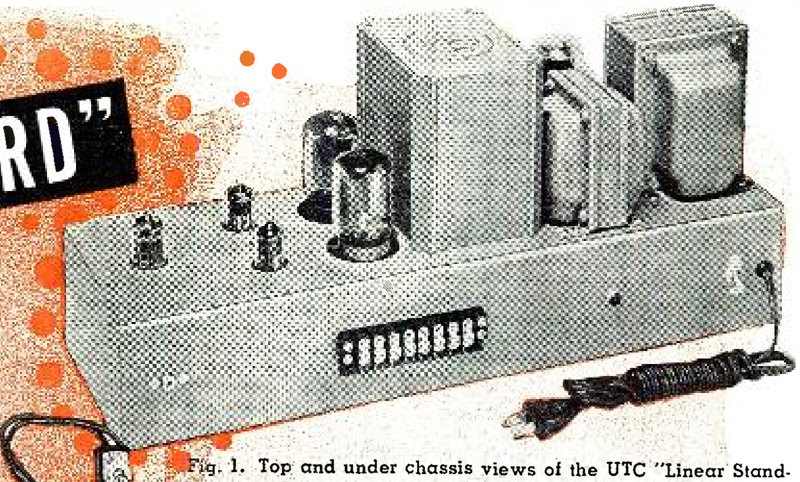
THE "LINEAR STANDARD" AMPLIFIER



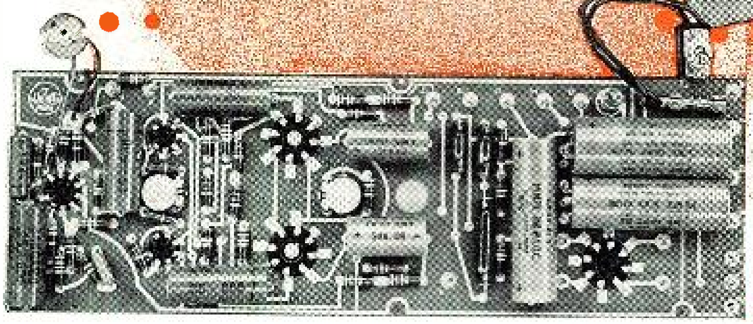


Fig. 1. Top and under chassis views of the UTC "Linear Standard" amplifier kit. Printed circuits are used for easy assembly.

By **JULIUS Z. KNAPP**
Audio Application Engineer
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A 20-watt multiple loop feedback amplifier that uses standard power and output transformers in its circuitry.

ABOUT a year ago our audio lab was given a project . . . to design an ideal audio amplifier for high-fidelity use. Before we were through, an entirely new concept of high-fidelity amplifier design had emerged.

At the start, we felt that practically all of the distortion in a well-designed, high-fidelity system would be found in things external to the amplifier . . . the recording or pickup distortion that occurs before the point at which signal enters the amplifier, and the distortion that occurs in the loudspeaker system after the signal leaves the amplifier. With this assumption, all that is required is an amplifier with high power handling ability, low distortion, and a frequency response extending four octaves on each side of the audio band. Unfortunately, a thorough investigation brought to light the fact that this did not provide an adequate means for obtaining full high fidelity. Additional requirements had to be placed upon the amplifier to assure excellent over-all performance.

An intensive laboratory program was then started to determine the nature of various distortions. Many tests were made and, after a careful analysis, we were able to find both cause and cure. We found, for example, that extension of an amplifier's bandwidth four octaves below the audio band did not guarantee good low-frequency transient response.

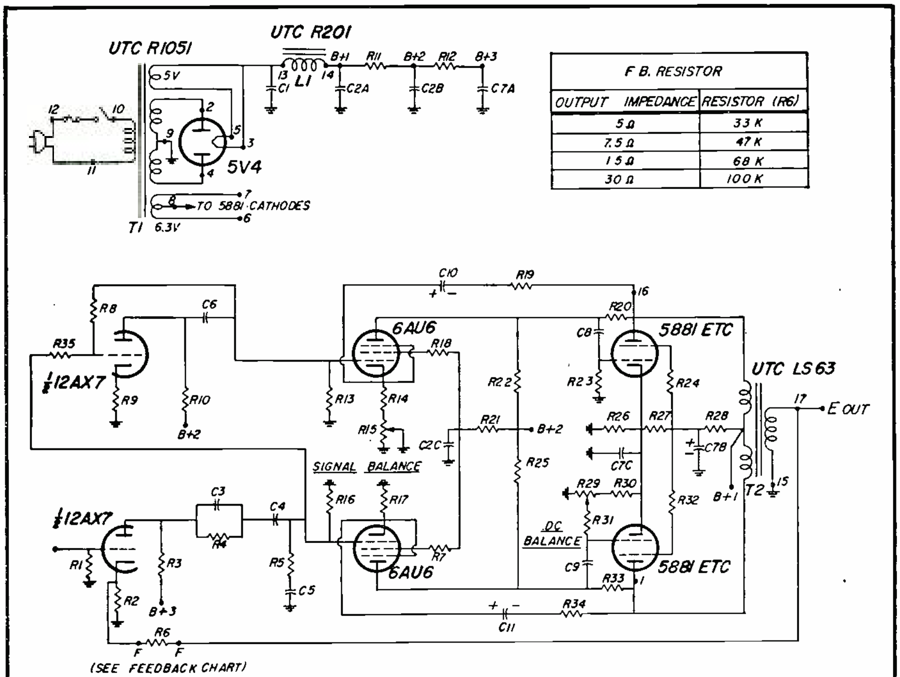
High-frequency oscillation was found to be a second problem. The capacitance in the test speaker leads and speaker system was sufficient to cause high-frequency oscillations in many quality audio amplifiers. These oscillations did not occur when the amplifiers were checked with a dummy resistor load, and being far above the audio range, could not be heard, but their effect in actual use was substantial, one of the peculiar characteristics of this oscillation being the fact that it would vary from zero to maximum under different signal conditions.

It was realized that a new amplifier circuit would have to be developed to provide the ideal high-fidelity amplifier called for in this project. Incidentally, between the start of this investigation and its completion, over a year's work was involved. Fig. 1 shows two views of the final amplifier design. In Figs. 2 and 3, the circuit diagram and the equivalent block diagram indicate the details of the final design. The evolution of this design and the data showing its characteristics as compared to previous circuitry follow.

We started with the fact that a very high amount of feedback would be required to reach the extremely low distortion levels desired for ultimate high fidelity. In the basic Williamson amplifier the feedback is provided in one step from the output to the input. This approach, in a multi-stage amplifier, results in a peaked response at both ends of the audio spectrum and a narrow margin of stability (Fig. 8). A basic design requirement of our amplifier was to correct this condition and, thus, obtain a much higher order of stability. This was accomplished through the use of multiple feedback loops. In Fig. 3 it can be seen that there are three feedback loops. The first is a local loop within the output stage. The second is a push-pull loop from driver stage to output stage. The third is an overloop from the output to the input. Twelve db of negative feedback is provided in each loop, thus effecting a total 36 db negative feedback around the output stage. The combined effect of the two inner feedback loops and the phase correcting network in the first interstage, all within the single over-all feedback loop, is to produce an amplifier free from response peaks and positive feedback at either end of the spectrum.

Fig. 4 shows the extremely low intermodulation distortion at all power levels resulting from the large amount of feedback. In Fig. 5 the frequency response curve of this amplifier is shown. The band trimming effect of the phase correction network in the first interstage is evident. Fig. 6, the curve of maximum power output versus frequency, shows the high power levels (0 db = 21.7 watts) that are obtained in a small package using all the component parts and tubes within their specified ratings. Incidentally, the hum level is 80 db below rated output.

Amplifiers with high amounts of feedback are sometimes critical as to components. However, in this circuit the stability is high enough to permit replacing one of the 5881 output tubes with a 6V6 with negligible effect, even though we had simulated extreme unbalance conditions. We also substituted a 6CB6 for one of the 6AU6's to simulate extreme driver unbalance with similar results. Resistors in all por-



F B. RESISTOR	
OUTPUT IMPEDANCE	RESISTOR (R6)
5 Ω	33 K
7.5 Ω	47 K
15 Ω	68 K
30 Ω	100 K

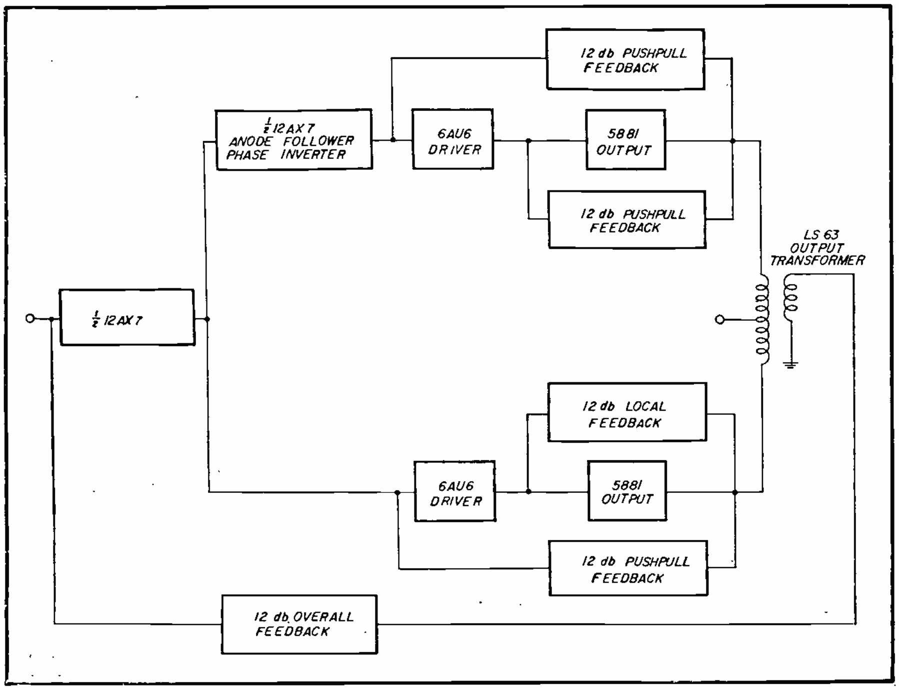
NOTES

1. ADJUST SIGNAL BALANCE CONTROL FOR CANCELLATION OF FUNDAMENTAL AT 1614 CATHODES LIFT 100mf BYPASS IF NECESSARY, TO OBTAIN ADEQUATE INDICATION

R_1—470,000 ohm, 1 w. res. ± 10%
R_2, R_9, R_{30}—3300 ohm, 1 w. res. ± 10%
R_3, R_{10}, R_{12}—180,000 ohm, 1 w. res. ± 10%
R_4—1 megohm, 1 w. res. ± 10%
R_5—10,000 ohm, 1 w. res. ± 10%
R_6—68,000 ohm, 1 w. res. ± 10% (see chart above)
R_7, R_{18}, R_{24}, R_{32}—180 ohm, 1 w. res. ± 10%
R_8, R_{35}—500,000 ohm, ½ w. res. ± 1%
R_{11}—2200 ohm, 1 w. res. ± 10%
R_{13}—150,000 ohm, 1 w. res. ± 10%
R_{14}—1000 ohm, 1 w. res. ± 10%
R_{15}, R_{29}—1000 ohm pot
R_{16}, R_{23}, R_{31}—330,000 ohm, 1 w. res. ± 10%
R_{17}—1500 ohm, 1 w. res. ± 5%
R_{19}, R_{34}—100,000 ohm, 1 w. res. ± 1%
R_{20}, R_{33}—510,000 ohm, 1 w. res. ± 5%
R_{21}—220,000 ohm, 1 w. res. ± 10%
R_{22}, R_{25}—100,000 ohm, 1 w. res. ± 5%
R_{26}—150 ohm, 5 w. wirewound res. ± 10%
R_{27}—20,000 ohm, 10 w. wirewound res. ± 10%
R_{28}—6000 ohm, 5 w. wirewound res. ± 10%
C_1—10 µfd., 600 v. elec. cond.
C_{2A}, C_{2B}, C_{2C}—40/8/1 µfd., 450 v. elec. cond.
C_3—.02 µfd., 600 v. cond.
C_4, C_6, C_8, C_9—.25 µfd., 600 v. cond.
C_5—150 µµfd. ceramic cond.
C_{7A}, C_{7B}, C_{7C}—8/8/100 µfd., 450/450/50 v. elec. cond.
C_{10}, C_{11}—8 µfd., 450 v. elec. cond.
L_1—Filter choke (UTC R201)
T_1—Power trans. (UTC R1051)
T_2—Output trans. (UTC LS 63)
1—12AX7 tube
2—6AU6 tubes
2—5881, 1614, 6L6, or KT66 tubes
1—5V4 tube

Fig. 2. Complete schematic and parts list covering the UTC Model MLF amplifier.

Fig. 3. Block diagram of amplifier. Other output tubes may be used. See Fig. 2.



tions of the circuit, except the few where precision resistors are employed, were changed by 30%, with no substantial effect on circuit performance.

The flaw in the single feedback system used in the Williamson type amplifier is well illustrated by the curve in Fig. 8. We made circuit variations and substituted transformers made by three manufacturers to assure ourselves that this was a general condition. In Fig. 8 the type and amount of feedback can be read as the difference in level between the curves of raw and net amplifier gain. From the basic definition of feedback, whenever the net amplification is less than the raw amplification, we have negative feedback with its attendant benefits. Whenever the net amplification is greater than the raw amplification, we have positive feedback with its many problems.

The low-frequency positive feedback peak is within the turntable rumble frequency band. For the majority of high-fidelity users who do not employ weighted transcription turntables with hysteresis synchronous motors, this is an important consideration. The positive feedback in the rumble range results in a loudspeaker damping factor fifty times worse than midband with twice the gain for rumble frequencies as compared to music signals. Because rumble has a high energy content, its signal can readily push the loudspeaker cone into a nonlinear portion of its operating characteristic. The result is that the program content suffers serious distortion. This was one of the points which made it necessary to evaluate the over-all system rather than measuring an amplifier on the lab bench.

To measure an amplifier's characteristic under steady state conditions alone is insufficient. However, with step function testing steady state *and transient response* can be accurately checked. Step function testing is simple, and with it response from d.c. to infinite frequency can be tested. Fig. 7A illustrates the simple apparatus employed. Essentially it consists of applying a sudden, constantly maintained, d.c. voltage. A clock is started at the instant the switch is closed and the graph of Fig. 7B records the result. The leading edge of the step, which is essentially a change in input voltage in zero time, would require an amplifier with an infinite high-frequency limit to reproduce exactly. The amount of time required for the amplifier to respond to this type of signal is called its "rise time." If the amplifier could amplify low frequencies down to d.c., its output waveshape would rise to its final value and stay there until the input step was removed. With an amplifier that cannot amplify d.c., the amount of time the output remains at the flat top of the step is an accurate indication of its amplification at low frequencies. From this we can see that a proper reading of the amplifier's response to the step function will give an accurate picture of the frequency response of our amplifier to a steady-state signal. Even more important, however, is the fact that this type of testing will show us what the amplifier is doing in the transient period *until* it comes to its final output. In the transient response we can see the relative stability of the amplifier against oscillation, and can deduce the direct and indirect effects on the total music producing system.

Fig. 11A shows the response of the "Linear Standard" power amplifier to a unit step. The faint dot visible on the zero axis is the time at which the step function was applied. It can be seen that there are two distinctly different rates of output signal decay. A glance at the schematic will show that we have a low frequency stabilizing phase lead network (C_3 and R_4 in the first coupling circuit) that is partially responsible for this. The overshoot, that portion of the response below the zero axis, is a basic part of *RC* coupling circuit pulse response. As is evident, the input pulse is equivalent to closing and opening a switch in the typical interstage circuit of Fig. 10. There would be an initial flow of current after the closing of the switch while the condenser acts as a short circuit. As the charge builds up on the condenser, the voltage across it will reduce the current flow through R_g, and so reduce the output voltage. The time constant is determined by R_g and C_g. When the switch is opened, the charge stored in the condenser will discharge through the circuit resistance (R and R_g) to produce the overshoot. This discharge time constant is determined by R_{total} and C_g. We can see that while there is overshoot in Fig. 11A, there is no low frequency oscillation.

Fig. 11A can be compared with Fig. 11B which shows the corresponding step function response of one Williamson-type circuit. By counting the timing cycle peaks, it can be seen that a low frequency damped oscillation occurs, which lasts 3.5 times the length of the overshoot shown in Fig. 11A, and whose initial value is 250% of the maximum value reached in overshoot. This low frequency oscillation (roughly one cycle-per-second) can be induced by commonly encountered phenomena as well as the step function. Sharp volume level changes which occur in program material having large dynamic range will cause this oscillation. The a.c. line voltage variations with their attendant "B+" level changes, switching of preamp or station tuning circuits, and many other transient impulses will produce this type of oscillation. The seriousness of this effect has already been described, and hinges on the fact that at this low frequency oscillation point we have peak-positive feedback, which not only increases the effect of amplifier gain, but the damping factor of the amplifier is more than fifty times worse than at midband. It is evident that any substantial amount of low frequency power (this oscillation represents considerable low frequency power) will drive the cone to its mechanical limit. Audio signals superimposed on top of this condition will be radically distorted, since in this displaced position the speaker can no longer duplicate an incoming signal. In other words, while our amplifier in a steady-state resistive load test circuit might show 1% distortion, under this condition of operating use 50% distortion is readily understandable. To minimize this distortion condition, the amplifier must be as free as possible from ringing or overshoot. Only in this way can high-fidelity performance result and listener fatigue be minimized.

Since the birth of high fidelity, there has been a constant movement to provide increased realism in program material. This improvement is represented by a decreased distortion content and an increased dynamic range, further increase of dynamic range being provided through the use of loudness controls that boost high and low frequencies. This results in a strong possibility of amplifier overload at certain passages even when the average loudness is at comfortable level. Under these conditions, we found that amplifier recovery from overload was an important factor to consider in the amplifier design. Fig. 11C illustrates the recovery from overload of the "Linear Standard" power amplifier. The bright line at the top and bottom of the left-hand portion of the oscillogram indicates that clipping is taking place. It is readily seen that the recovery is smooth and free from transient disturbances. Fig. 11D is the same picture with an expanded sweep, to re-examine the time interval close to the signal reduction point, the same 5 cycle timing wave is employed, and it is self-evident that recovery is smooth. Fig. 11E is a comparable oscillogram using a well-known amplifier. In this instance, the recovery from overload shows a low-frequency transient in the output envelope, which is illustrative of the condition producing the large voice-coil movement. This is why there are many comments that the single-loop feedback amplifier sounds "muddy" on orchestral crescendos.

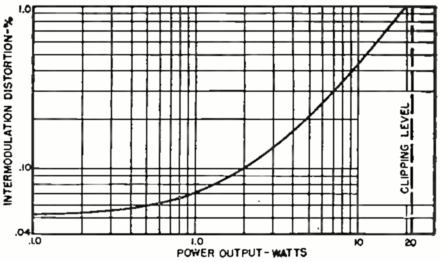


Fig. 4. IM distortion versus power output at 40 cps and 7 kc., mixed 4:1,16 ohms.

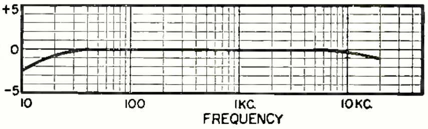


Fig. 5. Frequency response of the Model MLF at ½ watt output, 16 ohm connection.

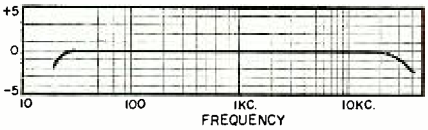


Fig. 6. Maximum power output of amplifier 0 db=21.7 watts, 16 ohm connection. Input is 1.1 volts for maximum output.

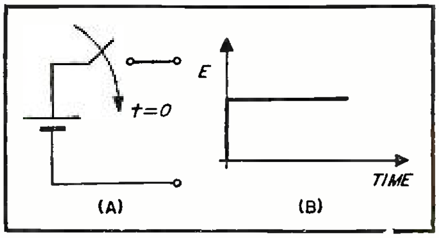
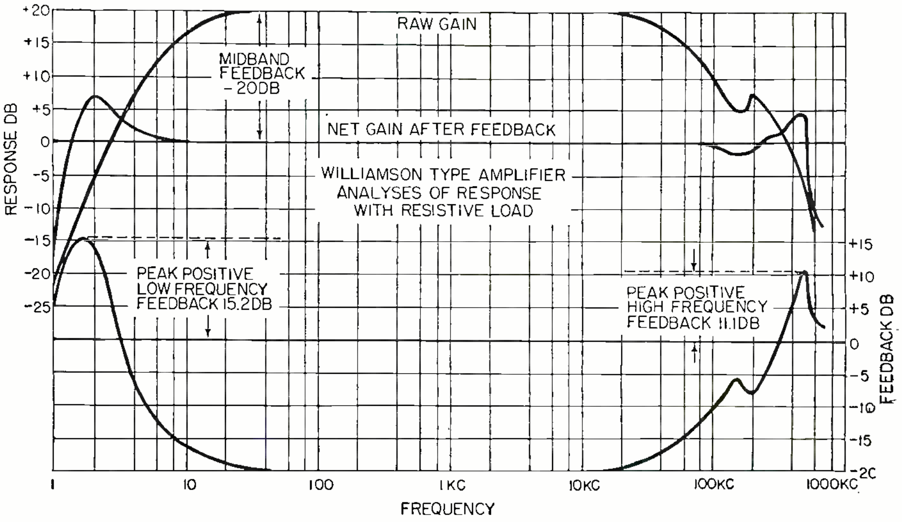


Fig. 7. Step function production and graph.

To investigate amplifier response at high frequencies, we found it necessary to expand the region near the start of the step function. This was accomplished by using square waves in lieu of the step, and adjusting the horizontal scale to exactly 10 microseconds per box with a 10 kc. square-wave input (precisely 10 kc., set with an events-per-unit-time-meter). Using the standard rise time as the time it

Fig. 8. A typical response pattern for a basic Williamson-type amplifier.



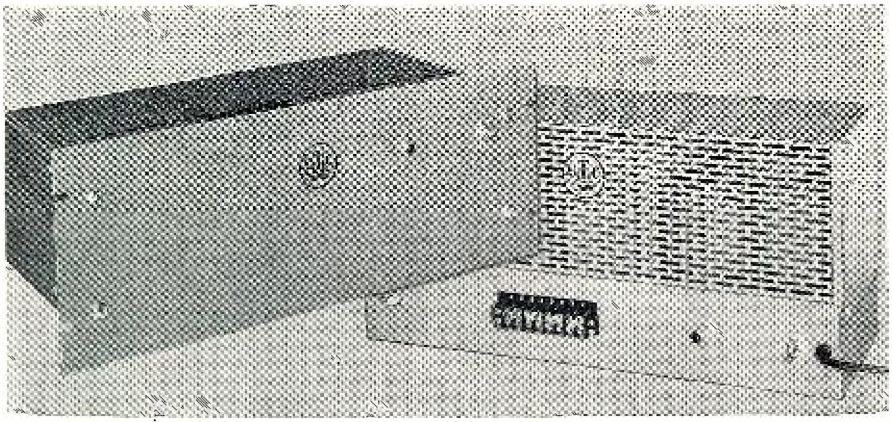


Fig. 9. The commercial version of the "Linear Standard" amplifier comes complete with dust cover as shown. If desired, it can be easily adapted for rack mounting.

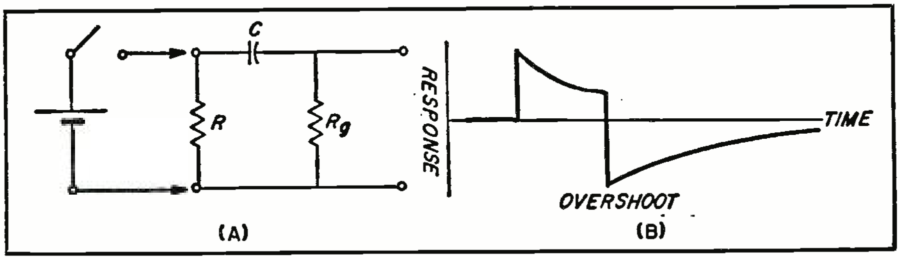


Fig. 10. Typical interstage and its pulse response for any RC amplifier.

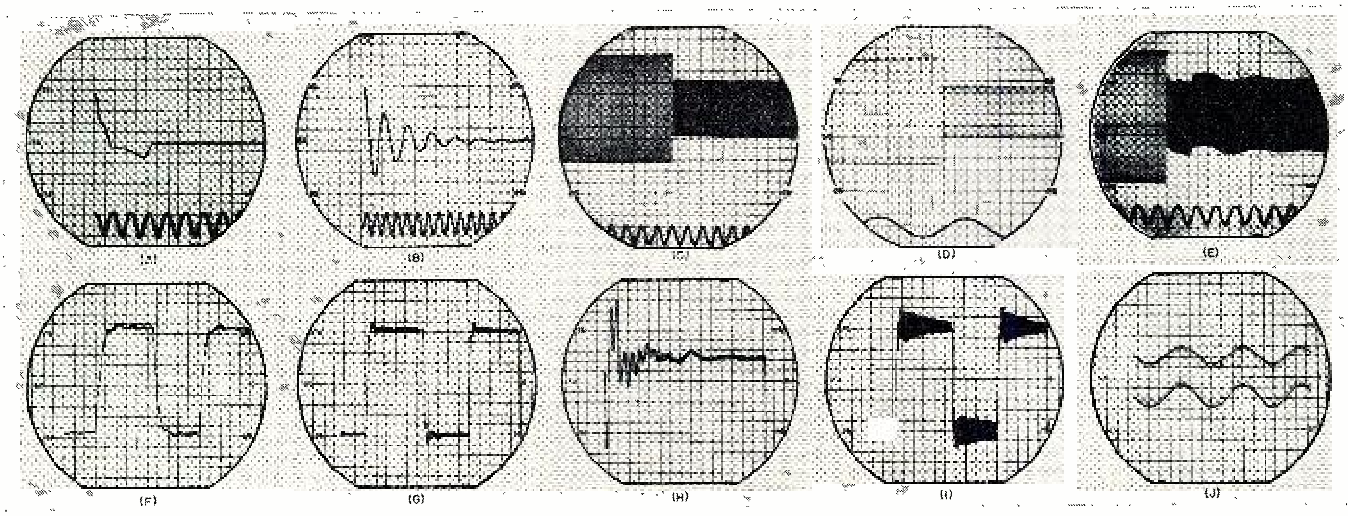
takes to go from 10% to 90% response, we can see from Fig. 11F that the "Linear Standard" power amplifier has a rise time of 6.6 microseconds, which is adequate for any acoustic waveforms that can be encountered. Reading the flat top of the wave, we find a transient oscillation, but of very small magnitude and highly damped. This rise time has been set in the design of the phase lag network (R_5-C_5) so that with the 36 db multiple feedback system, stability against oscillation with any type of load has been effected. Fig. 11G shows a similar square-wave oscillogram with a widely used hi-fi amplifier. Here the rise time is unnecessarily shorter, since it is not required for audio fidelity, but the increased bandwidth results in poor stability. A close inspection of the flat top in this figure shows a persistent r.f. oscillation. Fig. 11H is an expansion of this flat top showing the extent and seriousness of this ringing. The lead and speaker system capacity of a typical high-fidelity amplifier load was measured and found to be on the order of .0025 μfd. and greater. Fig. 11I was obtained by loading the amplifier with this amount of capacity in addition to its resistive load, and it can be seen that the amplifier is close to ultrasonic oscillation. Under test it was found that the actual frequency of oscillation depended, in addition, on circuit capacities and the output transformer used. Over the range of tests tried, this oscillation frequency was found to be anywhere from 25 kc. to 490 kc. Further tests were run to determine the effect of this oscillation. As shown in Fig. 11J (signal freq. here is 1 kc. and the oscillation freq. is 485 kc.), if the oscillation is not too great the waveform distortion is comparable to that found in table model radios at peak output. Further investigation indicated that the basic Williamson amplifier could oscillate on zero audio signal, and then as audio signal was injected, oscillation amplitude would decrease on negative peaks and finally disappeared at peak signal input. This is shown in Fig. 12, where the audio signal input was raised from zero to maximum in four steps until the r.f. oscillation disappeared. A possible explanation for this variable stability may lie in the fact that the output tube g_m cannot be considered constant at high signals, but must be considered as varying through the signal cycle.

We have indicated that loudspeaker systems, as used, represent loads with substantial capacity. While at first thought this would not seem so, in practice we find this to be true, particularly with the remote multiple speaker installations so commonly used. Cable capacities run from 40 to 80 μμfd./ft. and the shunt capacities per speaker range from 50 to 150 μμfd. With the "Linear Standard" amplifier this is of no particular consequence because of the excellent stability that it provides.

It is easy to sum up the radical step that this new amplifier provides in high-fidelity design. For quite some time, it has been realized that good transient response is an essential for high-fidelity reproduction. The approach heretofore was to extend the amplifier bandwidth far beyond the region of audio use, with the feeling that an amplifier whose bandwidth is so much greater than the audio band must have good transient response at the center of the band. In other words, the center of the band repre-

(*Continued on page* 113)

Fig. 11. (A) Step function response of the Model MLF and (B) a Williamson amplifier. (C) Overload recovery of the Model MLF and (D) with expanded time scale. (E) Overload recovery of a Williamson-type unit. (F) 10 kc. square-wave response and rise time of Model MLF and (G) Williamson-type. (H) Expanded scale square-wave top Williamson-type amplifier. (I) Square-wave ringing with capacitive load Williamson-type. (J) A Williamson-type amplifier in high-frequency oscillation.



"Linear Standard" Amplifier

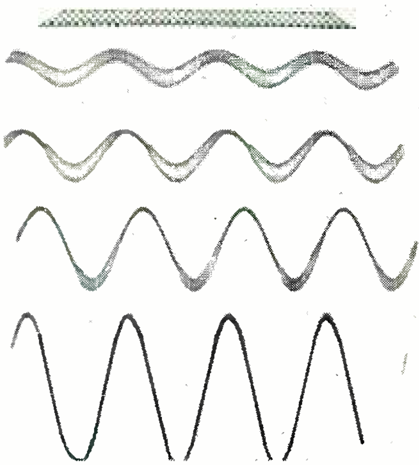
(*Continued from page* 46)

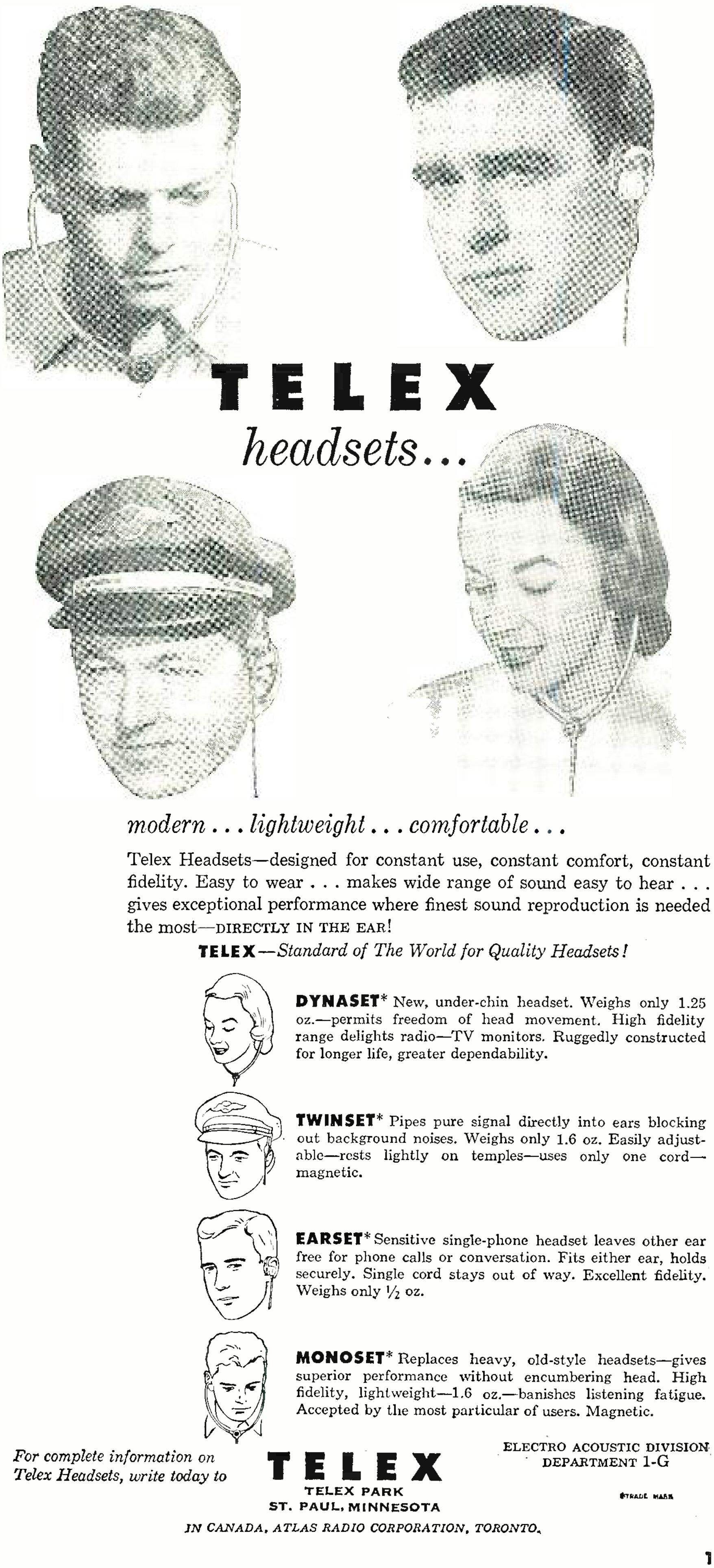
senting the audio range would have small phase shift and a musical waveshape coming through this region would be undistorted. The concept in this new amplifier circuitry involves a realization that a linear phase condition required for optimum *transient* response actually involves a smaller bandwidth than can be obtained if *amplitude* response is considered alone. The "Linear Standard" circuit designed by J. M. Diamond of our laboratories and discussed in the article "Multiple Feedback Audio Amplifier" (Electronics, November 1953) is a big step in this direction. It actually provides bandwidth for optimum *transient* response, and recognizes the necessity for a rugged, stable structure that can give long, trouble-free service. Components and tubes are conservatively used within their specified ratings.

It was required that the amplifier be easy to assemble—there would have to be uniformity between the lab models and those sold—and long term trouble-free stability was essential. To meet these requirements the amplifier ended up with an etched circuit design requiring for assembly merely the making of 17 numbered screw-type connections.

The etched circuit with all components in place is shown in Fig. 1. Etched circuit soldering technique is used, making total soldering time in manufacture somewhat less than 10 seconds per amplifier. Tube sockets, pilot lamp, fuse clips, etc. are all incorporated directly into the etched circuit board. A simple suspension method, illustrated in Fig. 13, protects both sides of the etched circuit board and maintains low, pre-determined, ground capacities. The layout is such that the vacuum-tube filaments are kept above the top surface of the metal chassis, so that their heat radiates into the surrounding air.

Fig. 12. Multiple oscillogram of Williamson-type amplifier output with capacitive loading as input audio signal is varied, showing the conditional stability obtained. See text for the complete discussion.





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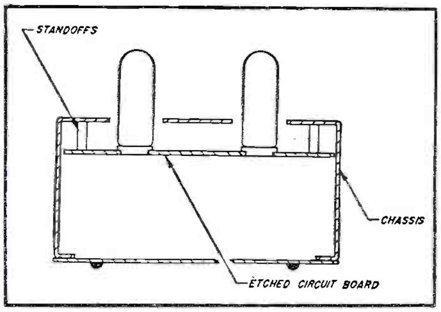

Fig. 13. Cross-section drawing of amplifier.

The heavy magnetic components are mounted to the metal chassis, and make connection to the amplifier circuit through screw terminals located on the etched circuit board. While this amplifier is sold as a kit, the etched circuit construction makes it possible to pre-check each kit with its own set of tubes prior to shipment, to assure optimum performance to the purchaser. The user merely has to wire up the 17 screw connections, and if he has an 8 or 16 ohm speaker, he is finished. For other speakers and matching problems, all the transformer secondary connections are brought out to a barrier terminal strip and connections for impedances from 1.2 to 30 ohms are readily available. To get optimum transformer efficiency, the secondary of a high-fidelity output transformer must be sectionalized for series-parallel arrangements which will permit the use of all the secondary copper in any of the widely used impedance values.

The *UTC* LS-63 transformer employed has exceptionally wide frequency response with minimum phase shift in the passband. If line impedances are required, type LS-61 is available. With the terminal strip arrangement provided, it is possible to cover a wide range of impedance values with a minimum of effort. However, for loads other than 8 or 16 ohms the feedback resistor (see chart on schematic Fig. 2) must be changed. This resistor is held between two screw connectors for easy change. The values of feedback resistors required for additional output impedance values are listed in Fig. 2.

With the realization that size is an important factor in many high-fidelity installations, this unit has been designed to remarkably small dimensions (5¼"x17⅛"x8") for its performance. The bottom is protected by a cover plate equipped with bumper feet to prevent the marring of furniture. These dimensions also allow the mounting of the amplifier on a 7" relay rack panel for studio use. No resoldering is required, it merely being necessary to prepare the panel for the mounting of the amplifier and mount the unit on it.

The "Linear Standard" power amplifier, while a universal amplifier, provides new standards of performance. Its technical qualifications are of professional caliber, yet its constructional requirements through the use of modern technology are in the province of the music lover. —30—