adjacent wafers as shown in Table 2. For example, C(KM)-1 mounts between poles K and M at position 1. Poles S1A and S1B are on the wafer closest to the front panel. The capacitor and resistor designations for switch-mounted components assume that the tracking product filters are being implemented and that their components are mounted on the switch sections closest to the front panel. Note that the tuning capacitors for the highest frequency range have a small resistor in series with them. This resistor compensates for a high-frequency phenomenon in active filters known as "Q-enhancement" which results from op-amp high-frequency rolloffs. These resistors can be mounted on the unused position-5 switch terminals. Note that the tuning capacitors are wired so that there is always some capacitance connected even when the switch is between positions, preventing undesirable transients. This is accomplished by wiring the position-4 terminals in parallel with their respective wipers. The use of shorting-type switches would also have accomplished the transient suppression.

The high-pass product filter capacitors [C(BD) and C(DF)] for the 20-kHz range are also used for the 200-kHz range by connecting positions 3 and 4 of the associated switch poles together. This was done because stability of higher frequency active high-pass filters would have been a problem, and the additional filtering is not really necessary on the highest range.

As shown in Fig. 29, the four frequency trimmers (R1 to R4) were mounted on a small piece of perforated board and mounted to poles J and H of S1 with 18-gauge solid bare wire. R206 is mounted on the switch between the two wipers.

After S1 is assembled and loaded with components, mount it and make all possible interconnections to the circuit boards. Each of the four tuning capacitors [C(KM), C(LN), C(OQ) and C(PR)] is connected to the circuit boards by seven inches of low-capacitance shielded cable. The capacitance of the shielded cable is directly in parallel with that of the associated tuning capacitor. Instead of being grounded, the shield interconnects one side of the tuning capacitor to the *output* of the associated integrator. Thus, for example, the shield connects one side of C(KM) to E3. The capacitance of this length of cable has been taken into account in the values of the tuning capacitors for the 200-kHz range, and appropriate alterations should be made to these capacitors if other values of shielded cable capacitance are used. The shields are connected to switch poles K, L, Q, and R.

Frequency switch S3 consists of eight 11-position, single-pole wafers, and

TABLE 2

Range	Position	C (AC)	C (EG)	C (BD, DF)	C (GI)	C (KM, LN)	C (OQ, PR)
200 Hz	1	0.1 µF	0.068 µF	0.22 µF	1.0 µF	0.22 µF*	0.22 µF*
2 kHz	2	0.01 µF	6800 pF	0.022 µF	0.47 µF	0.022 µF*	0.022 µF*
20 kHz	3	1000 pF	680 pF	2200 pF	0.1 µF	2200 pF†	2200 pF†
200 kHz	4	100 pF	47 pF	2200 pF	0.01 µF	200 pF†	200 pF†
						+68 Ω	+180 Ω

Table 2 — Capacitor connections on range switch S1. The asterisk (*) indicates polypropylene, polycarbonate or polyester of at least 100 V working voltage. The dagger (†) indicates polystyrene or silvered mica, again of at least 100 V working voltage. The others are not critical.

TABLE 3

Frequency	Position	Desig.	R (A, B)	R (C)	R (D)	R (E, F, G, H)
20	1	R ( ) 1-2	1500	3600	9100	7500
25	2	R ( ) 2-3	1000	2400	6800	5620
30	3	R ( ) 3-4	1300	3000	7500	6190
40	4	R ( ) 4-5	750	1800	4700	3830
50	5	R ( ) 5-6	680	1600	4300	3480
65	6	R ( ) 6-7	430	1000	2700	2150
80	7	R ( ) 7-8	360	910	2400	1960
100	8	R ( ) 8-9	330	820	2200	1780
130	9	R ( ) 9-10	220	510	1300	1100
160	10	R ( ) 10-11	180	470	1200	1000
200	11	R ( ) 11-*	750	1800	4700	3830

Table 3 — Resistor connections on the frequency switch S3. The asterisk indicates a tie-point, position 12 if available; otherwise use an insulated terminal. R (E, F, G, H) should be 1%, ¼-watt carbon-film types where each group of four like values should be matched to within 1%. Others are standard 5%, ¼-watt carbon film. All values are shown in ohms.

should be constructed in the same way as S1 above. If possible, it is recommended that switch shields be installed between sections 4 and 5 and between sections 6 and 7. The resistors on S3 are mounted between adjacent positions on a given wafer. The wiring is documented in Table 3. For example, R(A) 1-2 goes on S3A, the wafer closest to the front panel, between positions 1 and 2.

Although precision 1% resistors are preferred for R(E) through R (H), the only requirement is that the four resistors of each position be matched to each other within 1%. Thus, you may save some money or hassle by measuring and matching 5% carbon-film resistors. If you buy 10 of a given value at the same time, there is a very good chance you'll find four with the required match. Try not to get all of the resistors which err on the high side placed on one wafer, and vice versa.

As with the tuning capacitors, S3 is wired so that resistance is present even when the switch is between positions. This is done by wiring the position-1 terminal to the switch wiper. The free end of the lowest valued resistor connected to position 11 can be tied to position 12 if you have a 12-position switch or to a small, insulated terminal on or near the switch if you have an 11-position switch.

With S3 assembled and loaded with components, mount it and make all of the remaining interconnections. Where possible, make the interconnections with positions on S1 that already have a wire running back to the appropriate circuit board terminal.

Connection of the tracking-filter components on S1 and S3 to E29, E34, E35, E36, E37 and E38 can be done with shielded cables as discussed earlier for the fixed filtering option. In this case, however, the connections to E34 and E36 must be made with low-capacitance shielded cable. The value shown for C(EG) for the 200-kHz range assumes about eight inches of this cable. The product filter interconnections between S1 and S3 need not be shielded, but should be dressed as far away as possible (i.e., against the front panel) from the signal leads and components of the oscillator and analyzer sections. There is a very substantial amount of gain between the oscillator/BPF circuits and the product filters. Failure to get adequate isolation here could result in oscillations, particularly on the 200-kHz range. Leads associated with the analyzer section should also be dressed away from those of the oscillator section. Assembly of the analyzer is now complete.

Test And Calibration

The signal source should be checked first. Center trimmers R1 to R4. Apply power, and monitor the main output on a 'scope and a.c. voltmeter. Also monitor the d.c. voltage at E8, the gate bias for Q1. Check operation at all frequencies. Check frequency response flatness and level stabilization time. Check to see that the gate voltage of Q1 does not get within 0.5V of either zero or the measured pinchoff voltage at any frequency. Check the action of the output attenuator and level control. If you have a frequency counter, check all the frequencies; at this point they should be within ±20% of the selected value, and should increase monotonically as the frequency switch is advanced. Check for oscillations as well.

Set the analyzer to 650Hz, and adjust frequency trimmer R2 for a source frequency of exactly 650Hz if you have a frequency counter. Otherwise use a Lissajous pattern with a 650-Hz oscillator as a reference. Connect the signal source to the analyzer input, and apply 1V rms on the 3V input range. Monitor the d.c. levels at E22 (frequency control) and E23 (amplitude control). Adjust R59 and R62 as necessary to get the analyzer to tune and to set these voltages to half the measured pinchoff voltages of the associated FETs.

The remaining frequency trimmers in the oscillator will now be adjusted to bring the oscillator into alignment with the center frequency of the analyzer for the remaining frequency ranges. At 65Hz, adjust R1 so that the d.c. voltage at E22 equals half the recorded pinchoff voltage for Q5. Adjust R3 at 6.5 kHz and R4 at 65 kHz in the same manner. Now check the voltages at E22 and E23 at all frequencies to make sure that neither one gets within 0.5V of either zero or the associated pinchoff voltage. Make compromise adjustments among R1, R3, R4, R59, and R62 as appropriate. A problem with the E22 voltage (frequency control) may mean an incorrect frequency-setting resistor somewhere on S3. Now that the oscillator trimmers are set, it would be useful to recheck the oscillator frequency calibration. Typically it should be within ±10%.

If the amplitude control voltage (E23) changes substantially toward the high end of the frequency range (between 50 kHz and 200 kHz), this could be an indication that the Q-enhancement compensator resistors in series with C(OQ) and C(PR) on the highest range need some adjustment. The value shown in the schematics is a good compromise value, but it does depend somewhat on the individual rolloff characteristics of the op-amps (ICs 10, 11, 12, 13, and 15). If E23 goes too positive (toward zero), these resistors may be too large. If E23 goes too negative, these resistors may be too small.

Another phenomenon to watch for toward the high end of the 200-kHz

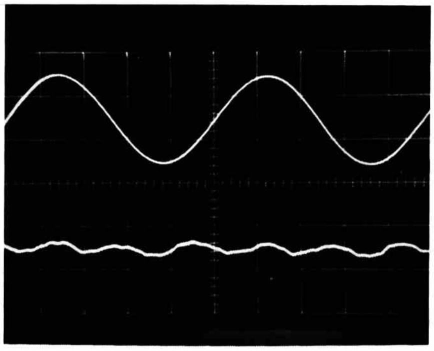

Fig. 30 — Analyzer residual at 20 Hz, 1V rms operating level in the 0.003% sensitivity range. (Scale: 0.2 V/div.)

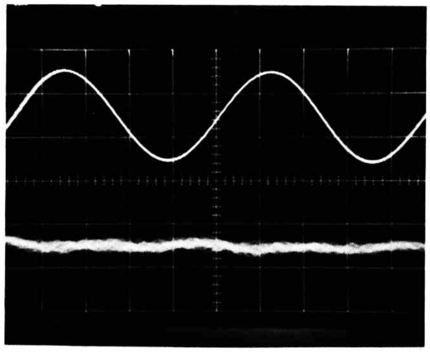

Fig. 31 — Analyzer residual at 1 kHz, 1V rms operating level in the 0.003% sensitivity range. (Scale: 0.2 V/div.)

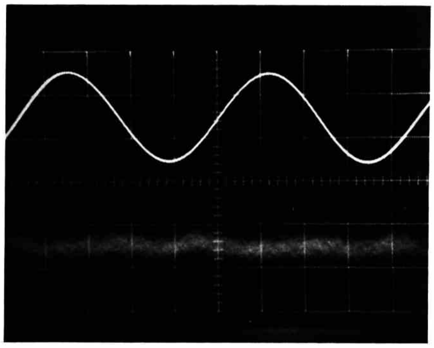

Fig. 32 — Analyzer residual at 20 kHz, 1V rms operating level in the 0.003% sensitivity range. (Scale: 0.2 V/div.)

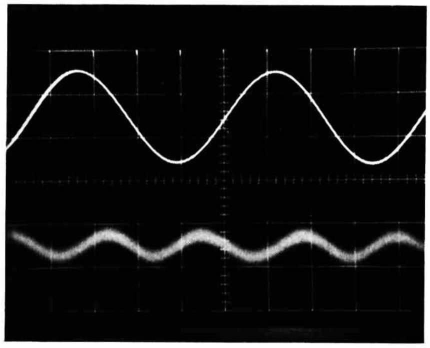

Fig. 33 — Analyzer residual at 200 kHz, 1V rms operating level in the 0.03% sensitivity range. (Scale: 0.2 V/div.)

range is "slewing oscillations." Too much phase lag around an active-filter loop can cause Q-enhancement and, ultimately, oscillation. if the signal being handled by an active filter causes one or more of the op-amps to slew-rate limit, the effect is equivalent to a substantially increased phase lag. This can result in oscillations which drive the amplifiers even deeper into slew-rate limiting. The only way to stop such an oscillation is to tune to a lower frequency or remove power. The normal signal levels in this analyzer cannot touch off such an oscillation, but a sufficiently large transient can. That is why the range and frequency switches are wired so as not to generate transients when they are operated. However, occasionally a power-on transient can trigger such an oscillation in this analyzer if it is powered up when tuned to greater than about 100kHz.

The frequency response of the tracking product filters should be checked at this point by injecting a signal at their input in place of E29. If the level at three times the front-panel setting is taken as 0 dB, then the lower and upper 3-dB-down frequencies should be at 1.4 and 10 times the set frequency, respectively (0.14 and about 8 times on the 200-kHz range).

To calibrate the distortion reading, two signal sources should be used. Apply 1V rms at 1 kHz to the analyzer from the internal signal source. Put S6 in the "Level" position and adjust R192 for a full-scale reading with the input attenuator on the 1V range. Apply 1V rms at 3 kHz from a second audio generator through a 62-kilohm resistor. The analyzer will now see 0.99V at 1 kHz and 10.1mV at 3 kHz, or a "distortion" level of 1.02%. Set the sensitivity switch (S5) to the 1% range and adjust R180 for a meter reading just a hair over full-scale.

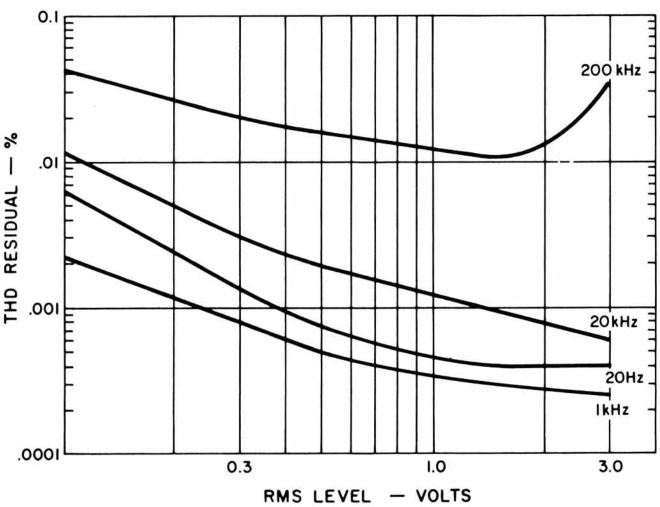

Fig. 34 — Residual vs. level as a function of frequency in the 3V input range.

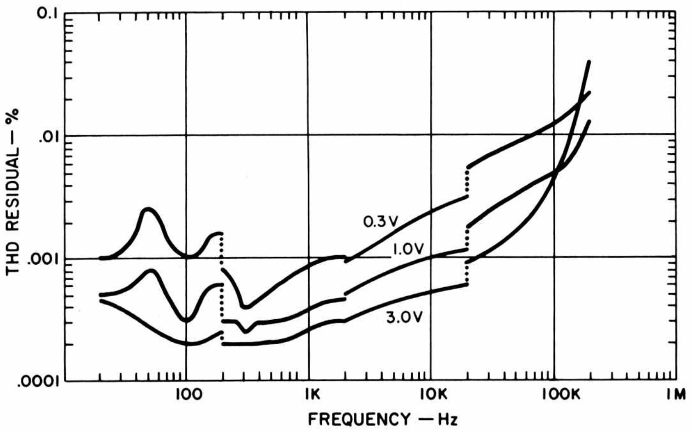

Fig. 35 — Residual vs. frequency as a function of input level in the 3V input range.

To complete testing, measure the analyzer's residual at all frequencies and at various levels by connecting the signal source directly to the analyzer input. It is useful to observe the "Dist. Out" signal on a 'scope at this point.

If the residual seems particularly noisy or jumpy on only one range, don't hesitate to suspect the trimmer pots and the tuning capacitors. This is a sensitive application and even minor deficiencies in these components may cause trouble; I've experienced trouble with both. I strongly recommend the use of high-quality tuning capacitors.

Hum can be particularly insidious in an instrument such as this where full-scale sensitivities on the order of 30 microvolts are encountered. Although the construction details are intended to minimize hum, you may still have to fight it. It will be most noticeable on the 200-Hz range. Remember, hum can be picked up capacitively by a high-impedance circuit (shielding helps here) or it can be magnetically induced into any circuit, including grounds. Hum will probably be reduced when the instrument is fully housed in its enclosure.

Performance

Performance of the prototype is illustrated in Figs. 30 to 35. Scope photos of the analyzer's residual at the nominal 1V internal operating level for 20 Hz, 1 kHz, 20 kHz, and 200 kHz are shown in Figs. 30 to 33.

The total residual (noise and distortion components) is plotted as a function of level for the four frequencies above in Fig. 34. The residual as a function of frequency for 0.3, 1.0 and 3.0V rms internal operating levels is plotted in Fig. 35. Best performance is generally achieved near the high end of its allowable range of operating levels. At operating levels above about 1.5V rms, the residual is below 0.001% across the full audio band.

Parts Availability

A serious attempt was made to design the THD analyzer with readily available parts, and many constructors will have no trouble finding most of the parts at normal outlets. As an aid, however, several dealers of various parts are listed below. Because of the substantial number of parts involved in this project, I recommend obtaining and searching through the catalogs that many of these and other companies make available. Although most of these companies provide broad lines, a few are worth special mention because they have some of the less commonly available parts. The NE5534AN op-amps and the Centralab rotary switches are available from Newark Electronics ($25.00 minimum order). The 2N4091 J-FETs and a suitable power transformer are available from CFR Associates. Precision one-percent resistors are available from International Electronics Unlimited.

Digi-Key Corp.
P.O. Box 677
Thief River Falls, Minn. 56701
800/346-5144

Active Electronic Sales Corp.
P.O. Box 1035
Framingham, Mass. 01701
617/879-0077

CFR Associates, Inc.
Newton, N.H. 03858

Jameco Electronics
1355 Shoreway Rd.
Belmont, Calif. 94002
415/592-8097

Newark Electronics
146 Route 1
Edison, N.J. 08817
201/572-2103
(or contact nearest branch)

International Electronics Unlimited
435 First St., Suite 19
Solvang, Calif. 93463
805/688-2747

PARTS LIST

All resistors are ¼-watt, 5-percent carbon-film unless otherwise specified. Those specified as "1 percent" are ¼-watt metal-film types. Substitution of 5-percent resistors for the 1-percent type will only degrade accuracy of the attenuators.

R1, R2, R3, R4, R59, R62, R192—5 kilohm trimpot (Panasonic K4A53)
R5, R19, R58, R102, R116, R140, R141, R162, R163, R190—6.8 kilohm
R6, R11, R14, R15, R18, R22, R23, R25, R26, R27, R56, R60, R61, R63, R64, R67, R71, R77, R80, R87, R96, R134, R136, R143, R145, R147, R156, R158, R165, R168, R178, R188, R195, R197, R199, R208—10 kilohm
R7, R66—150 kilohm
R8, R72, R74—560 ohm
R9, R73, R75—330 ohm
R10, R68, R76—270 ohm
R12, R69, R78, R137, R204—1.5 kilohm
R13, R70, R79—750 kilohm
R16, R33, R50, R86, R105, R119, R120, R123, R142, R146, R164, R171, R174—100 kilohm
R17, R31, R82, R128, R149, R150, R183, R185, R186, R187—1 kilohm
R20, R35—1.3 kilohm
R21, R41, R42, R43, R53, R103, R117—1 megohm
R24, R135, R157—1 kilohm trimpot (Panasonic K4A13)
R28, R57, R126, R133, R138, R139, R155, R160, R161, R206—22 kilohm
R29—5.6 kilohm
R30—2.5 kilohm potentiometer
R32, R84—2.2 kilohm
R34—2.0 kilohm
R36—1.8 kilohm
R37—820 ohm
R38—620 ohm
R39, R40, R213, R214—220 ohm
R44—68.1 kilohm, 1 percent
R45—42.2 kilohm, 1 percent
R46—90.9 kilohm, 1 percent
R47—11 kilohm, 1 percent
R48—100 kilohm, 1 percent
R49—3.16 kilohm, 1 percent
R51, R176—1 kilohm, 1 percent
R52—2.05 kilohm, 1 percent
R54, R65—82 kilohm
R55, R85—18 kilohm
R81, R196, R198—33 kilohm
R83, R98, R99, R101, R112, R113, R115, R129, R130, R131, R132, R148, R153, R154, R167, R172, R173, R175, R181, R182, R207—100 ohm
R88—1.1 kilohm, 1 percent
R89—10 kilohm, 1 percent
R90—7.5 kilohm, 1 percent
R91—2.15 kilohm, 1 percent
R92—750 ohm, 1 percent
R93—316 ohm, 1 percent
R94—6.2 kilohm
R95—1.1 kilohm
R97, R100, R106, R111, R114, R118—15 kilohm
R104—470 ohm
R107, R108, R109, R110, R125, R151, R152—4.7 kilohm
R121—910 kilohm
R122—22 megohm
R124—12 kilohm
R127, R179, R200, R201, R202, R203—2.7 kilohm
R144, R166—68 ohm
R169—390 ohm
R170—3.3 kilohm
R177—9.09 kilohm, 1 percent
R180—2 kilohm trimpot (Panasonic K4A23)
R184—9.1 kilohm
R189—20 kilohm
R191—270 kilohm
R193—8.2 kilohm
R194—39 kilohm
R205—2.7 megohm
R209, R210—3.3 ohm, 2-watt; remove if using 40/3004 transformer
R211, 212—10 ohm, 2-watt; see text
R(A) through R(H)—See Table 3 and text
C1, C25, C27—15 pF silver mica (Arco DM15-150)
C2, C3, C26, C28—22 pF silver mica (Arco DM15-220)
C4, C5, C23, C41, C43, C45, C46, C47, C49—10 μF, 25-V radial electrolytic (Panasonic ECE-AIEV100S).
C6, C7, C8, C17, C18, C35, C36, C42, C52, C53, C55, C56, C57, C59, C66, C67, C72, C73, C83, C84—100 μF, 16-V radial electrolytic (Panasonic ECE-AICV101S)
C9—1 μF, 100-or 250-V metallized polyester (Panasonic ECQ-E2105KZS)
C10—0.47 μF, 100-V metallized polyester (Plessey Minibox 0.47/100 F box)
C11—0.1 μF, 100-V metallized polyester (Plessey Minibox 0.1/100 C box)
C12, C76—0.01 μF, >100-V metallized polyester (Plessey Minibox 0.01/630 C box)
C13, C14, C15, C16, C29, C30, C31, C32, C33, C34, C60, C61, C62, C63, C64, C65, C81, C82—0.1 μF, 25-V ceramic disc (Panasonic ECK-DIE104ZFZ)
C19, C20, C37, C38, C39, C40, C44, C48, C50, C68, C69, C70, C71, C74—1 μF, 50-V radial electrolytic (Panasonic ECE-AIHV0-10S)
C21 — 2 μF or 2.2 μF, 250-V metalized polyester (Panasonic ECQ-E2225KZS)
C22 — 47 pF silver mica (Arco DM15-470)
C24 — 10 pF silver mica (Arco DM15-100)
C51 — 0.22 μF, 100-V metallized polyester (Plessey Minibox 0.22/100 D box)
C54, C58 — 0.47 μF, 50-V (Radio Shack 272-1071)
C77, C78, C79, C80 — 470 μF, 35-V radial electrolytic (Panasonic ECE-AIVV471S)
C (AC) through C (PR) — See Table 2 and text
D1 through D23 — Switching diode (1N914, 1N4148 or equiv.)
D24 through D28 — Red LED (Opto Electronics XC209R)
D29 through D32 — 1N4002, 1N4003, 1N4004 or equiv.
Q1, Q5, Q6, Q7, Q8, Q9 — 2N4091 J-FET (National)
Q2, Q3, Q4 — 2N3904 or equiv. gen. purpose silicon; NPN
IC1, IC2, IC3, IC4, IC8, IC9, IC10, IC11, IC12, IC13, IC14, IC15, IC16, IC17 — NE5534AN (Signetics, TI)
IC5, IC6, IC7, IC18, IC19, IC23, IC25, IC28, IC31, IC32, IC33, IC34, IC35, IC36 — LM318N (National, TI, etc.)
IC20, IC22, IC26, IC29 — LM1496N (National, Mot., etc.)
IC24 — LF356N (National, Fairchild, etc.)
IC27, IC30 — LM1458N (National, Mot.)
IC37 — UA741CN (Fairchild, National, etc.)
IC38 — LM324N (National, etc.)
IC39 — LM340T-15 or UA7815CT (National, Fairchild)
IC40 — LM320T-15 or UA7915CU (National, Fairchild)
T1 — 32-48 V c.t., 1-amp power transformer (e.g., CFR Associates Tranny 1 or Avel-Lindberg 40/3004)
F1 — 1-A 3AG slow-blow fuse
S1 — 5-position, 9-section, 18-pole rotary switch (Centralab PA302 6-inch index assy., Newark #22F652 plus 9 PA-32 sections, Newark #22F842 or see text). (If using fixed filters, 5-position, 6-section, 12-pole, PA1033, Newark #22F833)
S2 — 5-position, 2-section, 4-pole rotary switch (Centralab PA1013, Newark #22F813)
S3 — 11-position, 8-section, 8-pole rotary switch (Centralab PA302 6-inch index assy., Newark #22F652 plus 8 PA-30 sections, Newark #22F840 or see text). (If using fixed filters, 11-position, 4-section, 4-pole, PA1015, Newark #22F815)
S4 — 5-position, 1-section, 2-pole rotary switch (Centralab PA1003, Newark #22F803)
S5 — 11-position, 4-section, 4-pole rotary switch (Centralab PA1015, Newark #22F815)
S6 — Miniature SPDT switch
S7 — Minature SPST switch
M1 — 1-mA meter movement, preferably with 0-1 and 0-3 scales (MURA PM-702)
Misc. — case; power supply and input attenuator enclosures; line cord; BNC jacks; knobs; shielded cable; PWB terminals; DIP sockets; mounting hardware, etc. A set of three etched, drilled and solder-plated circuit boards (CP1, CP2 and CP3) is available for $35.20 post-paid (in continental U.S.A.) from Circuit-Works, 1118 7th Ave., Neptune, N.J. 07753. New Jersey residents must add 5-percent sales tax. Please allow 3 to 4 weeks for delivery.