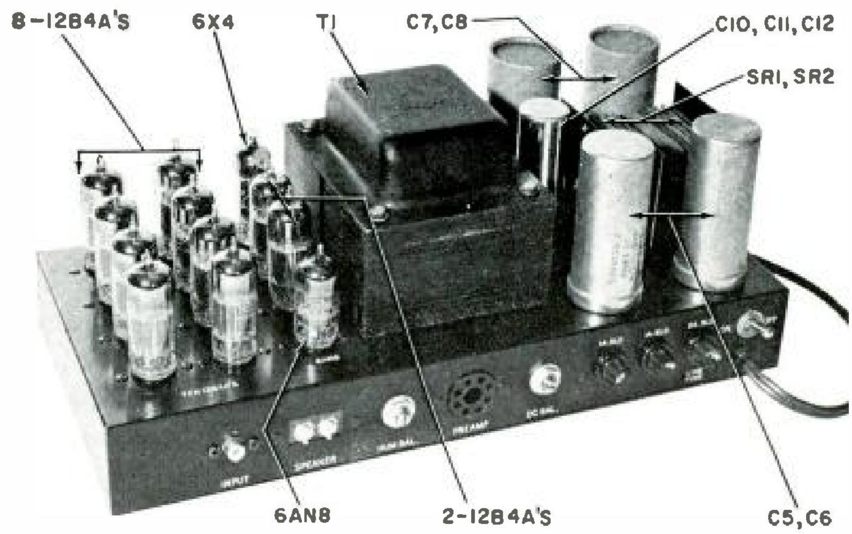
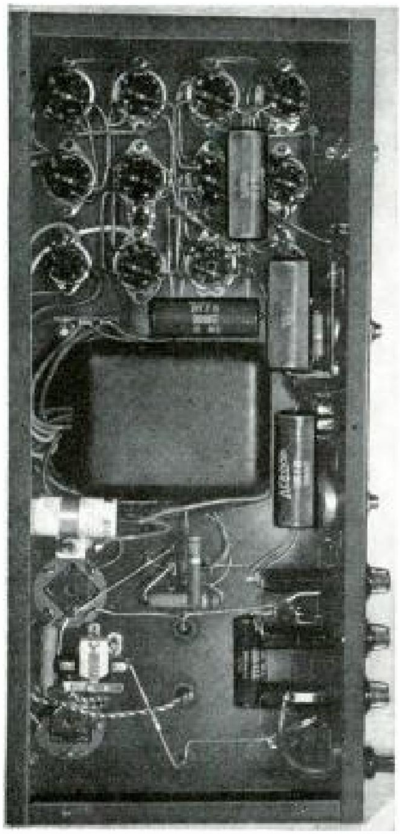
Ultra-stable OTL Hi-Fi Amplifier

By JULIUS FUTTERMAN





Over-all and under-chassis views of the ultra-stable amplifier are shown here.

Full construction details on output-transformerless amplifier that boasts a damping factor of eighty.

THE author has been intrigued with output-transformerless (OTL) hi-fi amplifiers for years. He felt that if the output transformer could be eliminated from an amplifier design, while keeping all other phase-shifting components to a minimum, then even with very large ratios of over-all negative feedback there would be no problem of instability. The present model, which will be fully described, is the culmination of several years' work. It is designed to operate with conventional loudspeakers. The only test equipment essential for its construction is a 20,000-ohms-per-volt multimeter.

The basic design is extremely simple. Referring to Fig. 1, a pentode, V_1, is operated as a high-gain voltage amplifier and is directly coupled to the phase-splitter tube V_2. The cathode load resistor of V_2 is returned to ground through the output load, which may be the 16-ohm voice coil of a conventional loudspeaker. Signal voltage developed across the plate load resistor of V_2 is applied between grid and cathode of output tube V_3. Likewise, signal voltage 180 degrees out-of-phase, developed across the cathode load resistor of V_2, is applied between grid and cathode of output tube V_4. Careful testing has substantiated the fact that with low values of cathode and plate resistors, the signals from this type of phase-splitter are balanced over the audio-frequency range.

The output tubes are connected in series push-pull and are biased for Class AB operation. The load for the amplifier is connected with its high side to the cathode of V_3 and plate of V_4 and its low side to ground. Each of the output tubes has its own power supply, consisting simply of a metallic rectifier *SR* and a capacitor *C*. Due to the balanced nature of the circuit there is no d.c. in the output load.

The potentiometer in shunt with the load has its arm in the cathode circuit of the voltage amplifier tube V_1. When the arm of the potentiometer is at ground, there is no over-all negative feedback and the full gain of the amplifier is obtained. With the arm at the high side of the load, there is 100% negative feedback and the gain of the amplifier is essentially unity. Because of the minimum of phase-shifting components in this amplifier, large amounts of negative feedback may be used. The author has constructed amplifiers of this type with as much as 60 db of feedback without any instability!

In this circuit, the output tubes are working as cathode followers and thus require large driving voltages from the phase-splitter tube. With this

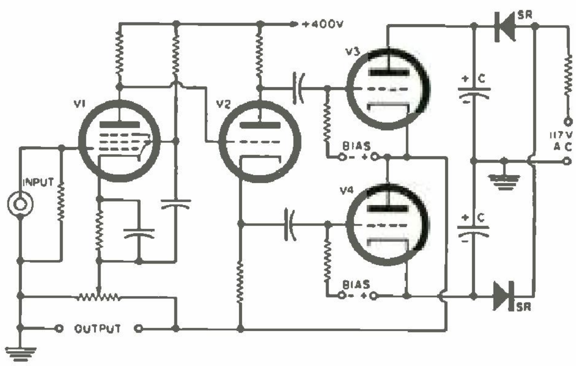
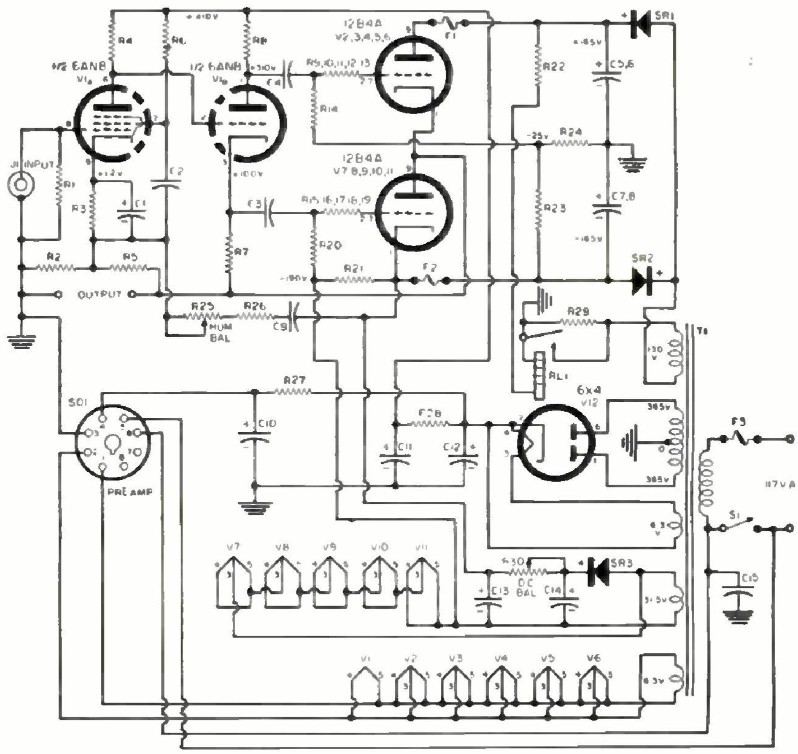


Fig. 1. The diagram shown here is the basic circuit arrangement employed in the output-transformerless hi-fi amplifier.

type of phase-splitter, the signal voltage across the plate and cathode resistors is essentially of the same magnitude as the input voltage to the tube. Normally, this would require a large voltage from V_1. Fortunately, because the speaker load is also in the input circuit of the phase-splitter tube and in the correct sense to provide positive feedback, a much lower voltage suffices. In fact, the peak signal voltage to the input of the phase-splitter need be only as high as the fixed bias applied to the power tubes, for maximum output. A novel feature of this amplifier, as will be noted in Fig. 1, is that the output load is part of the input circuits of all the tubes used in the amplifier for the purpose of obtaining both positive and negative feedback. This has been accomplished without the use of any reactive components which might produce undesirable phase shifts.



R_1—270,000 ohm, 1/2 w. res.
R_2, R_9, R_{10}, R_{11}, R_{12}, R_{13}, R_{15}, R_{16}, R_{17}, R_{18}, R_{19}—100 ohm, 1/2 w. res.
R_3—5100 ohm, 1/2 w. res. ± 5%
R_4—1.8 megohm, 1 w. res. ± 5%
R_5—750 ohm, 1/2 w. res.
R_6—8.2 megohm, 1 w. res. ± 5%
R_7, R_8—18,000 ohm, 2 w. res. (matched with ohmmeter)
R_{14}, R_{20}—47,000 ohm, 1/2 w. res. ± 5%
R_{21}, R_{24}—15,000 ohm, 1/2 w. res. ± 5%
R_{22}—82,000 ohm, 1/2 w. res.
R_{23}—82,000 ohm, 1 w. res. ± 5%
R_{25}—250,000 ohm pot ("Hum Balancing")
R_{26}—22,000 ohm, 1/2 w. res.
R_{27}—6800 ohm, 1 w. res.
R_{28}—10,000 ohm, 1 w. res.
R_{29}—300 ohm, 5 w. res.
R_{30}—10,000 ohm pot ("D.C. Balancing")
C_1—50 µfd., 6 v. elec. capacitor
C_2, C_3, C_4, C_9—.22 µfd., 400 v. capacitor
C_5, C_6, C_7, C_8—300 µfd., 175 v. elec. capacitor (two paralleled, see text)
C_{10}-C_{11}-C_{12}—15/20/20 µfd., 350/450/450 v. elec. capacitor
C_{13}-C_{14}—10/10 µfd., 50 v. elec. capacitor
C_{15}—.047 µfd., 600 v. capacitor
SR_1, SR_2—500 ma., 130 v. a.c. silicon power rectifier (Sarkes Tarzian M500 or Audio Devices A750)
SR_3—20 ma., 65 v. selenium rectifier (Radio Receptor 4Y1)
J_1—Phono jack
RL_1—9000-ohm relay (Sigma type 11F)
S_1—S.p.s.t. switch (see text)
SO_1—Octal socket (to match preamp used with this amplifier)
F_1, F_2—1 amp fuse (Slo-Blo type)
F_3—3 amp fuse (Slo-Blo type)
T_1—Power trans. 365-0-365 v. @ 30 ma.; 6.3 v. @ .6 amp; 6.3 v. @ 5 amps; 31.5 v. @ .6 amp; 130 v. (d.c. resistance of winding to be less than 1.5 ohms), 117 volt primary with the d.c. resistance of winding to be less than 1.5 ohms (see text)
V_1—6AN8 tube
V_2, V_3, V_4, V_5, V_6,
V_7, V_8, V_9, V_{10}, V_{11}—12B4A tube
V_{12}—6X4 tube

Fig. 2. Complete schematic diagram and parts listing for the ultra-stable amplifier.

Amplifier Circuit

The complete amplifier is constructed on a 13½ x 6 x 1¾ inch chassis. The schematic is given in Fig. 2 and along with the accompanying photographs indicates the construction. A 6AN8 tube is used as a combined voltage amplifier and phase-splitter. The unusually large plate load resistor (1.8 megohms) of the voltage amplifier produces a gain of over 1000 from this stage and is entirely practical since the direct coupling to the phase-splitter eliminates the usual loading effect of the following grid resistor.

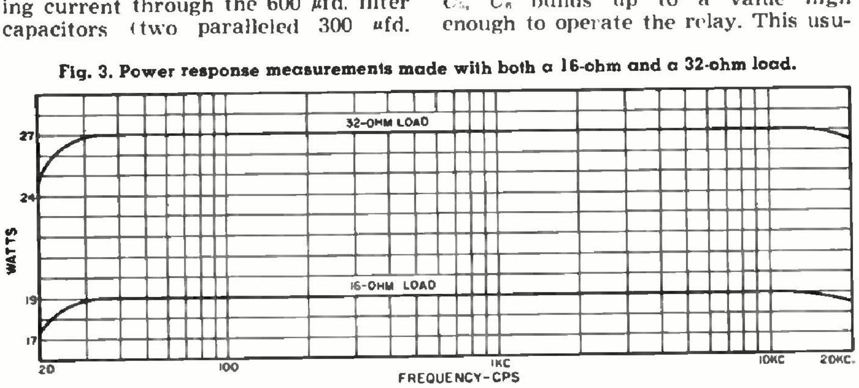
Each half of the series-connected push-pull output stage consists of five type 12B4A tubes connected in parallel. There are two identical plate current supplies for this stage, each consisting simply of a silicon or selenium rectifier and two 300 µfd. electrolytic capacitors connected in parallel. The power transformer is a special low-impedance unit in which the primary and the 130-volt winding feeding the power supplies for the output stage, each has a d.c. resistance of less than 1.5 ohms. This is essential so that the large current demands of the power tubes, when peaks of program material are handled, can be met. Despite the absence of filter chokes or resistors in these power supplies, the signal-to-hum ratio of the amplifier is very high, better than 50 dbm. This is because the amplifier itself acts as an electronic filter.

To prevent the initial surge of charging current through the 600 µfd. filter capacitors (two paralleled 300 µfd. units) from damaging the rectifiers when the amplifier is first turned on, a surge-limiting resistor of 300 ohms (R_{29}) is connected in series with the rectifiers. The function of the relay (RL_1) is to short out this resistor when the voltage across the filter capacitor C_5, C_6 builds up to a value high enough to operate the relay. This usually takes approximately two seconds. The *Sigma* type 11F relay used here is an inexpensive unit selling for $1.80 at most parts distributors.

Fixed negative bias of 25 volts for the upper half of the output stage is obtained from a voltage divider R_{23}, R_{24} connected across the plate supply of the lower output tubes. These lower tubes also have a fixed bias of approximately 25 volts, which is developed across R_{21}, SR_3, C_{13}, and C_{14}, supply this voltage. The d.c. balance pot (R_{30}) is used to adjust this bias so that there is no d.c. in the speaker voice coil.

Plate voltage for the 6AN8 voltage amplifier and phase-splitter is obtained from a 6X4 rectifier tube (V_{12}). The current required is less than 6 ma. and is well filtered by C_{11}, C_{12}, and R_{28}. Plate voltage for an external preamplifier is available at the octal socket and is filtered by C_{10} and R_{27}. Most preamplifiers such as the *Heathkit* and *Dyna-*

Fig. 3. Power response measurements made with both a 16-ohm and a 32-ohm load.



kit require a heater supply that is not grounded and this is also provided for at the octal socket. The line switch on the amplifier is a convenience. If it is desired to operate the amplifier from the "on-off" switch on the preamp, then the amplifier switch should be left in the "off" position and the preamp switch wired to pins 5 and 6 of the octal socket.

Construction

Actual construction of the amplifier is relatively simple. The parts layout shown in the photographs is recommended. It will be noted that the tubes which are the primary heat-producing elements are separated by the power transformer from the electrolytic capacitors and rectifiers. C_7 and C_8 are insulated from the chassis.

Wiring is point-to-point, as direct as possible. The 100-ohm suppressor resistors are conveniently mounted across pins 2 (grid) and 8 (unused) of each 12B4A tube socket. The pin 8 contacts are then connected in parallel. The only precaution necessary in wiring the amplifier is to keep the lead from the input jack to the grid of the 6AN8 tube (pin 8) short and direct. Particularly, dress it away from the high side of the output. If a different layout is used and this lead is more than 3 inches long, then use shielded wire.

Since the photographs of the amplifier were taken, silicon power rectifiers have become available in addition to the selenium units shown. The specific types recommended for this circuit are given in the parts list.

Except for the power transformer and possibly the 300 µfd. electrolytic capacitors, all the components used in this amplifier are standard items available at any parts distributor. The power transformer and capacitors, also the chassis with all holes punched, can be obtained from *Radio & Television Service Co.*, 2768 Broadway, New York 25, N. Y. Cost of the transformer is $11.90, each electrolytic is $1.85, and the punched chassis and bottom plate is $6.80.

Testing

In testing the amplifier it is advisable to adhere to the following procedure:

(1) Temporarily remove the two silicon power rectifiers. If they are of the pigtail type, unsolder one lead from each. Short the amplifier input by means of a phono plug, across which has been soldered a short length of wire. Connect to the output terminals a resistor of any value from 10 to 100 ohms.

(2) Connect the amplifier to the a.c. line and allow a one minute warm-up. Check to see that all the tubes are lit. Use the 20.000-ohms-per-volt range of the meter and measure the following voltages: (A variation of ±20% is permissible.)

a. Chassis to C_{11}: 410 volts.
b. Chassis to pin 9 of 6AN8 tube: 1.2 volts.
c. Chassis to pin 3 of 6AN8 tube; 100 volts.
d. Pin 1 of 6AN8 tube to C_{11} (across R_5); this voltage should measure the same as in step "*c*".

If the voltage measured in steps "*c*" and "*d*" is lower than 80 or higher than 120 volts, then either of the following two expedients may be adopted: (1) Substitute another 6AN8 tube and repeat steps "*b*", "*c*", and "*d*". (2) Parallel R_8 (8.2 megohms) with a resistor of 22 megohms (½ watt, 10%) if the voltage is high. If low, then series R_8 with a resistor of 470,000 ohms. Repeat steps "*b*", "*c*", and "*d*".

(3) Measure the bias voltage across R_{21} (15,000 ohms) plus side of meter to end of resistor that goes to pin 1 of the 12B4A tubes. Adjust this voltage to 25 volts by means of R_{30} (d.c. balance pot). Turn amplifier off and replace the two power rectifiers. Remove the 1-amp fuses F_1, F_2. Turn amplifier on again and note if the relay closes. (If the amplifier should be turned off at this point, it will take from 30 seconds to a minute for the relay to open. This is so because, with the power tubes not drawing any plate current, the filter capacitor takes a long time to discharge. In normal operation of the amplifier the relay will both open and close in approximately two seconds). Measure the bias voltage across R_{21} (15,000 ohms) plus side of meter to chassis. This should be 25 volts, ±10%.

(4) Replace the two fuses. With the voltmeter across the output terminals, and using a progressively lower range, adjust the d.c. balance pot (R_{30}) for zero volts. Again measure the two bias voltages (as in step "3"); they should be within one volt of each other. If not, then adjust R_{30} to equalize the bias voltages and, monitoring the voltage across the output, interchange the five

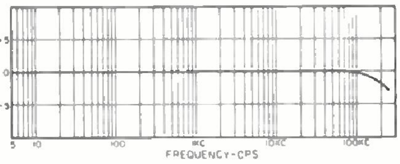
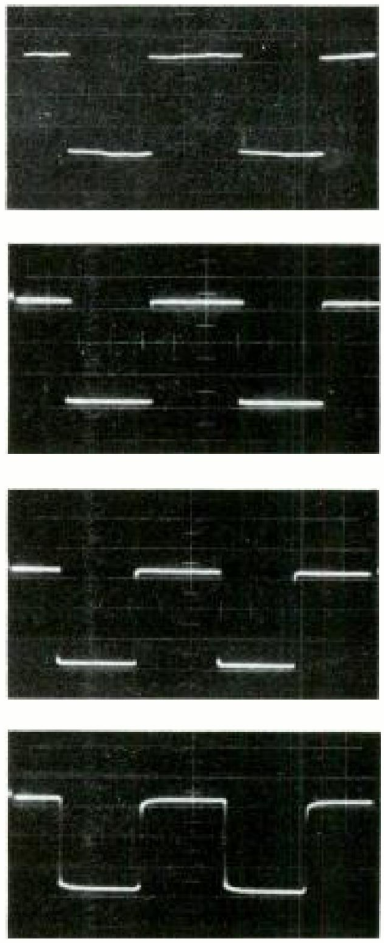


Fig. 4. Frequency response of amplifier.

Fig. 5. Square-wave amplifier response. (A) 20 cps. (B) 200 cps. (C) 2 kc.. (D) 20 kc.



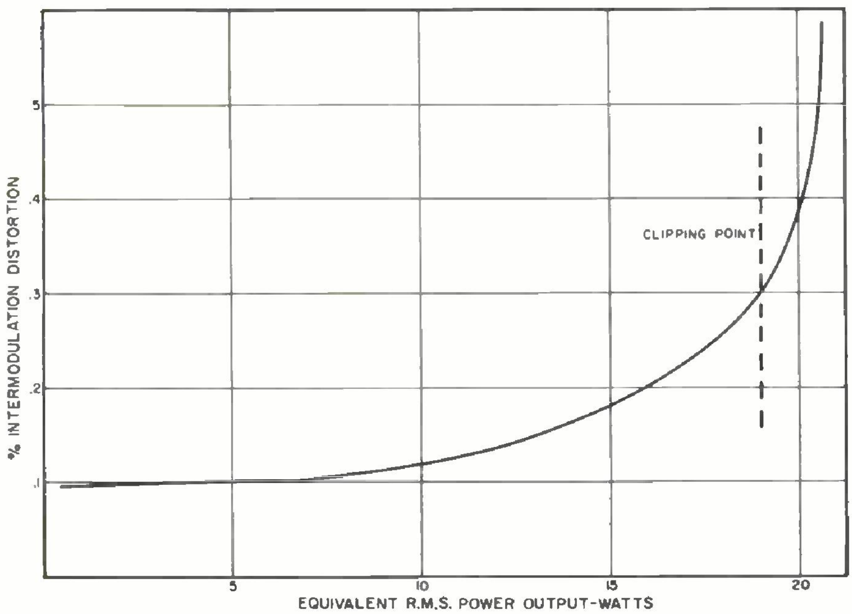
A

B

C

D

Fig. 6. Intermodulation distortion measurements with clipping point shown (16-ohm load).



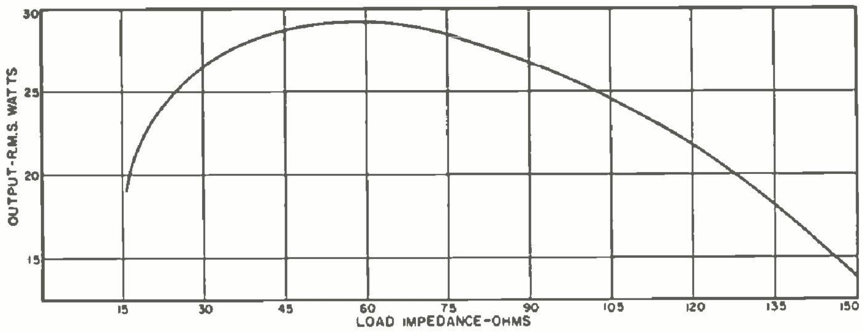
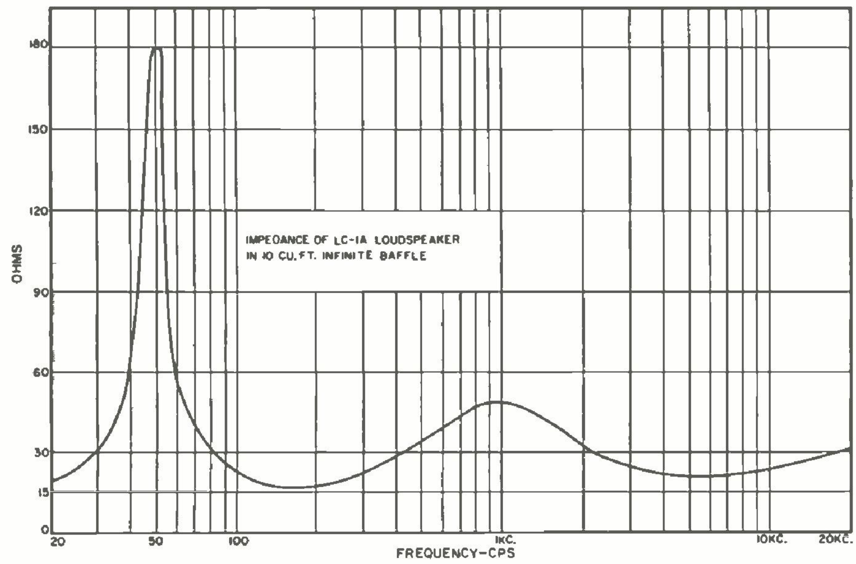


Fig. 7. The power output of the amplifier varies with amount of load that is presented.

Fig. 8. Impedance of RCA LC-1A speaker may be used to calculate the power.



upper 12B4A tubes with the five lower tubes (one pair at a time) for a minimum meter reading. It is not necessary to strive for a zero reading. This can be obtained with a slight re-adjustment of the d.c. balance control. This procedure results in maximum output from the amplifier and also assures that clipping will occur simultaneously on both positive and negative peaks at the overload point of the output signal.

(5) Turn amplifier off and remove either of the 1-amp fuses. Connect the meter to the fuse post terminals, using the 600 ma. range on the meter. Turn amplifier on. The meter will indicate the total plate current of the five 12B-4A tubes in one-half of the output stage. To insure low distortion on small output signals the plate current should be from 100 to 120 ma. If the plate current is low, then parallel R_{21} with another resistor (220,000 to 470,-000 is about right); if high, parallel R_{23} (82,000 ohms) with a resistor of about 1 to 2.2 megohms. Re-adjust for zero d.c. across the output with the d.c. balance control and check the plate current again.

(6) Remove the temporary load resistor from the output terminals and connect the loudspeaker. For this adjustment the amplifier should be close to the loudspeaker. Listen closely and adjust the hum balancing control (R_{25}) for minimum hum. The null point, where the residual hum voltages of the amplifier cancel in the output, is quite sharp, so it is advisable that this operation be performed in a quiet room. If a scope or a.c. vacuum-tube voltmeter is available it can be connected to the output, in parallel with the loudspeaker, so as to more easily ascertain the correct setting. Remove the input shorting plug (first turning off the amplifier) and the unit is ready for use.

Performance

It has been found that in all cases, the foregoing test procedure will result in the optimum performance designed into the amplifier. Of course, for those fellow experimenters who have access to more elaborate test equipment, such as a sine-square-wave signal generator, distortion analyzers, oscilloscope, etc., the following impressive specifications can be checked.

Frequency response: Measured with a *Hewlett-Packard* 200 CD oscillator and *Precision* 550 oscilloscope at 1-watt output, 16-ohm load. Flat from below 5 cycles to 100,000 cps, three db down at 250,000 cps with no peak in response at any frequency. See Fig. 4.

Power response: Flat within 1 db from 20 to 20,000 cps at maximum undistorted output. See Fig. 3. This was measured with both a 16- and 32-ohm load. The *Precision* 550 scope was used to monitor the output and the signal set to just below the clipping point at each test frequency. The power output was then determined. This procedure of testing for maximum output with a sine-wave signal has to be done quickly in order to avoid overloading the output tubes. This will be covered later.

Harmonic distortion: Extremely low at any frequency from 20 to 20,000 cps. No graph is shown and precise figures not given for the reason that with the test equipment available (*Hewlett-Packard* 200 CD oscillator and 330B distortion analyzer, also *Precision* E300 signal generator) the distortion measurements, at any output below overload, were in the realm of the residual figures of the instruments themselves. As an estimate we would say that the harmonic distortion, at any audio frequency below overload, is below 0.1 per-cent.

Intermodulation distortion: This is a more sensitive method of measuring

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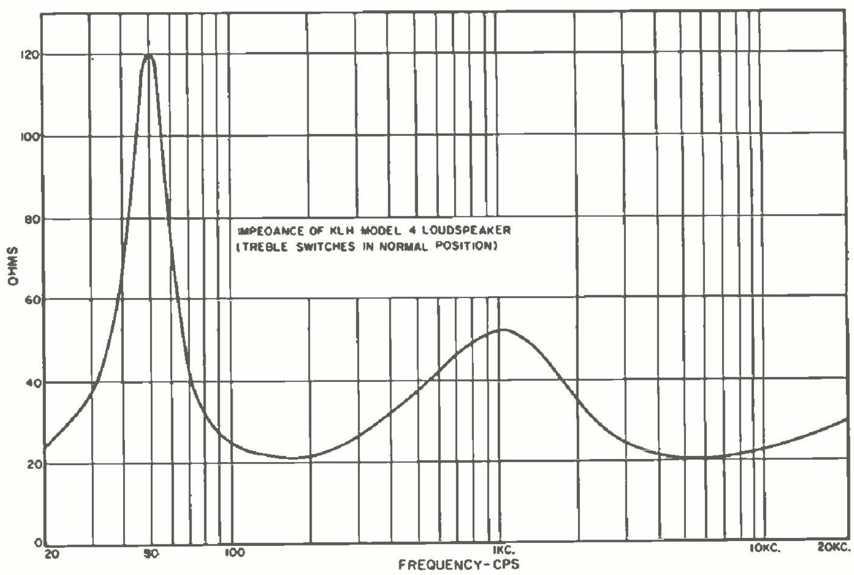
Fig. 9. Impedance curve of KLH Model 4 speaker may be used to calculate the power.



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distortion and the instrument used was a *Measurements* Model 31 IM analyzer. See Fig. 6.

Transient response: This can best be evaluated with a square-wave signal. See Fig. 5. These photographs were taken with a *Tektronix* Model 514 oscilloscope. The output load was a 16-ohm resistor. Note the absence of tilt on the 20-cycle square wave and the complete absence of ringing on the 20,000-cycle square wave. Few output-transformer-coupled amplifiers can duplicate this response.

Power output: This varies with the impedance of the loudspeaker. See Fig. 7. It is recommended that a 15-ohm or higher impedance loudspeaker system be used. With a 16-ohm loudspeaker the peak power is 38 watts. At frequencies where the impedance of the loudspeaker rises, the peak power is correspondingly increased. Figs. 8 and 9 show the impedance curves of two loudspeaker systems owned by the author; an *RCA* LC-1A mounted in a ten-cubic-foot infinite baffle and a *KLH* Model 4. It is interesting to calculate the power output capabilities of this OTL amplifier at various frequencies when using these loudspeaker systems.

Listeners who have visited the author's home (average size living room) have agreed that there is more than adequate power available, even when reproducing heavy orchestral passages. This was so even on the *KLH* Model 4. Careful monitoring of selected program material, using an oscilloscope, has shown a moderate amount of clipping at signal peaks, but the extremely fast overload recovery of the OTL amplifier has not made them discernible to the ear.

Gain: The gain of the amplifier is 8.5; that is, 1 volt of signal into the amplifier will produce 8.5 volts across the output. For maximum output using a 16-ohm load slightly over 2 volts is required. This is available from most preamplifiers.

Feedback: This amplifier uses 35 db of over-all negative feedback. The complete stability of the OTL amplifier can be dramatically demonstrated by connecting a 3000-ohm control in parallel with the feedback resistor $R_{..}$. The normal gain of the amplifier is 8.5; with the total resistance of the control in the circuit the gain is approximately 8 and the feedback 36 db. When the control shorts out $R_{..}$, there is 100% negative feedback (54 db) and the gain of the amplifier is reduced to unity. Even under these conditions there is no evidence of instability. Again, no output-transformer-coupled amplifier can duplicate this stability. (If there is need for a remote gain control, such as in a stereo setup, then this control is ideally suited as it is in a very low impedance circuit.)

Damping factor: Referred to 16 ohms, the damping factor is 80. This figure was arrived at as follows. A signal at 400 cycles from the *Precision* E300 signal generator was fed to the input of the amplifier. The meter section of the *Hewlett-Packard* 330B distortion analyzer was connected to the output of the amplifier and the signal level adjusted to read full-scale on the .3 volt range of the meter. This was with no load connected to the output. A *General Radio* 1432F decade box was then connected to the output and the resistance reduced until the meter reading was .15 volt. This occurred at a load resistance of .2 ohm, the damping factor being the ratio of the internal impedance of the amplifier (.2 ohm) and the output load.

Miscellaneous additional specifications of interest include: Hum and noise—50 dbm. Power consumption at a 117-volt line, when reproducing program material at average room volume, is 110 watts.

At this point it might be well to consider that this amplifier is designed to reproduce program material only; that is, music and speech. It is not intended for sine-wave signals and prolonged testing, at high outputs, with this type of signal will shorten the otherwise long life of the 12B4A output tubes. It should be appreciated that in the amplification of the complex signals that make up music and speech, the instantaneous power requirements are very many times the power averaged over a period of time. What we desired is an amplifier which, in the absence of signal input, uses a minimum amount of current from its power supplies and a minimum amount of plate dissipation and, when called upon to do so, can deliver a large amount of undistorted power within the average plate dissipation of its power tubes. This we have accomplished in what we believe is a novel and economical manner in the amplifier described here.

Enough of specifications! How does the amplifier sound? We honestly believe that it is the closest thing to perfection yet developed in an audio power amplifier. Given associated components of first-class quality and good program material, it recreates thrilling sound.

—30—

"OK, Joe. That's perfect, tighten her up!"